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TRaCK Tropical Rivers and Coastal Knowledge

Technical report

Ecohydrological regionalisation of Australia: A tool for management and science

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Project objectives

- To develop and validate continental-scale ecohydrological classifications of Australia's rivers using a combination of empirical and deductive approaches.
- To assess the extent to which within-drainage variation in regime exceeds variation at broader spatial scales (i.e. confounds regional classification) and understand the factors responsible for this variation.
- To test whether the developed classification is consistent across all key ecologically relevant aspects of the riverine flow regime.
- To provide a rigorous foundation for the incorporation of ecohydrological principles into scientific investigation and management of Australia's rivers.

Project final milestones

- Final validated continental-scale ecohydrological classifications of Australia's rivers.
- Consistency of the classifications across key ecologically relevant aspects of the flow regime.
- Understanding of the extent to which within-drainage variation in flow regime exceeds variation at broader scales.
- Clear documentation of the River Analysis Package (RAP).
- Flow data prepared and stored according to Land & Water Australia guidelines.
- Knowledge and adoption plan completed.

An introduction to the project's aims and methodologies underpinning the examination are given in **Appendix 1**.

a) and b) Continental-scale classification of Australia's rivers and validation

Empirical classification

A review of classification methods and of other hydrological classifications for Australia and elsewhere was undertaken (**Appendix 2**).

A review of anthropogenic factors influencing streamflow in unregulated streams was undertaken (**Appendix 3**). These reviews provide the background to the process of classifying contemporary streamflow data and the context in which classifications relate to the natural flow regime. From these reviews, we constructed a protocol for the classification, outlining all significant methodological steps required. Flow information was obtained for 830 gauges. The minimum period of record within these 830 gauges was 15 years. Whilst this relatively short record length was initially considered sub-optimal for the estimation of some flow metrics, their inclusion greatly increased geographic coverage and accordingly, substantial work was undertaken to estimate, and control for, the effect of the inclusion of these short-record length gauges in the classification. Significant work was also undertaken in screening the data to satisfy our criteria for inclusion and infilling periods of missing record (see **Appendix 4**).

Classification was undertaken using a Bayesian soft clustering technique. The resultant classification (**Appendix 5**) was composed of 12 groups broadly separated according to predictability, timing of flows and degree of intermittency. The fidelity of group membership was very high for the majority of gauges and groups. Comparison of classification outputs resulting from the total data set, long term gauge data only and short term gauge data only, revealed high concordance, thus lending confidence in the final classification in which all 830 gauges were included. Similarly, the use of different error terms (based on the long or short gauge records) to inform the clustering process did not result in widely divergent classification outcomes. Many of the classification groups were very widely distributed but a clear distinction between tropical/subtropical and temperate regions was detected. ANOSIM (Analysis of similarity) and regression tree analysis revealed that flow regime group membership could be significantly predicted based on a limited set of landscape oriented variables, thus allowing greater confidence in the outcome of the modelled (deductive) classification process. Comparison of the classification scheme with other regionalisation/classification schemes (not necessarily hydrological) at the continental scale was undertaken. Concordance was frequently poor. For example, the Australian Water Resources Advisory Council (AWRAC) basin classification is a poor description of flow regime variation except at the broadest scale of tropical versus temperate. Nonetheless, AWRAC drainage divisions remain a convenient construct for discussion of differences in flow regime type.

Deductive classification

A spatial framework was developed to supply the spatial units for the deductive classification and the representation of surface drainage pathways necessary for the attribution of catchment climatic and landscape characteristics on which the classification is based (**Appendix 7**). It was derived using new methods of drainage analysis that accommodate the uncoordinated and distributary drainage systems found over much of the Australian continent, underpinned by the latest revision of the national 9 second digital elevation model (DEM). Although the significant delays in the completion of the DEM update affected the timelines for this task this was justified by the improved accuracy of the outcomes that resulted. We generated a number of environmental classifications of the 1.2 million stream reaches with a non-hierarchical clustering method, varying the sets of attributes, their weighting and transformations and the number of groups (**Appendix 8**). A 30 group 'hydroecological/environment' classification was selected for further analysis, based on its ability to recover the flow regime classes generated by the empirical classification, its classification strength and the ease with which the classification might be communicated. The groups are primarily differentiated by attributes describing the catchment climate and water balance and secondarily by attributes characterising catchment morphology, substrate and vegetation cover. The performance of the classification was mixed. The classification strength was relatively high (75% of that for a comparable empirical classification). The groups differentiated significant variation in flow characteristics though less reliably for those metrics describing the frequency and duration of extreme events. However, the classes defined by the empirical classification were only moderately well recovered by the hydroecological environment groups. We suggested some ways in which this might be improved including better characterisation of some hydrological processes, notably those that control the groundwater contribution to streams, and alternative classificatory strategies. These would be the subject of future research. The classification is available from the author (Stein). It is provided as a Geographic Information System (GIS) layer of the stream network with associated attribute tables indicating the group membership and summary statistics of both the environmental attributes from which it was derived and the flow metrics.

c) Spatial variation at different scales

As mentioned above, the clear distinction between the flow regimes present in northern and southern Australia was one outcome of the classification and not surprisingly reflects differences in climate. Arid zone streams (Divisions VII, X and XII) grouped with tropical divisions (see

Appendix 6). These arid zones divisions contained a low diversity of flow regime types. More flow regime types were present in southern than northern Australia, reflecting the greater complexity of the landscape and weather patterns generating stream runoff. Division I in northern Australia and Division II in southern Australia were the most hydrologically diverse.

Northern flow regime types were distributed across the region with little spatial pattern. In southern Australia, two flow types (6 and 9: *predictable winter intermittent* and *predictable winter highly intermittent*, respectively) were characteristic of south-western Australia although they occurred infrequently in other southern divisions also.

Latitudinal and longitudinal differences between flow regime classes were noted although not transcending that described above. Geographic position was found to be a significant predictor of flow class membership however (**Appendix 5**). Caution was expressed when comparing flow regime diversity across divisions because of the non-uniform distribution of gauges; nonetheless regression analyses suggest that the conclusion that northern flow regime types are less diverse is valid.

Catchment size had a significant effect on flow regime diversity although it must be stressed that this analysis was focussed on determining diversity at the gauge location level not the whole catchment level. Overall (and also when examination was stratified according to a primary split of tropical and temperate climates), small streams (<100 km^2) contained a diverse range of streamflow types. Slightly larger diversity was observed for moderate (100-1000 km^2) and moderate to large streams (1000-10000 km^2). A reduced diversity was observed for the very largest of stream sizes (>10000 km^2). We reasoned that very large streams, by virtue of their large size, were restricted to draining inland areas which receive a low diversity of weather patterns. We examined whether sampling intensity (i.e. number of gauges within each stream size class) may have produced this pattern by randomisation analyses. Although flow diversity is significantly related to sampling intensity, asymptotic levels had been reached prior to the number of samples within each size class. This analysis also confirmed the earlier finding that northern Australia was typified by lower hydrological diversity than southern Australia.

Small streams were notable for the high number of flow regime classes typified by high predictability or stable flows, contrary to what may be expected. However, care must be exercised when comparing across streams of different size because the placement of gauges is not random and primarily reflects the needs of hydrographers and planners. Initial concerns that small streams were characterised by highly variable flow regimes and accordingly would show little spatial pattern in distribution proved unfounded.

Comparison of the present classification with prior regional and basin centred classifications revealed a range of levels of concordance. Relatively high concordance with that developed by Hughes (1987)[1] for Tasmania was observed, probably because the spatial patterns of rainfall were sufficiently well-defined and hydrologically important to be detected by both schemes. This proved not to be the case for the Victorian classification developed by Hughes and James (1989)[2]. Greater diversity and more spatially significant grouping of streams were observed in the present study. We analysed spatial variation for a number of other regions and river basins. The general outcome was that the continental-scale classification was unable to fully encompass flow diversity at these smaller scales. This is perhaps not surprising given that the continental-scale classification is constrained to include all variation at this large scale within a limited

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[1] Hughes, J.M.R. (1987). Hydrological characteristics and classification of Tasmanian rivers. *Australian Geographical Studies* 25: 61–82.

[2] Hughes, J.M.R. and James, B. (1989). A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. *Australian Journal of Marine and Freshwater Research* 40: 303–326.

number of groups. When additional sources of information were used (e.g. PC scores) greater spatial resolution could be achieved. It was suggested that where examination of spatial variation in flow diversity at small scales is required, then additional classifications be performed limited to the area of interest.

d) Documentation of the River Analysis Package (RAP)

RAP was an essential tool in the preparation of data and metrics used in the classification. Several features developed during the course of the project have been incorporated within RAP and will be made publicly available in subsequent releases. These include:

1) *Simulation capacity* – RAP now has a Monte Carlo runner to allow multiple time segments of a single time series to be analysed. This feature is used to determine appropriate record length for each metric, or to quantify the expected metric error due to short record length. The Monte Carlo Runner allows the user to specify the minimum and maximum record length (e.g. 2 years and 30 years respectively) to be sub-sampled from a longer base record. The user can specify the number of subsamples of each record length (default 1000). Duplicate records are removed, so that each subsample record is unique.

2) *New metrics* – Although the initial available array of metrics computed by RAP is extensive, a number of additional metrics were considered as useful for defining differences between flow regimes. These additional metrics have been added to RAP to ensure all metrics used in the project can be computed. The entire suite of metrics calculable by RAP is included as Table 9.1 as part of **Appendix 9**.

3) *Flexibility* – Flexibility in the way RAP handles series of differing record length has been added so that multiple non-concurrent records can be simultaneously calculated.

4) Metric *review* – Due to the addition of new metrics and modification of existing metrics for this study a full review of all numerical functions contained within RAP is currently underway.

Potential further developments of the capacity of RAP to incorporate the outcomes of the present study are expanded upon in **Appendix 9**.

e) Flow data prepared and stored according to Land& Water Australia guidelines

Data resulting from the project include:

1. cleaned and infilled streamflow data for each of 830 gauges
2. hydrologic metrics (a total of 120 metrics).

These data will eventually be housed in the ARI web address and will be available on request after consultation with the original data providers (i.e. state agencies). Flow metrics and flow regime class for each of the 830 stream gauges are provided in **Appendix 10**.

In addition, the environmental classification will result in:

3. GIS map-based classification
4. stream network.

We expect the stream network and associated attribute tables to be distributed by Geoscience Australia (www.ga.gov.au). We plan to package it with an associated nested catchment framework being developed by Hutchinson and Stein. The classification would also logically be included in this package. In the short term, the Fenner School will house the classification and make it available on request to Janet Stein (Janet.Stein@anu.edu.au). This smaller 'classification' package would include the streamline network with each stream link (segment) attributed with its landscape classification group plus lookup tables summarising the environmental characteristics of the groups.

Adoption

It is envisaged that adoption of the classification outcomes will occur once the project's outcomes are published and the results become more widely known and available to the scientific and managerial community. Production of a final newsletter before project's end (June 2008) will aid this. In addition, future and further incorporation of the outcomes into RAP and eWater CRC catchment Modelling Toolkits will also assist in uptake. The outcomes of the project are ready to form the framework upon which environmental flow rules will be developed within the Tropical Rivers and Coastal Knowledge program.

Accompanying documents

Appendix 1 – Introduction to the ecohydrological classification project
Appendix 2 – Protocols for hydrologic classification and a review of Australian applications
Appendix 3 – Issues associated with classification of contemporary flow data: do contemporary flow regimes approximate the 'natural flow regime'?
Appendix 4 – Quantifying uncertainty in estimation of hydrologic metrics – implications of hydrologic record length and record period
Appendix 5 – Ecohydrological classification of Australia's flow regimes
Appendix 6 – Spatial variation in the ecohydrological classification
Appendix 7 – Development of a continent-wide spatial framework for the ecohydrological classification
Appendix 8 – Ecohydrological classification based on landscape and climate data
Appendix 9 – Future development of ecohydrological classifications and limitations of the current classification approach
Appendix 10 – Xcel file containing hydrological metrics for each gauging station used in the classification and attribution of each gauge to its flow regime class.

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Appendix 1

Introduction to the ecohydrological classification project

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Figures 4.2 (in Appendix 4), 5.3, 5.5 and 5.12 (in Appendix 5) incorporate data which is © Commonwealth of Australia (Geoscience Australia) 2006. The data has been used (in Figures 5.3, 5.5 and 5.12) with the permission of the Commonwealth. The Commonwealth has not evaluated the data as altered and incorporated within Figures 5.3, 5.5 and 5.12, and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose.

The maps shown in Figures 7.1 to 7.8 (in Appendix 7) incorporate data which is © Commonwealth of Australia, Geoscience Australia 1992 and 2004. The maps shown in Figures 8.6, 8.7, 8.8 and 8.10 (in Appendix 8) incorporate data which is © Commonwealth of Australia, Geoscience Australia 1997 and 2004.

Köppen Climate classification provided by National Climate Centre, Bureau of Meteorology (2007) and IBRA V6.1 provided by the Australian Government Department of the Environment, Water, Heritage and the Arts.

Finally we gratefully acknowledge Land & Water Australia and the Tropical Rivers and Coastal Knowledge (TRaCK) research consortium for funding this study.

Summary

This Appendix summarises the need for a continental-scale classification of Australia's riverine flow regimes and introduces the two different approaches used to achieve this. The first approach involved empirically derived streamflow discharge data from 830 gauges located throughout Australia. The location and characteristics of the gauges is appended to this report. A total of 120 hydrologic metrics were calculated for each gauge and a Bayesian clustering technique was used to group gauges according to similarity in flow regime. The second technique used data derived from Geographic Information Systems (GIS) to model streamflow for 1.2 million stream segments to derive a classification flow.

This Appendix outlines the structure of the research and the preparatory work undertaken prior to classification.

1.1 Introduction

1.1.1 The need for ecohydrological information

The flow regime is recognised as a key driver of riverine ecology (Poff *et al.* 1997; Bunn and Arthington 2002) and ecohydrology seeks to quantify and explain the relationships between hydrological processes and biotic dynamics at a catchment scale (*sensu* Zalewski *et al.* 1997). The ecohydrology paradigm, based on functional relationships between hydrology and biota (Zalewski 2002), provides the theoretical basis for predicting impacts of changes to the hydrologic regimes. Aquatic habitats and biota are threatened by many processes (McAllister *et al.* 1997; Cambray and Bianco 1998), especially hydrologic changes due to land use change, water extraction and from projected climate change (Sala *et al.* 2000; Vörösmarty *et al.* 2000, 2004; Postel and Richter 2003). Environmental water allocation, scenario testing and risk analysis of various management options and planning for the impacts of global climate change all need to be based on predicted changes in the hydrologic regime (Poff *et al.* 2003; Stewardson and Gippel 2003; Richter *et al.* 2006). The ability to predict change is constrained by not knowing the role of the natural flow regime, how much flow regimes vary between rivers and regions and the extent to which such variation results in natural changes to riverine ecology.

1.1.2 Landscape scale approach

The large scale of rivers and the complexity of their flow regimes require a landscape-scale inferential approach to knowledge gathering. For example, spatial variation in flow regime at many scales is a natural feature of the riverine landscape (Poff *et al.* 1997) and studies in which ecological processes and system dynamics have been compared in rivers with contrasting hydrologic regimes, or across natural gradients in hydrology, form the basis of much known about the relationship between hydrology and ecology (Horwitz 1978; Schlosser and Angermeier 1995; Pusey *et al.* 2000). Indeed, regional classification schemes based on streamflow characteristics have been used to reveal patterns in the dynamics of community regulation and life history adaptation (Poff and Ward 1989; Poff and Allan 1995).

1.1.3 Classification

Classification/regionalisation schemes are an important step in developing generalisations concerning how natural systems or landscapes respond to changing global phenomena or natural resource management options (Higgins *et al.* 2005). In Australia, such schemes exist for, among others, water chemistry types (McNeil *et al.* 2005), freshwater fish distributions (Unmack 2001), aquatic plants (Jacobs and Wilson 1996), agro-climatic regions (Hutchinson *et al.* 2005), landscape type (Hobbs and McIntyre 2005), streamflow (Hughes 1987; Hughes and James 1989; Nathan and McMahon 1990; Zoppou *et al.* 2002) and the IBRA classification (Thackway and Cresswell 1995) of land surface based on regional and continental-scale data on climate, geomorphology, landform, lithology and characteristic flora and fauna. Hydrological classification/regionalisation, at global or regional scales, has tended to focus on certain aspects of the hydrograph such as seasonality, flood behaviour or low flow characteristics (Haines *et al.* 1988; Nathan and McMahon 1992; Burn and Arnell 1993; Bates 1994).

There has been a recent trend to explicitly link aquatic ecology and hydrology with the development of ecohydrological classification schemes derived from a large suite of ecologically relevant hydrological regimes (Poff and Ward 1989, Clausen and Biggs 1997; Snelder and Biggs 2002; Baeza Sanz and Garcia del Jalon 2005). Substantial global effort (e.g. Global Rivers Sustainability Project) is currently aimed at identifying the hydrological determinants of riverine ecosystem goods and services and of which both continental and global classification of discharge regimes is a key component (Poff *et al.* 2006).

The absence of regional frameworks based on spatial variation in the aquatic environment (both biotic and physical) is an impediment to effective management of aquatic resources, assessment of aquatic biodiversity, identification of priorities for protected area networks and assessment of the effects of global climate change (Richter *et al.* 2003; Anon. 2004; Dunn 2004). Classification allows rivers to be placed into a wider spatial context and maximises the extent to which insights gained in one river or region may be meaningfully applied to another (both within Australia and elsewhere). Regions that can be subdivided into groups of stream segments and/or river catchments that are hydrologically distinctive at landscape scales can be expected to discriminate differences in ecological character (Poff *et al.* 1997). Knowledge of patterns in hydrological character should make it possible to infer spatial patterns in assemblage composition, species traits and community functioning (Jowett and Duncan 1990; Poff and Allan 1995; Snelder *et al.* 2005). Furthermore, predictions about how riverine ecology might respond to flow regime change can be made by comparing ecological attributes across hydrological gradients, aiding assessments of present-day environmental water requirements and assessment of changes to Australia's aquatic resources under differing scenarios of global climate change and dam construction. An explicit spatial context would allow researchers to develop meaningful generalisations about the interaction between hydrology and ecology in Australia, and provide the benchmark against which the response of biological communities to hydrological alteration can be assessed.

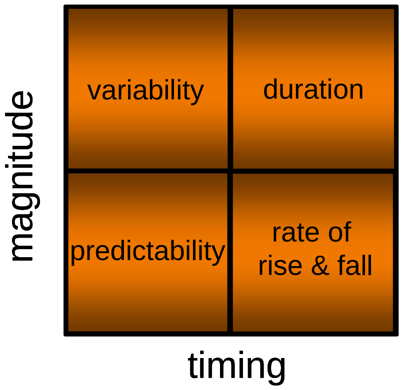

Figure 1. The six key facets of the flow regime recognised by Poff *et al.* (1997) as having ecological importance. Magnitude and timing are primary facets as they are measurable whereas the remainder are secondary facets as they are based upon timing and magnitude.

1.1.4 Ecohydrology

Ecohydrology (or hydroecology, the difference being largely semantic) aims to describe and quantify the physical aspects of the environment of aquatic organisms as defined by the six key facets of the hydrologic (flow) regime (Figure 1.1). As such, ecohydrology seeks to integrate the climatic, landscape (topographic and geologic) and geomorphological factors responsible for shaping a particular flow regime (Figure 1.2). For example, climate describes average weather conditions which determine daily rainfall and transpiration/evaporation rates that in turn directly influence stream water yield. Thus, climatic variation is imparted to hydrology with a similar pattern of variation (timing, variability and predictability) that is then modulated by interactions with topography and geomorphology.

Local variations in the interaction between average weather conditions and topographic features influence stream yield through such factors as cloud capture and orographic forcing. Such influences may prolong or intensify stream yield beyond the normal pattern imposed by prevailing weather patterns.

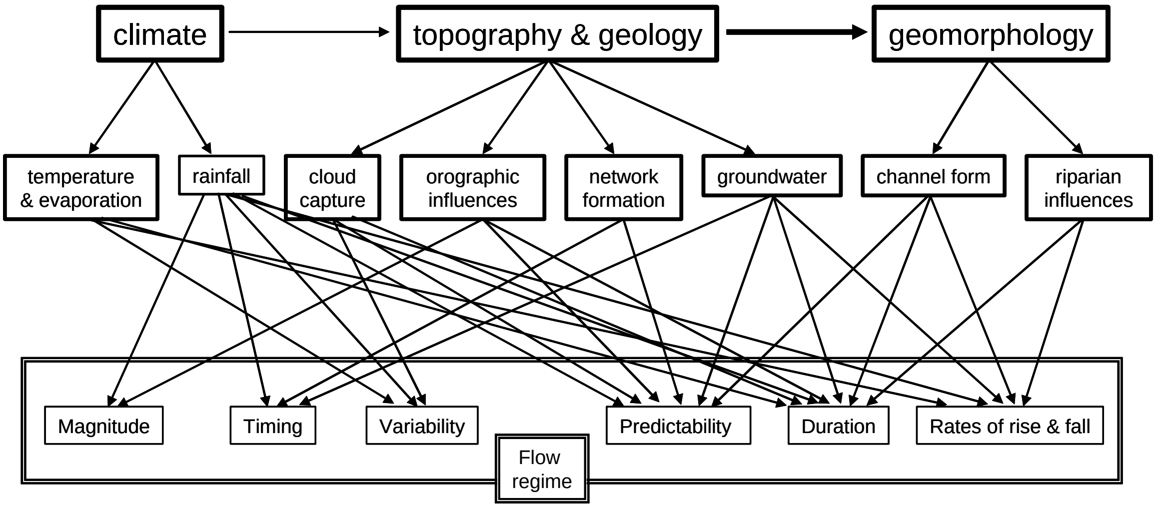

Figure 2. Interactions between climate, topography and geology and geomorphology and the six key facets of the flow regime.

Erosive work by flowing water coupled with the relative erodibility of the underlying lithography interactively influence the development of drainage networks and channel morphology thus controlling the behaviour of water within the channel (i.e. stage height and the rate at which it moves downhill). Thus, water delivered with one channel within a network may have a particular flow regime signal that is then altered by mixing with water from another channel with which it joins. This may alter the timing, predictability, duration or rates of rise and fall if climatic signals or the relative influence of topography varies between the two catchments. In addition, geological variation (i.e. presence of karst formations or basalt) may influence the extent to which water is stored in the ground and later released to the stream potentially influencing such facets as duration and rates of change. Clearly, the processes shaping a stream's flow regime are complex and multifactorial and accordingly spatial variation in flow regime at many scales is a natural feature of the riverine landscape (Poff *et al.* 1997).

1.2 Research aims, approach and report structure

The aims of the research described in the present report are broadly to describe and quantify the spatial variation in natural flow regime signatures across a very broad spatial scale (i.e. the Australian continent) and to develop a classification system applicable at this broad scale. We first examined what methodologies had been used previously in Australia and globally to classify riverine flow regimes (**Appendix 2**). Second, we assessed to what extent contemporary flow regimes approach the 'natural flow' regime by a review of natural and anthropogenic influences on flow regime at various time scales (**Appendix 3**).

1.2.1 Empirical approach

Two alternative approaches to the classification were devised (Figure 1.3). The first approach, the empirical approach, used gauged streamflow data from 830 locations throughout Australia (the locations and characteristics of these gauges are appended here as **Appendix 11**). Flow data were screened for quality (missing data etc.), missing data were infilled where appropriate. Flow data were then analysed to determine the influence of record length on metric accuracy and to determine what effect difference in time period has on comparisons between different gauges. These issues are fundamental as many of Australia's stream gauges cover short periods of record only, many of which do not cover the same time period. Our intent here was to define the minimum records length possible and minimum overlap necessary in order to increase our geographic coverage (**Appendix 4**). Based on our review of available and appropriate methodologies, we then used a Bayesian clustering technique to group gauging stations (**Appendix 5**). Spatial variation in flow regime was then assessed and described at a variety of scales (**Appendix 6**).

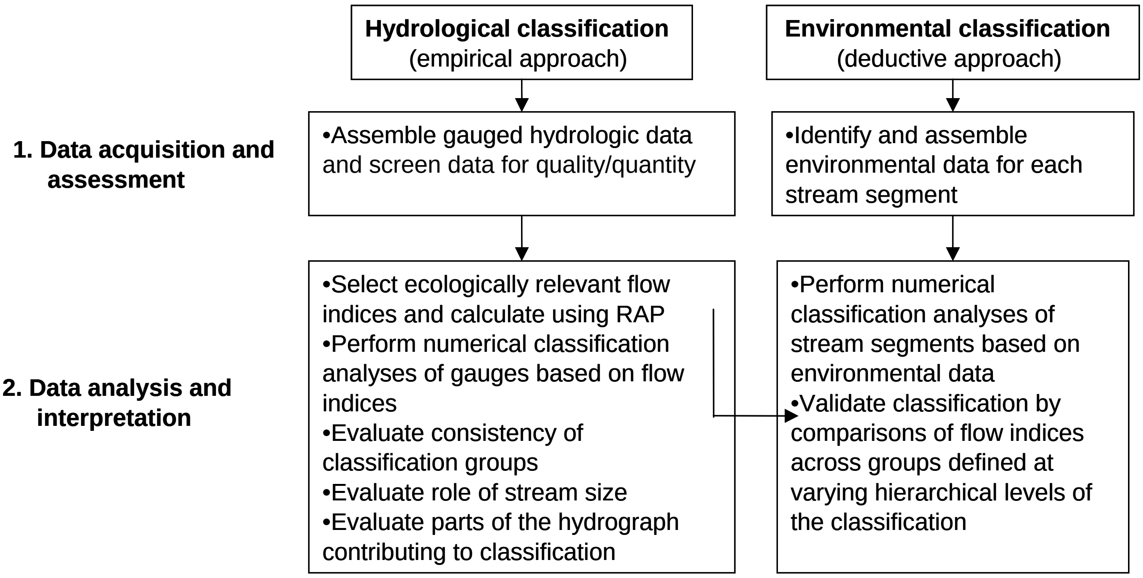

Figure 1.3. Alternative approaches to the classification of flow regimes at broad spatial scales

1.2.2. Deductive approach

The second approach, the deductive approach, used spatially explicit data concerning climate, topography, geology and geomorphology available in GIS format to model streamflow. The 9 second digital elevation model (DEM) of Australia was used to define 1.2 million stream segments across Australia (**Appendix 7**). Streamflow was then modelled for each segment and classified using a numerical classification procedure (ALOB) especially suited to such large data sets. Comparison of the two approaches was undertaken and is detailed in **Appendix 8**.

Finally, we suggest further areas of research that might result from the project's outcomes (**Appendix 9**) and detail communication activities undertaken during the project (**Appendix 10**). An excel file containing summary data and flow regime class for each of the 830 stream gauges is included as **Appendix 11**.

1.3 References

Anon. (2004). *National biodiversity and Climate Change Action Plan.* National Resource Management Ministerial Council. Department of Environment and Heritage, Canberra. 52 pp.

Baeza Sanz, D. and Garcia del Jalon, D. (2005). Characterisation of streamflow regime in central Spain, based on relevant hydrobiological parameters. *Journal of Hydrology* 310: 266–279.

Bates, B.C. (1994). *Regionalisation of hydrologic data: a review.* Report as part of Project D2: regionalization and scaling of hydrologic data. Cooperative Research Centre for Catchment Hydrology, Monash University, Melbourne. 61 pp.

Burn, D.H. and Arnell, N.W. (1993). Synchronicity in global flood responses. *Journal of Hydrology* 144: 381–404.

Bunn, S.E. and Arthington, A.H. (2002). Basic principles and consequences of altered hydrological regimes for aquatic biodiversity. *Environmental Management* 30: 492–507.

Cambray, J.A. and Bianco, P.G. (1998). Freshwater fish in crisis, a Blue Planet perspective. *Italian Journal of Zoology* 65 (Suppl.): 345–356.

Clausen, B. and Biggs, B.J.F. (1997). Relationships between benthic biota and hydrological indices in New Zealand streams. *Freshwater Biology* 38: 327–342.

Dunn, H. (2004). Defining the ecological value of rivers: the views of Australian river scientists and managers. *Aquatic Conservation: Marine and Freshwater Ecosystems* 14: 413–433.

Haines, A.T., Finlayson, B.L. and McMahon, T.A. (1988). A global classification of river regimes. *Applied Geography* 8: 255–272.

Higgins, J.V., Bryer, M.T., Khoury, M.L. and Fitzhugh, T.W. (2005). A freshwater classification approach for biodiversity conservation planning. *Conservation Biology* 19: 1–14.

Hobbs, R.J. and McIntyre, S. (2005). Categorizing Australian landscapes as an aid to assessing the generality of landscape management guidelines. Global Ecology and Biogeography 14: 1–15.

Horwitz, R.J. (1978). Temporal variability patterns and the distributional patterns of stream fishes. Ecological Monographs 48: 307–321.

Hutchinson, M.F., McIntyre, S., Hobbs, R.J., Stein, J.L., Garnett, S. and Kinloch, J. (2005). Integrating a global agro-climatic classification with bioregional boundaries in Australia. Global Ecology and Biogeography 14: 197–212.

Hughes, J.M.R. (1987). Hydrological characteristics and classification of Tasmanian rivers. *Australian Geographical Studies* 25: 61–82.

Hughes, J.M.R. and James, B. (1989). A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. *Australian Journal of Marine and Freshwater Research* 40: 303–326.

Jacobs, S.W.L. and Wilson, K.L. (1996). A biogeographical analysis of the freshwater plants of Australasia. *Australian Systematic Botany* 9: 169–183.

Jowett, I.G. and Duncan, M.J. (1990). Flow variability in New Zealand rivers and its relationship to in-stream habitat and biota. *New Zealand Journal of Marine and Freshwater Research* 24: 305–317.

McAllister, D.E., Hamilton, A.L. and Harvey, B. (1997). Global freshwater biodiversity: striving for the integrity of freshwater systems. *Sea Wind* 11: 1–140.

McNeil, V.H., Cox, M.E. and Preda, M. (2005). Assessment of chemical water types and their spatial variation using multi-stage cluster analysis. *Journal of Hydrology* 310: 181–200.

Nathan, R.J. and McMahon, T.A. (1990). Identification of homogeneous regions for the purposes of regionalisation. *Journal of Hydrology* 121: 217–238.

Nathan, R.J. and McMahon, T.A. (1992). Estimating low flow characteristics in ungauged catchments. *Water Resources Management* 6: 85–100.

Poff, N.L and Ward, J.V. (1989). Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* 46: 1805–1818.

Poff, N.L. and Allan, J.D. (1995). Functional organization of stream fish assemblages in relation to hydrologic variability. *Ecology* 76: 606–627.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997). The natural flow regime: a paradigm for river conservation and restoration. *BioScience* 47: 769–84.

Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B., Arthington, A.H., Rogers, K.H., Meyer, J.L. and Stanford, J.A. (2003). River flows and water wars: emerging science for environmental decision-making. *Frontiers in Ecology and the Environment* 1: 298–306.

Poff, N.L., Olden, J.D., Pepin, D.M. and Bledsoe, B.P. (2006). Placing global streamflow variability in geographic and geomorphic contexts. *River Research and Applications* 22: 149–166.

Postel, S. and Richter, B. (2003). *Rivers for life: Managing water for people and nature*. Island Press, Washington, DC. 253 pp.

Pusey. B.J., Kennard. M.J. and Arthington, A.H. (2000). Discharge variability and the development of predictive models relating stream fish assemblage structure to habitat in north-eastern Australia. *Ecology of Freshwater Fish* 9: 30–50.

Richter, B.D., Warner, A.T., Meyer, J.L. and Lutz, K. (2006). A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications* 22: 297–318.

Richter, B.D., Mathews, R., Harrison, D.L. and Wigington, R. (2003). Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* 13: 206–224.

Rutherford, I. D., Wiszniewski, I., Askey-Doran, M. and Glazik, R. (eds). Pp. 548–552. Department of Primary Industries, Water and Environment, Hobart.

Sala, O.E., Chapin, F.S.I., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.R., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M. and Wall, D.H. (2000). Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.

Schlosser, I.J. and Angermeier, P.L. (1995). Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. *American Fisheries Society Symposium* 17: 392–401.

Stewardson, M.J. and Gippel, C.J. (2003). Incorporating flow variability into environmental flow regimes using the Flow Events Method. *River Research and Applications* 19: 459–472.

Snelder, T.H. and Biggs, B.J.F (2002). Multiscoe river environment classification for water resource management. *Journal of the American Water Resources Association* 38: 1225–1240.

Snelder, T.H., Biggs, B.J.F. and Woods, R.A. (2005). Improved eco-hydrological classification of rivers. *River Research and Applications* 21: 609–628.

Thackway, R. and Cresswell, I.D. (1995). *An interim biogeographic regionalisation for Australia: a framework for setting priorities in the national reserve system cooperative program*. Australian Nature Conservancy Agency, Canberra. 88 pp.

Unmack, P.J. (2001). Biogeography of Australian freshwater fishes. *Journal of Biogeography* 28: 1053–1089.

Van Sickle, J. (1997). Using mean similarity dendograms to evaluate classifications. *Journal of Agricultural, Biological and Environmental Statistics* 2: 370–388.

Vörösmarty, C.J., Green, P. Salisbury, J. and Lammers, R.B. (2000). Global water resources: vulnerability from climate change and population growth. *Science* 289: 284–288.

Vörösmarty, C.J., Lettenmaier, D., Leveque, C., Meybeck, M., Pahl-Wostl, C., Alcamo, J., Cosgrove, H., Grassl, H., Hoff, H., Kabat, P., Lansigan, P., Lawford, R. and Naiman, R. (2004). Humans transforming the global water system. *EOS* 85: 509–514.

Zalewski, M., Janauer, G.A. and Jolankai, G. (1997). *Ecohydrology. A new paradigm for the sustainable use of aquatic resources*. UNESCO IHP Technical Document in Hydrology 7. IHP – V Projects 2.3/2.4, UNESCO, Paris. 58 pp.

Zalewski, M. (2002). Ecohydrology – the use of ecological and hydrological processes for sustainable management of water resources. *Hydrological Sciences Journal* 47: 825–834.

Zoppou, C., Nielsen, O.M. and Zhang, L. (2002). Regionalization of daily streamflow in Australia using wavelets and *k*-means analysis. CMA Research Report MRR02-003, Australian National University, Canberra. Available at: http://wwwmaths.anu.edu.au/research.reports/mrr/02/003/.

Appendix 2

Protocols for hydrologic classification and a review of Australian applications

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Summary

Hydrologic classification is the process of systematically arranging streams, rivers or catchments into groups that are most similar with respect to characteristics of their flow regime. Previous classification efforts have relied on a plethora of hydrologic metrics that account for characteristics of flow variability that are hypothesised to be important in shaping ecological and physical processes in lotic ecosystems. We review the process of hydrologic classification by (i) exploring its past application in the ecological sciences; (ii) reviewing existing statistical approaches to identify and characterise hydrologic classes; and (iii) providing a methodological framework for hydrologic classification that depicts critical components of the classification process.

Ecologists have used hydrologic classification to place individual streams and rivers into a broader spatial context with the goal of maximising the transferability of knowledge among rivers of the same hydrologic class. Regionalisation analyses to predict streamflow behaviour in ungauged catchments often comprise a set of regression models based on several different classes of certain hydrological information at gauged sites. Consequently, by dividing a study area into homogeneous groups that are considered to exhibit similar hydrologic characteristics, records may be extrapolated with more precision, and regionalisation models based on catchment characteristics may be used with greater confidence.

Hydrologic classification plays a central role in environmental flow assessments aimed at the development of ecologically sustainable practices for water management. Holistic methods to assess environmental flows either implicitly or explicitly involve the hydrologic classification of rivers as they can help establish the expected ecological condition of river basins by class, which alleviates the burden of developing ecological standards on a river-by-river basis. Recent interest has focused on the conservation planning of freshwater ecosystems for regional-scale biodiversity and hydrologic classification may be a useful tool for the targeted management of streams, rivers or entire catchments with representative flow regimes, and therefore, representative biological communities.

A variety of classification techniques have been used in the past to derive hydrological classifications and regionalisations. These include: hierarchical and flat clustering algorithms, self-organising maps, multivariate ordination and hard and soft classification algorithms such as fuzzy clustering and Bayesian classification. We reviewed the different methods available and the information needs and processes required to satisfy several statistical assumptions and requirements. We used a protocol for classification that addresses issues about data quality and comparability, choice of classification method and assessment of results.

We also reviewed previous applications of hydrological classification in Australia, covering Australian examples of both hydrological and ecohydrological classifications but coverage of the former is not exhaustive. These prior classifications provided a means of comparing the outcomes of the classification developed in the present project.

2.1 Introduction

Hydrologic classification is the process of systematically arranging streams, rivers or catchments into groups that are most similar with respect to characteristics of their flow regime. This process has frequently been applied by hydrologists seeking to extend insights gained from well-gauged regions to ungauged or sparsely gauged regions or rivers (Bates 1994). Typically, only specific components of the flow regime are included (e.g. flood series) (Nathan and McMahon 1990; Bower *et al.* 2004). Hydrologic classification is playing an increasing role in the ecological sciences for understanding riverine flow variability (Mosley 1981; Haines *et al.* 1988; Poff 1996; Harris *et al.* 2000), exploring the influence of streamflow on biological communities and ecological processes (Jowett and Duncan 1990; Poff and Allan 1995; Pusey *et al.* 2000; Snelder *et al.* 2004; Monk *et al.* 2006, 2007), aiding hydrologic modeling in regionalisation analyses (Nathan and McMahon 1990), providing an inventory of hydrologic types for water resource management (Snelder and Biggs 2002; Wolock *et al.* 2004; Arthington *et al.* 2006), and prioritising conservation efforts for freshwater ecosystems (Nel *et al.* 2007; Snelder *et al.* 2007). Consequently, hydrologic classification has practical use as an organising framework for both river research and management purposes.

Three broad categories of hydrologic classification exist that serve to describe flow regime similarities among rivers: those according to geographic proximity, environmental attributes, or hydrologic characteristics. Geographical regions have been identified based upon political, administrative, river basin and climatic boundaries (Arnell *et al.* 1990). The delineated regions are located in close geographic proximity to one another, however this often does not guaranteed that the regions will be hydrological homogenous. An alternative approach is to define classes based on the environmental factors that are assumed to broadly produce similar hydrological responses. This represents a deductive approach to hydrologic classification that is often geographically-independent and depicted by a mosaic pattern of hydrologic types across the landscape (Detenbeck *et al.* 2000). Numerous physical-based or geomorphic classifications of rivers have been conducted; including those based on geology, topography, and climate (e.g. Kondolf 1995), as well as combined hydrogeomorphic typologies (e.g. Snelder and Biggs 2002; Snelder *et al.* 2005; Dollar *et al.* 2007; Schmitt *et al.* 2007; reviewed in Kondolf *et al.* 2003). These classifications are common, but do not reflect only hydrological variation because they encompass more general principles concerning the causes of spatial variation in ecological characteristics of streams and rivers. To overcome these difficulties, delineating patterns in hydrologic character have also been identified directly through empirically-based methods that use hydrologic metrics describing different components of the multi-facet riverine flow regime. In this application, hydrologic classification schemes attempt to provide order to inherently complex flow data by identifying and characterising similarities among rivers according to a set of diagnostic hydrologic attributes that vary spatially across the landscape (Mosley 1981; Jowett and Duncan 1990; Poff 1996; Harris *et al.* 2000). This approach to hydrologic classification is the focus of this section.

A number of hydrologic characteristics comprise the natural flow regime, including the seasonal patterning of flows; timing of extreme flows; the frequency, predictability, and duration of floods, droughts, and intermittent flows; daily, seasonal, and annual flow variability; and rates of change (Poff *et al.* 1997). Accordingly, previous classification efforts have relied on a plethora of hydrologic metrics that account for characteristics of flow variability that are hypothesised to be important in shaping ecological and physical processes in lotic ecosystems (Hughes 1987; Poff and Ward 1989; Hughes and James 1989; Pusey and Arthington 1996; Richter *et al.* 1996; Poff *et al.* 1997; Puckridge *et al.* 1998; Clausen and Biggs 2000; Harris *et al.* 2000; Bunn and Arthington 2002; reviewed by Olden and Poff 2003; Bower *et al.* 2004; Monk *et al.* 2006). Many of these metrics have proven to be highly suitable for hydrologic classification. Moreover, these aspects of the hydrologic regime are likely to be most frequently altered by human activities such as river regulation by dams (Poff *et al.* 2007), and are predicted to be sensitive to global climate change (Milly *et al.* 2005).

Researchers have applied a number of statistical approaches and used a variety of hydrologic metrics in attempts to develop hydrologic classifications at catchment, regional, national, continental and global scales (Table 2.1). For example, efforts at global or continental scales have primarily focused on certain aspects of the hydrograph such as seasonality, flood behaviour or low flow characteristics, whereas regional classifications have utilised a larger suite of hydrologic metrics. Challenged by the need to quantify flow similarities among rivers and map their distribution across hydrologic landscapes (sensu Winter 2001), ecologists have turned to a bewildering array of statistical approaches using an equally diverse set of protocols to conduct their hydrologic classification (Table 2.1). During the last two decades considerable effort has gone into analysis and development of methodological approaches to hydrologic classification. As a result, several groups of methods are in use, and to-date no single approach has been demonstrated to yield universally acceptable results. Consequently, most researchers reach into their same statistical toolbox when required to tackle a classification problem and are unaware of important considerations and new techniques available to them.

Herein, we review the process of hydrologic classification by (i) exploring its past application in the ecological sciences; (ii) reviewing existing statistical approaches to identify and characterise hydrologic classes; and (iii) providing a methodological framework for hydrologic classification that depicts critical components of the process in order that researchers will be better informed regarding the selection and proper implementation of methods for hydrologic classification. To close, we also review the outcomes of prior attempts to classify Australian rivers and suggest an appropriate way to proceed with a classification of Australian flow regime types.

2.2 Ecological applications of hydrologic classification

Hydrologic classification has been conducted for a number of purposes in ecology. Below we briefly highlight some of the more common applications of hydrologic classification in the literature.

2.2.1 Increasing our understanding of flow variability among streams and rivers by identifying hydrologic classes

Ecologists have used hydrologic classification to place individual streams and rivers into a broader spatial context with the goal of maximising the transferability of knowledge among rivers of the same hydrologic class and to show broader application of intensely studied sites to unstudied sites (Table 2.1). Hydrologic classes are expected to have similar biological responses to both natural and human-induced variability in patterns of magnitude, frequency, duration, timing and rate of change in flow conditions. Consequently, systems that show commonalities in their hydrologic characteristics have provided a basis for testing whether hydrology influences the structure and function of biological communities in a similar fashion (e.g. Poff and Ward 1989; Jowett and Duncan 1990; Poff and Allan 1995; Snelder *et al.* 2004). Recent efforts have also focused on how rivers in different classes vary with respect to the degree of human influence (e.g. land use, river regulation), thus providing a benchmark against which the response of biological communities to these factors can be assessed.

2.2.2 Hydrologic classification for the purposes of guiding regionalisation analyses

Classification has a long history of use in the regionalisation of hydrologic models that attempt to achieve continuous streamflow predictions in ungauged basins (e.g. Tasker 1982; Nathan and McMahon 1990; Abdulla and Lettenmaier 1997; Merz and Bloeschl 2004; Wagener *et al.* 2007; Yadav *et al.* 2007). Regionalisation analyses often comprise a set of regression models based on several different classes of certain hydrological information at gauged sites. Consequently, by dividing a study area into homogeneous groups that are considered to exhibit similar hydrologic characteristics, records may be extrapolated with more precision, and regionalisation models based on catchment characteristics may be used with greater confidence.

2.2.3 Developing environmental flow recommendations for water resource management

Hydrologic classification plays a central role in environmental flow assessments (Tharme 2003) aimed at the development of ecologically sustainable practices for water management (Richter *et al.* 2006). Holistic methodologies to environmental flow assessments, such as the application of the benchmarking methodology (Brizga *et al.* 2002), Downstream Response to Imposed Transformations (DRIFT: King *et al.* 2003), and the Ecological Limits of Hydrologic Alteration (ELOHA: Poff *et al.* in review), either implicitly or explicitly involve the hydrologic classification of rivers to varying extents. Arthington *et al.* (2006) describe how the classification of undeveloped rivers can help establish the expected ecological condition of river basins by class, which alleviates the burden of developing ecological standards on a river-by-river basis. As a result, environmental flow rules for rivers with detailed data can provide interim recommendations for rivers in the same class where data are sparse and the response of biota to hydrological patterns is unknown but may be assumed to be similar to those occurring in hydrologically similar rivers for which flow ecology relationships are known.

2.2.4 Identifying and prioritising conservation efforts for freshwater ecosystems

Recent interest has focused on the conservation planning of freshwater ecosystems for regional-scale biodiversity (e.g. Saunders *et al.* 2002, Moilanen *et al.* 2008). Hydrologic classification may be a useful tool for the selection of streams, rivers or entire catchments with representative flow regimes, and therefore, representative biological communities (Nel *et al.* 2007, Poff *et al.* 2007).

2.3 Methodological approaches to hydrologic classification

The strategy of hydrologic classification is to ascribe objects (i.e., streams, rivers, catchments) to empirically-based groupings or classes, so as to maximise the similarity between the members of each group and minimise the similarity between groups. Because of the many ways that magnitude and variability of flow can be characterised (Olden and Poff 2003) analysing hydrologic metrics using a multivariate approach is an effective means to determine similarities or differences among and/or within rivers. The multivariate techniques for identifying classes of river and organising them into a hydrologic topology are numerous and vary in output properties, such as whether the classes are hierarchical or flat, whether boundaries between classes are hard (i.e. defined) or soft (i.e. fuzzy), and/or whether rivers can belong to one or more classes (described in detail below). As Nathan and McMahon (1990) point out, a major problem encountered when using cluster analysis for hydrologic classification is the plethora of different linkage algorithms and distance measures available. Unfortunately, different clustering techniques applied to the same set of data will often produce structures that are substantially different. This is because the choice of a clustering method implicitly imposes a structure on the population and is often tantamount to defining a structure. Therefore, the choice of statistical approach used in hydrologic classification is critical. Below we provide a preliminary review of different methodologies that have been used to develop hydrologic classifications in the past, and finish by describing differences between hard versus soft classifications.

2.3.1 Hierarchical and flat clustering algorithms

Both hierarchical and flat clustering algorithms have been used to develop hydrologic classifications (Table 2.1). Hierarchical clustering proceeds iteratively by either combining smaller clusters into larger ones (agglomerative), or by splitting larger clusters to smaller ones (divisive) to produce a classification of objects typically presented as a dendrogram of clusters. Flat clustering techniques identify clusters of equal distinction, and thus are not represented in a hierarchy. Certain algorithms can be adapted to provide either hierarchical or flat classifications.

Gordon (1987) provides a good overview from a statistical perspective. Rao and Srinivas (2006) outline eight common algorithms for agglomerative hierarchical clustering of rivers according to their flow regimes: 1) single linkage or nearest neighbor; 2) complete linkage or furthest neighbor; 3) average linkage (UPGMA); 4) weighted average linkage; 5) centroid; 6) median or weighted pair-group centroid; 7) density or k-linkage; and 8) Ward's algorithm. The k-means algorithm is a commonly employed divisive clustering technique for non-hierarchical classification. The algorithm groups cases according to Euclidian distance from initial, randomly chosen cluster centers of a predetermined number. Then it iteratively redefines cluster centers as the means of the cases in the latest cluster, until cases no longer change membership. The method is efficient for large datasets, and results are often sufficient, although subjectivity of the initial cluster centroids must be considered.

Hierarchical and flat clustering methods can be used in tandem to optimise hydrologic classification (called hybrid clustering). For example, Rao and Srinivas (2006) used a partitional clustering procedure to identify groups of similar catchments by refining the clusters derived from agglomerative hierarchical clustering algorithms using the k-means algorithm. Similarly, Kahya *et al.* (2007) considered results of a hierarchical, average-linkage algorithm to help identify an optimal number of clusters for subsequent flat classification using k-means.

Determining the number of clusters is a problem inherent to most if not all conventional clustering techniques. For flat algorithms, the number of clusters must be predetermined before the patterns of input data have even been analysed. For hierarchical algorithms, selection of the degree of cluster distinction between tiers is subjective. Several approaches for optimising the number of clusters have been discussed in the literature.

2.3.2 Self-organising maps

Machine learning approaches provide a powerful set of tools for analysing complex ecological data (Olden *et al.* 2008). Self-organising maps (SOM; Kohonen 1982, 2000) provide a means of representing high-dimensional data in a low-dimensional view; typically a two-dimensional map. The goal is for the map to retain topological properties of the input data, in contrast to information losses common to other data-reduction techniques such as principal component analysis. Using SOM as a framework for performing cluster analysis and discrimination analysis of hydrological factors in one step has been presented by Lin and Wang (2006) as a novel and efficient method for hydrologic classification. Their

SOM-based cluster and discrimination analysis (SOMCD) produces three maps in a single step for use in classification. The feature density and discrimination maps can be used to assign unknown catchments to classes at one time, eliminating the step of post-clustering discriminant analysis for each unknown catchment. As well, the ability to define the number of clusters at multiple resolutions from the feature and density maps is argued as a top advantage of the method.

2.3.3 Multivariate ordination

Multivariate ordination techniques, including principal components analysis (PCA) and principal coordinate analysis, have been used to develop (or aid in) hydrologic classification (Table 2.1). PCA involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible (Legendre and Legendre 1998). In many applications, the composition scores from a small number of principal components are retained and then clustered to identify rivers with similar flow regimes (Table 2.1).

2.3.4 Hard versus soft classification

Clustering algorithms can lead to either hard or soft (i.e. fuzzy) classifications. A hard clustering method is based on the assumption that feature vectors can be divided into non-overlapping clusters with well-defined boundaries between them. Each feature vector is assigned to one of the clusters with a degree of membership equal to unity. In other words, a catchment is classified as belonging to a cluster on the basis of distance (or dissimilarity) between the catchment and the cluster centroid in the multi-dimensional space of attributes depicting the flood response of catchments. A brief review of hard clustering algorithms in regionalisation is found in Srinivas *et al.* (2002) and Rao and Srinivas (2003).

It is reasonable to suppose, however, that most catchments partially resemble several catchments and therefore assigning a catchment to one region (cluster) or another may not be justified. Consequently, identification of regions with vague boundaries between them is preferable, compared to crisp regions with well-defined boundaries as in the case of hard clustering. The fuzzy set theory (Zadeh 1965), which straddles ordination classification and clustering analysis (Roberts 1986), is a natural way to represent such a situation. Fuzzy partitional clustering allows a catchment to belong to all the regions simultaneously with a certain degree of membership. The distribution of membership of a catchment among the fuzzy clusters specifies the strength with which the catchment belongs to each region. The knowledge of this distribution is particularly useful to identify ambiguous catchments. A threshold to maximum membership values can be applied to derive crisp, vector-based representations from raster, fuzzy classifications. Rao and Srinivas (2006) argue that given the intricate process interactions controlling channel morphology and the inadequacies of conventional stream classification methods, fuzzy representations of in-stream habitat present an appealing alternative.

Another fuzzy partitional method available is Bayesian mixture modeling (Gelman *et al.* 2004). In this approach, the observed distribution of data is modeled as a mixture of a finite number of component distributions in order to determine the number of distributions, their parameters, and object memberships (Webb *et al.* 2007). The approach is fully probabilistic and uncertainty can be explicitly reported in terms of data specification, class specification and the final classification chosen (Cheeseman and Stutz 1996; Webb *et al.* 2007). Multiple plausible classifications are produced, which are then ranked on their estimated marginal likelihoods to select the most parsimonious classification that is guaranteed to have the highest posterior probability; the probability of the model being correct given the data (Cheeseman and Stutz 1996; Gelman *et al.* 2004; Webb *et al.* 2007).

Table 2.1. Examples of hydrologic classifications of riverine flow regimes. Flow regime attributes: Magnitude (M), Frequency (F), Duration (D), Timing (T), Rate of Change (R). Temporal scale (of the flow regime attributes analysed): Daily (D), Monthly (M), Annual (A). NOTE: This table presents the results from a preliminary review of the literature.

Spatial Scale	Location	Flow attributes	Temporal scale	Classification methodology	Reference(s)
Basin					
	Burdekin River, north-eastern Australia	M, F, D, T	D, M, A	Principal components analysis and discriminant functions analysis	**Pusey and Arthington (1996)**
	Condamine–Balonne River, Australia	M, F, D, T, R	D, M, A	Flexible-unweighted pair-groups using arithmetic averages (UPGMA) fusion strategy	**Thoms and Parsons (2003)**
	Missouri and lower Yellowstone Rivers, USA	M, T	M, A	Hierarchical, agglomerative cluster analysis using group centroid method	**Pegg and Pierce (2002)**
	Tagus River, Spain	M, F, D, T	D, M, A	Method not stated	**Baeza Sanz and Garcia del Jalon (2005)**
Regional					
	Victoria, Australia		D	PCA & average linkage clustering	**Hughes and James (1989)**
	Tasmania, Australia		D	PCA & complete linkage clustering	**Hughes (1987)**
	South-eastern Australia	M, D, R	D,M	Ordination	**Growns and Marsh (2000)**
	Quebec, Canada	M, D, T, R	M	PCA & heuristic classification method (based on rules and signs of loadings on PC's)	**Assani and Tardif (2005)**
	Alabama, Georgia & Mississippi, USA	M, T	M	Hierarchical, agglomerative cluster analysis using average linkage method	**Chiang *et al.* (2002a) (see also Chiang *et al.* (2002b))**
	Indiana, USA	M, T	D, M, A	Hierarchical clustering algorithms based on single linkage, complete linkage and Ward's algorithms, while the partitional clustering algorithm used is the K-means algorithm	**Rao and Srinivas (2006)**
	Arizona, USA	M, F	D, A	Hierarchical, agglomerative cluster analysis using complete linkage method	**Tasker (1982)**
	Southern Taiwan	M, T, F		Cluster analysis and discrimination analysis in one step using self-organising maps	**Lin and Wang (2006)**
	South-eastern Australia	N/A		Physical catchment variables identified as important predictors of low flow characteristics were classified using cluster analyses	**Nathan and McMahon (1990)**

Spatial Scale	Location	Flow attributes	Temporal scale	Classification methodology	Reference(s)
National/Continental					
	Australia	M, T	M	Hierarchical, agglomerative cluster analysis using within-group average method with cosine similarity measure	**Finlayson and McMahon (1988)**
	United Kingdom	M, T	M	Two-stage procedure: (i) hierarchical, agglomerative cluster analysis using Ward's method, followed by (ii) non-hierarchical, k-means cluster analysis	**Bower et *al.* (2004) (see also Harris et *al.* (2000), Hannah et *al.* (2000))**
	Austria	M, T	D	PCA & partitive cluster analysis (partitioning around medoids (PAM)	**Laaha and Blöschl (2006a) (see also Laaha and Blöschl (2006b))**
	Australia	F, T	D	An orthogonal Haar wavelet transform was used to describe the temporal multi-scale variability of the streamflow. The spatial organisation of this spectral multi-scale variability was organised using k-means analysis.	**Zoppou et *al.* (2002)**
	United Kingdom	M, T	M	Hierarchical, agglomerative cluster analysis using Ward's method	**Monk et *al.* (2006, 2007) (see also Harris et *al.* (2000); Hannah et *al.* (2000); Bower et *al.* (2004))**
	United Kingdom	M, T	M	Hierarchical, agglomerative cluster analysis using average linkage	**Harris et *al.* (2000) (see also Hannah et *al.* 2000))**
	Nepal	M, T	M	Hierarchical, agglomerative cluster analysis using Ward's method	**Hannah et *al.* (2005) (see also Harris et *al.* (2000); Hannah et *al.* (2000); Bower et *al.* (2004))**
	Sweden	M, T	M	Pairwise group arithmetic average & PCA	**Gottschalk (1985)**
	United States	M, T	Y	PCA & visual assessment	**Lins (1985)**
	USA	M, F, D, T	D, M, A	Non-hierarchical cluster analysis using k-means	**Poff and Ward (1989)**
	USA	M, F, D, T	D, M, A	A priori (permanent vs. intermittent) & density linkage (based on all flow metrics)	**Poff (1996)**
	USA (five river basins)	M, F, D, T	D, M, A	UPGMA agglomerative clustering (Euclidean distances) (also PCA)	**Poff et *al.* (2006)**
	New Zealand	M	D	Hierarchical cluster analysis (using BMDP2M cluster analysis program)	**Mosley (1981)**
	New Zealand	M, F	D, A	Two-way indicator species analysis (TWINSPAN)	**Jowett and Duncan 91990)**

Spatial Scale	Location	Flow attributes	Temporal scale	Classification methodology	Reference(s)
	Tanzania	M, F	A	Three-step process: (1) Geographic information was used to identify likely homogeneous regions that are geographically continuous; (2) Each region that was identified in the previous step was checked for similarity in the statistics of observed flood data. Based on this step, regions obtained in step (1) were modified; (3) A test of homogeneity was applied to confirm that the delineated regions were statistically homogeneous.	**Kachroo and Mkhandi (2000)**
	Turkey	M	A	Non-hierarchical, k-means cluster analysis	**Kahya *et al*. (2007)**
	South Africa, Lesotho and Swaziland	T, M	M	Index of variability (CVB = CV/BFI) divided into 8 statistically derived classes (using cumulative deviations from homogeneity plots)	**Hughes and Hannart (2003), Nel *et al*. (2007)**
	Scandinavia	M, T	M	Flow regime class discriminating criteria based on the time of occurrence of the highest (3 classes) and lowest (2 classes) of mean monthly flow	**Gottschalk *et al*. (1979), Krasovskaia and Gottschalk (1992, 2002)**
	Scandinavia and western Europe	M, T	M	Flow regime class discriminating criteria based on the time of occurrence of the highest (3 classes) and lowest (2 classes) of mean monthly flow	**Krasovskaia *et al*. (1994) (see also Krasovskaia (1995))**
	Scandinavia	M, T	M, A	Two-step approach: (1) Flow regime class discriminating criteria based on the time of occurrence of the highest (3 classes) and lowest (2 classes) of monthly flow, (2) entropy based groupings based on interannual variation in monthly flows (allows quantification spatial variation in the temporal regularity of seasonal flow patterns defined in step 1)	**Krasovskaia (1997) (see also Krasovskaia *et al*. (1999))**
	Southern Africa	M	A	Delineated flexible homogeneous regions based on available information on topography, mean annual rainfall, drainage pattern and maximum flood peak regions	**Mkandi and Kachroo (1996)**
	Europe & UK	M, T, F, D		Hierarchical, agglomerative cluster analysis using Ward's method	**Stahl (2001)**
	France	M, T	M	Proportion of flow within each of four seasons, together with estimation of the genetic origin of flow (i.e. snow melt, glacier melt, rainfall)	**Parde (1955) (see Sauquet *et al*. (2000) for application)**

Spatial Scale	Location	Flow attributes	Temporal scale	Classification methodology	Reference(s)
	Russia	M, T	M	Proportion of flow within each of four seasons, together with estimation of the genetic origin of flow (i.e. snow melt, glacier melt, rainfall and groundwater). The mean average monthly flow pattern satisfying the discriminating criteria is assigned a certain regime type.	**Lvovich (1973) (see Krasovskaia (1997))**
Global					
		M, T	M, A	Hierarchical, agglomerative cluster analysis using within-group average method with cosine similarity measure. Simplified version using decision tree with empirical rules/algorithms.	**Haines *et al.* (1988)**
		M	A	Two-step approach: (1) initial groupings based on regions of similar climatic conditions (based largely on Koppen's Climate Classification). A hierarchical agglomerative cluster analysis using the within-group average method was subsequently used to create a smaller number of groups based on similarity in annual maximum discharge.	**Burn and Arnell (1993)**
		M, F	A	Examined regional variation in mean annual flood magnitudes and flood frequency curves, where regions were defined using an empirical approach based firstly on physical and climatic characteristics, and second, by evaluation of the homogeneity of flood frequency curves within the defined regions.	**Meigh *et al.* (1997)**
		M, F, D, T R	D, M, A	Agglomerative hierarchical fusion (flexible UPGMA) on the Bray–Curtis matrix	**Puckridge *et al.* (1998)**
		M, T	M	Hierarchical, agglomerative cluster analysis using within-group average method with cosine similarity measure.	**Finlayson and McMahon (1988)**
		M, T	M	Non-hierarchical, k-means cluster analysis.	**Dettinger and Diaz (2000)**

2.4 A framework and protocol for hydrologic classification

Hydrologic classification should be an objective process, transparent, readily interpretable, explicitly account for uncertainty and for variability at multiple temporal and spatial scales, explicitly regard methodological biases and robustness, and provide definable class boundaries, objective group membership, and information on the diagnostic hydrologic characteristics of each class. We believe that for a hydrologic classification system to be widely adopted it must be founded on a defensible scientific framework (Figure 2.1). Below, we provide specific guidelines for achieving this goal.

1. *Define purpose of the study, geographic region of interest and objectives of the hydrologic classification.*

2. *Acquire and assess hydrologic data*

    a) What discharge data are available (gauged versus modeled data, temporal grain – daily, monthly or annual, time period, geographic coverage)?
    b) Select candidate set of gauges (if using gauged discharge data).
    c) If your purpose is to classify 'natural' flow regimes, then select gauges that are not likely to be affected by anthropogenic factors (e.g. dams, water extraction, land use) using best available information (e.g. spatial patterns of land use, dam location and attributes, expert knowledge and input from water managers, etc.).
    d) Evaluate quality of discharge data (i.e. missing data, poor quality measurement recordings as indicated by quality codes) and eliminate gauges with missing data and unsatisfactory gauge recordings.
    e) Ensure consistency of discharge measurement units among gauges (e.g. $m^3 \cdot sec^{-1}$ versus $ML \cdot day^{-1}$).
    f) Evaluate temporal period (e.g. 1965–2000) and duration (i.e. 35 years) of available discharge data for each gauge.
    g) Decide on criteria for acceptance of gauges (i.e. minimum versus fixed record length, completely overlapping versus partially overlapping period of record, period of record to include particular years, such as years including significant changes in climate).
    h) Evaluate geographic locations of gauges to ensure adequate spatial coverage (i.e. representing climate regions of interest).
    i) If the spatial coverage is not adequate, then evaluate potential for including additional gauges by:
        i. relaxing the acceptance criteria (step 2g), and/or
        ii. estimating missing data in the discharge time series (step 2d) by using linear interpolation for short periods, general linear regression for longer periods, or some other appropriate technique.

    Note that relaxing the acceptance criteria will decrease the comparability of gauges, and estimating missing data will increase the measurement uncertainty of flow data. Both options will compromise accuracy and precision of classification results (although some hydrologic metrics are more sensitive to record length and period overlap than others).

3. *Choose hydrologic metrics to include in the hydrologic classification*

   a) The selection of metrics depends primarily on purpose of the study (step 1). One might be interested in selecting a large number of metrics to characterise all facets of the flow regimes, or individual metrics of known/hypothesised ecological importance (see Olden and Poff 2003).
      i. General ecological rationale: set of metrics to characterise the totality of the flow regime.
      ii. Specific ecological rationale: individual metrics of known/hypothesised ecological importance for specific species, community, or ecosystem properties.
      iii. Driver rationale: metrics that are sensitive to an environmental or anthropogenic driver of interest (e.g. urbanisation, river regulation, climate change).
   b) Selection depends on temporal grain of flow data.
   c) Selection depends on intended software used to calculate metrics and practical capability of the researcher. Software options include dedicated hydrologic software (Indicators of Hydrologic Alteration (IHA): Richter *et al.* 1996; Hydrologic Assessment Tool (HAT): Henriksen *et al*. 2006; River Analysis Package (www.toolkit.net.au/rap) versus statistical/mathematical software.
   d) Selection based on quantifying statistical redundancy among metrics using univariate and multivariate approaches. The results will inform variable selection and dimensionality reduction (e.g. indirect ordination approaches to produce composite variables) if multicollinearity among metrics is a concern (see Olden and Poff 2003).
   e) No choice. Hydrologic classification will proceed using the raw discharge time series.

4. *Compute hydrologic metrics*

   a) Calculate the hydrologic metrics for each flow record according to decisions made in step 3.
   b) Screen datasets for outliers and/or gauges potentially affected by anthropogenic activity by:
      i. Examining diagnostic plots and descriptive statistics
      ii. Conducting indirect ordination (e.g. principal components analysis), plotting ordination scores of gauges in 2-dimensional space and looking for outliers that might be suggestive of modified flows, unique natural flows, or measurement/data entry errors
      iii. Plotting mean daily flow (or similar hydrologic metric) against catchment area (gauges with obviously lower discharge than expected for a given catchment size may be effected by water extraction).
   c) Eliminate gauges if necessary.
   d) Remove scale-dependence of flow magnitude metrics (if required, depending on objectives of the study) by standardising metrics by catchment area or mean daily flow.

5. *Conduct the hydrologic classification*

   a) Choose statistical approach depending on objective of classification, software and capability of the researcher (see review below).
   b) Decide which hydrologic metrics to include in classification analysis:
      i. All flow metrics

    ii. Subset(s) of metrics describing separate components of flow regime (this decision depends on the reason for classification, see step 1)
    iii. Prune the total number of flow metrics to a smaller set of high-information, non-redundant flow metrics (see Olden and Poff 2003)
    iv. Choice of metrics might also be dependent on statistical assumptions/requirements (data type, normality, etc.) of classification approach.

c) Decide whether metric transformations/standardisations are required.
d) Choose appropriate distance/similarity measure (if required).
e) Conduct classification analysis.
f) Delineate clusters, and decide on the number of hydrologic classes (i.e. clusters), class membership, and probabilities of class membership (see below).
g) Examine classification results for outliers and eliminate gauges if necessary; repeat steps 5d–f.

6. *Interpret the hydrologic classification*

a) Describe hydrologic characteristics of hydrologic classes, numerically, statistically, graphically, and verbally.
b) Examine geographic distribution of gauge class membership (e.g. using a Geographic Information System).
c) Optionally, validate the classification model using an independent dataset containing gauges not included in the classification or based on a set of environmental variables describing each gauge that are considered the most important for shaping flow regime characteristics (i.e. the results of a physical-based classification).

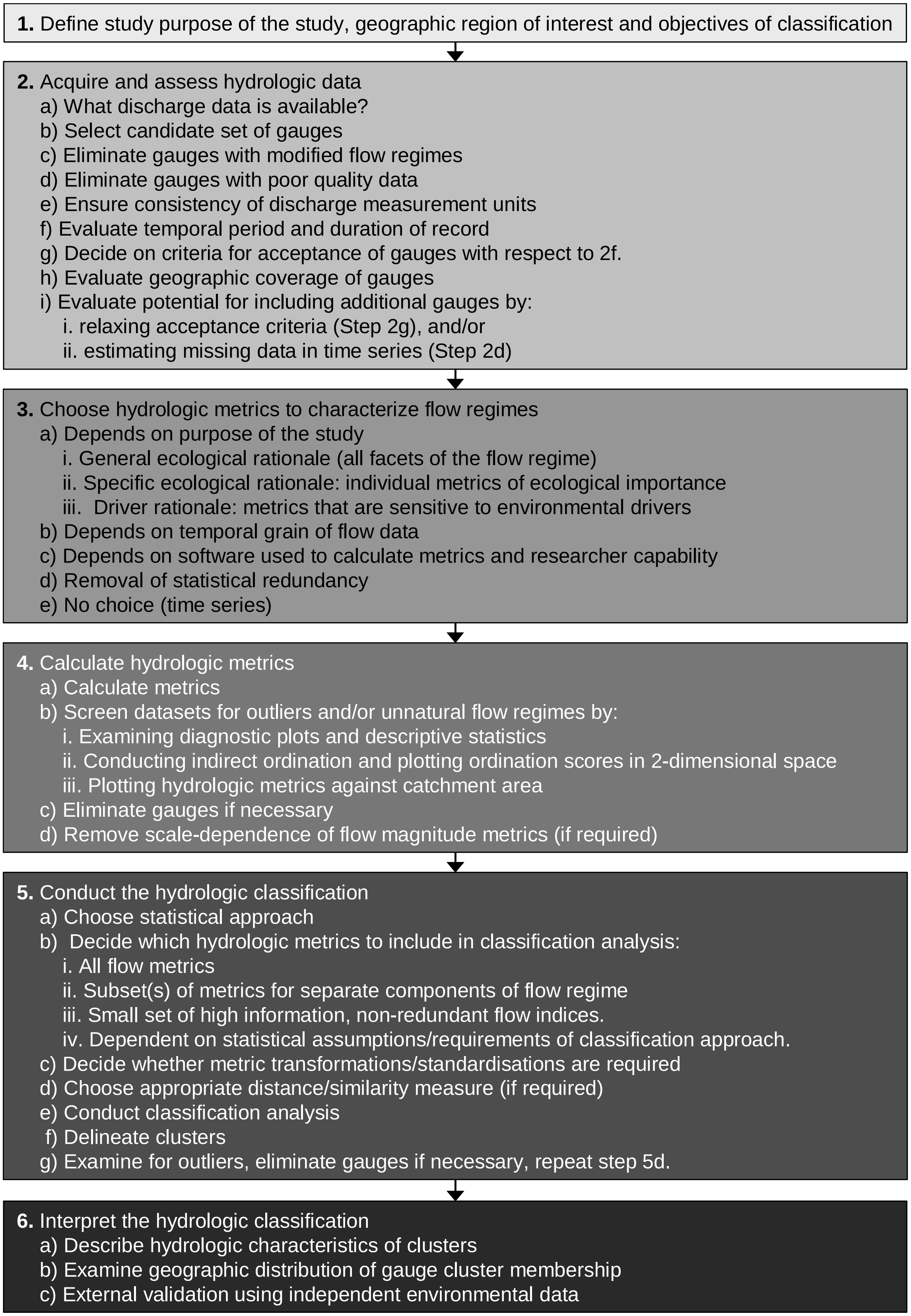

Figure 2.1. A protocol for the process of hydrologic classification.

2.5 The development and application of hydrological classifications in Australia

Hydrological classification of Australian rivers has been previously undertaken at a variety of spatial scales (Bates 1994). Typically, these undertakings have been primarily motivated by the need to extend known relationships about hydrological data to poorly gauged areas to assist in water management and civil engineering projects (i.e. bridge construction). In addition, some of the studies reviewed here do not consider actual daily flow data but consider environmental data that act as proxies for flow and frequently model a limited subset of hydrological parameters (i.e. flood series or low flows) using hydrological parameters that are not commonly used by biologists or that are not immediately perceived to have ecological relevance (McMahon and Finlayson 2003). Rarely are such studies undertaken with any ecological applicability in mind. Typically also, such endeavors are referred to as regionalisations rather than classifications as the primary intent is the derivation of mathematical relationships describing hydrological behaviour for a given region (e.g. Nathan and McMahon 1990). It is not our intent to review these studies here but to focus on ecologically-oriented classifications (although strictly hydrological studies do reveal some noteworthy insights into the nature of Australian flow regimes and such studies are discussed).

2.5.1 Classification at the basin scale

Studies that have examined ecohydrological variation within a single river or a basin (i.e. catchment) that consists of several rivers are considered first. Thoms and Parson (2003) undertook a classification of flow data from 43 locations within the Condamine-Balonne River, which with the Maranoa River forms a major headwater source of the Darling River. They used 73 years of modeled daily flow data for two water resource development scenarios *(no development* scenario and *current water resource development* scenario) to calculate many summary flow statistics (227 and 230 for the two scenarios, respectively), addressing most key facets of the flow regime (Poff *et al.* 1997) across three temporal scales (pulse, history and regime). The similarity matrix upon which classification (UPGMA) and ordination (Semi Strong Hybrid Multidimensional Scaling) analyses were based, was estimated using the Gower Index which standardises units across each variable. Prior standardisation of magnitude variables (i.e. by reference to catchment area or median daily flow) was not employed. No redundancy analysis was conducted prior to multivariate analyses and all variables were allowed into each analysis. Significant redundancy is evident in the pictorial representations of significant correlation (as determined by the principal axis correlation analysis) between objects and attributes in ordination space. Six groups of locations (modeled gauges) were formed by the classification aligned down the river in a sequence corresponding to spatial variation in a previously described geomorphic/river classification sequence for the study area. Although this sequential alignment of flow regime and geomorphology may have arisen because magnitude variables were not scaled to become essentially dimensionless prior to inclusion in the multivariate analyses, Thoms and Parsons (2003) argue the interaction between flow and channel morphology determines the regime state particularly with respect to spatial variation in temporal facets of the regime. These authors demonstrated that different sets of temporal parameters, equating to the time scales described above, became dominant contributors to the regime signature within various geomorphic zones.

Pusey and Arthington (1996) examined the spatial variation in the hydrologic regime of the Burdekin River in central Queensland. A common 19 year period of daily flow records for 26 gauges arrayed throughout the catchment was examined. Gauges were grouped *a priori*, based on landscape attributes (geographic position, subdrainage membership and river type) and a moderately concordant pattern of spatial variation in freshwater fish structure (Pusey *et al.* 1998). The investigation was primarily focused on describing spatial variation in hydrological variability and the choice of metrics used was consequently limited (n = 15) to statistics describing the variability of flows across different time periods (CV of daily, monthly and yearly flows), metrics quantifying predictability (Colwell's P) of monthly minimum, monthly maximum, monthly totals and ratio of maximum to minimum daily flows, and an annual exceedance frequency of a low flow threshold. Average annual and daily flows were also included but these metrics were not standardised (made dimensionless) prior to analysis. A formal examination of redundancy was not performed, but an analysis of the relationship between catchment area and hydrological metrics demonstrated that across all gauges, only mean annual and daily flow were related to catchment area. However, within some of the *a priori* formed groups, catchment area was correlated with up to six parameters in addition to mean annual flow. Discriminant functions analysis (stepwise) was used to test whether discharge regime varied predictably throughout the catchment. Eleven of the 15 parameters, including mean annual flow, varied significantly between groups and consequently highly significant concordance between flow regime and position in the catchment was detected (100% successful classification). Spatial variation in flow regime was largely due to gradients in perenniality and the variability of minimum, maximum and mean daily flows and was related to spatial variation in rainfall and underlying geology. The resultant classification was discussed with respect to the difficulty of setting environmental flow limits in systems of contrasting variability and origins of that variability.

Ransley *et al.* (2007) used a GIS map-based approach to classify and spatially model stream-aquifer connectivity in the Border Rivers catchment of the Murray-Darling. Stream-aquifer connectivity was identified as being both economically (i.e. with respect to water allocation) as well as ecologically important (i.e. environmental flow and water quality management). The authors, building on similar approaches developed for the rivers of inland NSW (Braaten and Gates 2002), identified four key determinants of connectivity. These were:

- depth to the water table (DWT – estimated from existing bore hole data from state agencies)
- stream bed sediments (SBS – derived from Layer 2 gridded (1.1 km^2 grain) NLWRA (1999) soil saturated hydraulic conductivity national data set)
- geology (G – existing maps and state water agency lithological logs for low-lying areas classed as undifferentiated alluvium)
- geomorphology (GM – Multi resolution Valley Bottom Flatness Index derived from the 9 inch DEM).

Values were scaled and combined according to the formula: connectivity index = 3DWT + 5SBS + 5G + 2GM; qualitatively classified as low, medium and high, and mapped. The relevance of the resultant classification to ecological management was not developed although the authors suggest that the method has value as a 'first cut' approach to identifying areas where groundwater/surface water interactions may be important. The extent to which this method can be extended elsewhere relies on the availability of spatial information and the resolution (grain) of that information and to this effect, may be limited in its application to much of northern Australia where geology is coarsely mapped.

Map-based GIS information, gauged and modeled flow data, and waterhole characteristics (e.g. size, persistence etc.) were combined in a very comprehensive analysis of the hydrology of the Lake Eyre basin (McMahon *et al.* 2005). Although the various data elements were not combined to produce a formal classification of flow regimes in the basin, the development of a model to explain spatial variation in water balance flows clearly identifies major hydrological differences across the basin. Laut *et al.* (1985) undertook a hydrological classification of the sub-basins of the Macleay Valley in New South Wales with the main intent being the development of relationships between catchment characteristics and streamflow with a view to extension to other catchments. Readily available landscape information was used to provide an explicitly derived classification of sub-basins based on the assumption that hydrologic similarity is a function of landscape similarity and rainfall similarity. The authors used a combination of analyses developed for numerical taxonomy (classification and ordination); the first time such approaches had been used in hydrological investigations in Australia. Landscape attributes were grouped into five classes: topography (5 attributes), aspect (3), wetland type (7), landcover (9) and lithology (9). Similarity was estimated using a combination of the Gower and Bray Curtis measures and the NEWCLAS algorithm. This study found significant relationships between the combined landscape and rainfall functions and various aspects of hydrology for nine gauged stations throughout the catchment, demonstrating the link between these functions and streamflow.

2.5.2 Classification at the regional scale

Several classification exercises have been undertaken for various parts or regions of south-eastern Australia. Spatial distribution of flow regime variation in Tasmanian rivers was undertaken by Hughes (1987) in the first Australian study to use multivariate techniques to spatially model streamflow at the regional scale. Hughes (1987) used daily flow data, varying in length from 15–81 years, to compute 13 flow metrics (mostly at the monthly and annual time scales) from 77 gauges distributed across 69 basins. Magnitude variables were not made dimensionless prior to analysis and no formal analysis of redundancy was undertaken. It is clear from the Principal Component's analysis and regression analyses however that many variables were correlated with mean annual runoff.

Four distinctive and spatially significant groups were recognised by classification. Spatial arrangement was largely determined by topography and climate (Figure 2.2).

- Group 1 streams were typically located on the north-western coastal zone of Tasmania and were distinguished by intermediate runoff values (mean = 410 mm), moderate CV of annual flows (0.52), moderate skewness of annual flows (0.75), comparatively high CVs of monthly (0.75), maximum (0.66) and minimum (1.19) flows lows, low variability of peak flows (0.29) but high variability of low flows (0.66).
- Group 2 streams were located in the south-east corner of the island and were characterised by low runoff (142 mm), high CV of annual flow (0.87), high skewness of annual flows (1.04) and high CVs of annual (0.87), monthly (0.70), maximum (0.67) and minimum flows (1.14).
- Group 3 streams were located in the southwestern portion of the island and were characterised by high runoff (1347 mm), very low CV of annual flow (0.23) and low skewness (0.46) and low CVs of monthly (0.49), maximum (0.44) and minimum (0.67) flows.

- Group 4 streams were located inland from Tasmania's northern coast and were characterised by moderately high runoff (762 mm), low CV annual flow and skewness (0.36 and 0.15, respectively), low to moderate CVs of monthly and monthly maximum flows (0.65 and 0.54, respectively) but high variability in low flows (CV = 0.91).

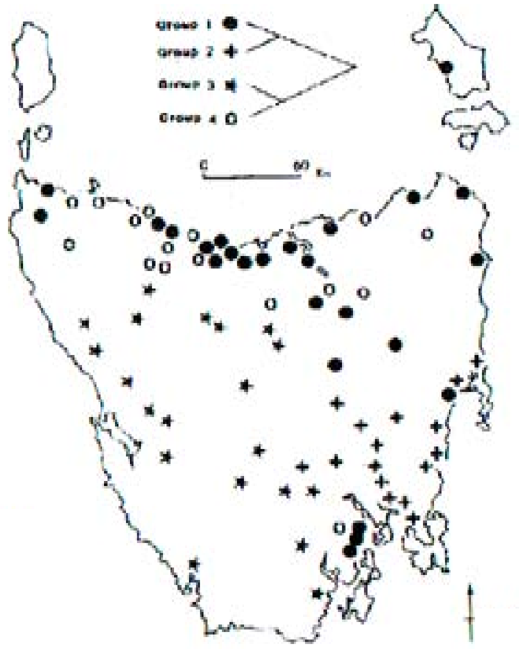

Figure 2.2. Distribution of flow regime types in Tasmania (Hughes 1987).

Hughes and James (1989) extended this type of examination in a study aimed at providing an objective classification of streamflow types in Victoria, based on quantitative streamflow records, for the purposes of informing stream ecology research and providing a predictive capacity for ungauged locations. Streamflow data were obtained from 138 gauges distributed across 117 basins. A total of 16 hydrologic metrics (no standardisation for variation in magnitude) were computed for each location from daily time series spanning at least 15 years. No flow data prior to 1950 were used so as to exclude the influence of a major climate shift occurring around this time. Two separate classifications (average linkage cluster) were conducted: one based on the entire flow record (13 metrics) and the other limited to the low flow period (7 metrics). The low flow classification produced four distinct classes with a spatially heterogeneous distribution across the state. The entire classification (5 groups) exhibited significant spatial clustering (see Figure 2.3) and spatial distribution of flow types was largely determined by topography and coincided with a previously described climatic regionalisation (Whetton 1988). Hughes and James (1989) described the major hydrologic differences between classification groups and attempted to ascribe ecological importance to these differences.

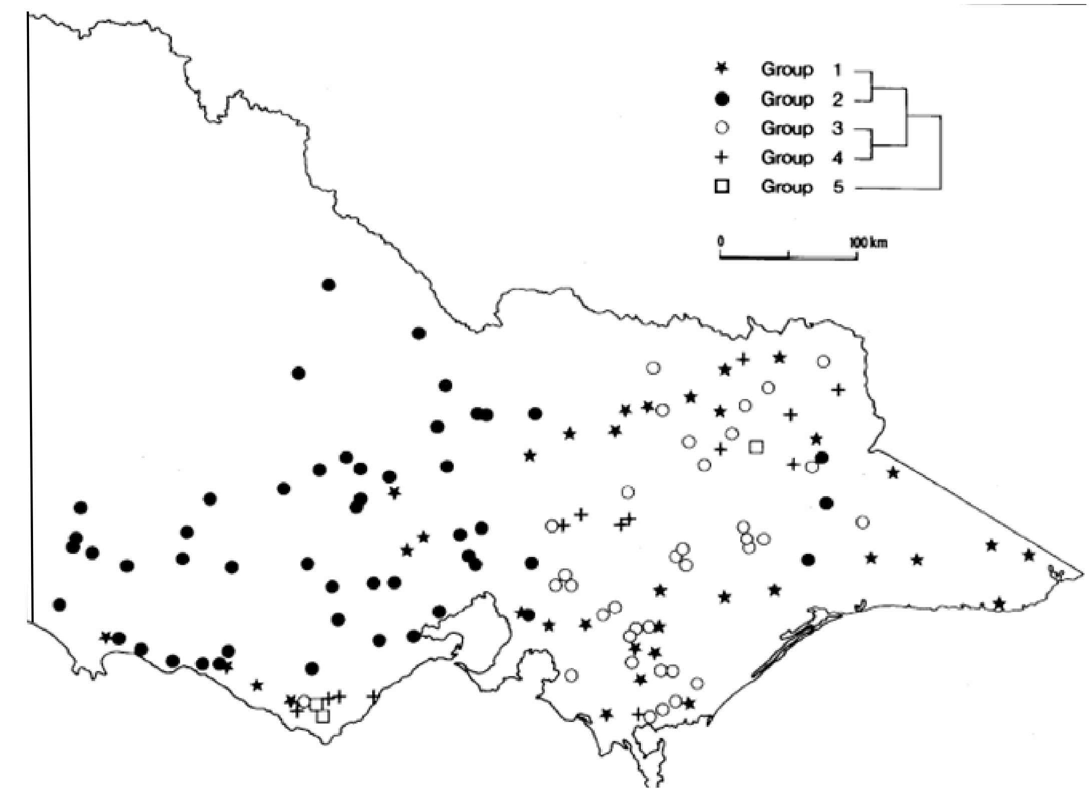

Figure 2.3. The distribution of flow regime classification groups across Victoria (Hughes and James 1989).

In a hydrologic regionalisation study, Nathan and McMahon (1990) applied a range of multivariate techniques in an investigation of the relationship between catchment and discharge characteristics for streams of south-eastern Australia (including eastern Victoria and south-eastern NSW). The focus of the study was on methods to determine the applicability of derived relationships for extension to ungauged catchments and was further focused on the low flow character of the hydrograph. Catchments examined were typically small (1–250 km^2) and discharge record length averaged only 17 years. A total of 19 catchment-related variables were estimated and included catchment area and basin morphometry, rainfall, vegetative cover and underlying geology. The study examined the outcome of using different clustering techniques and similarity measures, and different variable weighting on regional groups. The authors further examined the utility of Andrew's curves for identifying group outliers and tightening within-group cohesiveness. The spatial arrangement of the various groups derived from each classification was not displayed and the study focused more on identifying problems and biases associated with different analytical approaches. Nonetheless, this study did identify the utility of using catchment-related variables to predict hydrology across a large area.

Growns and Marsh (2000) undertook an analysis of flow regime variation across 107 gauging locations (including 10 simulated time series) in south eastern Australian (Victoria to southern Queensland) using a common 20 year daily flow series. Data from both regulated and unregulated streams were used. A total of 333 metrics were calculated and subsequently reduced to 91 variables after cross correlation redundancy analysis. The resultant attributes were then subjected to ordination (Semi Strong Hybrid Multidimensional Scaling) based on the

Gower metric of similarity. The analysis clearly identified differences in the flow regimes of regulated and unregulated streams. Unregulated streams were differentiated principally on the basis of a gradient in intermittency/permanency.

Leigh and Sheldon (2008) undertook an analysis of spatial variation in hydrology in rivers of the Gulf of Carpentaria Queensland, with a definite focus on ecological relevance. A total of 15 gauges spread across seven major catchments (Nicholson, Leichardt, Flinders, Gilbert, Mitchell, Coleman and Wenlock rivers) were examined. Daily discharge data were standardised by catchment area (i.e. converted to runoff). Partial removal of the effect of differing catchment size was achieved by inclusion of gauges from catchments only in excess of 1000 km^2. Twenty years of records were used and although time periods for each gauge were not common across all gauges, substantial temporal overlap was present as many records commenced in either 1967 or 1968, or 1970, 1972 or 1973. A total of 29 metrics was computed for each gauge covering the magnitude, duration and variability facets of the discharge regime. No formal examination of redundancy was undertaken prior to multivariate analyses and all variables were range standardised prior to analysis. The sample by sample (gauge) association matrix was estimated using the Euclidean distance measure, and the resultant ordination and classification based on this matrix were achieved by Non Metric Multidimensional Scaling and group average clustering, respectively. Classification resulted in the formation of two groups differentiated by permanence and 'flashiness' of discharge. A second classification based solely on variables relating to seasonal differences in wet and dry season discharge resulted in the formation of three groups, of which one group essentially related to one of the groups formed in the earlier classification. The two types of regimes were described as a 'tropical regime' (Nicholson, Gregory, Mitchell and Wenlock rivers) characterised by permanent regular discharge with major differences in nature and predictability of dry and wet season behaviour, and a 'dryland regime' (Flinders, Leichardt, Gilbert rivers and large tributaries of the Mitchell River) characterised by ephemerality, flash flooding and extended periods of zero discharge. Comparison of discharge metrics under natural and potentially modified regimes for the Flinders and Leichardt Rivers was achieved by reference to the water resource development conditions in the Darling River.

The Flinders River was also included in a comparison of discharge regimes in three rivers across northern Australia (Moliere 2006, Moliere *et al.* 2006). Daily discharge series (but not continuous data as whole years with missing data were excluded; Moliere 2006) covering at least 20 years of data were analysed for 13 gauges within the Daly River catchment in the Northern Territory, six within the Fitzroy River in the Kimberley region, Western Australia, and nine within the Flinders River drainage of the Gulf of Carpentaria, Queensland. Eight discharge metrics were calculated for each catchment (in addition to catchment area). Mean annual discharge was not made dimensionless prior to analysis but a formal redundancy analysis was conducted and this variable and two others were removed prior to analysis. Comparison between classification solutions (based on Euclidean distance and group average linkage cluster) revealed that only two variables, CV of annual discharge (CV) and the proportion of zero flow days (ZFD), drove most of the spatial variation and the final classification presented was based on these variables alone. Four hydrologic groups were identified and described as:

1. perennial (mean CV = 0.80, mean frequency of zero flow days = 0.06)
2. seasonal (CV = 0.82, ZFD = 0.46)
3. dry seasonal (CV=1.24, ZFD = 0.68)
4. seasonal intermittent (CV = 1.74, ZFD = 0.86).

Substantial geographic congruence was identified with eight of the Daly river gauges being allocated to the perennial group (plus one Fitzroy River gauge), five Fitzroy River gauges (plus one Daly River and one Flinders River) being allocated to the seasonal group, and seven Flinders River gauges (plus one Daly River) being allocated to the dry seasonal group. The fourth group, seasonal intermittent, contained two Daly River gauges and one Flinders River gauge. In those cases where gauges from one river were allocated to a group different from other gauges within that river, Moliere *et al.* (2006) demonstrated that these anomalous gauges were located in specific subcatchments with a dissimilar climate and geology. The authors noted that flood related parameters were not useful discriminators between groups perhaps because flood generation processes were associated with large scale meteorological processes common across the entire region. Moliere *et al.* (2006) went on to determine that four landscape variables: drainage density, mean catchment slope, mean average rainfall and elevation; were able to significantly predict spatial variation in CV and ZFD and suggested that these parameters were useful in predicting classification group membership in ungauged rivers.

2.5.3 Classification at the continental scale

Not surprisingly given the size of the task, efforts at providing a continent wide classification of Australian riverine discharge regimes have been limited. Comparison of certain aspects of the hydrologic regime of Australian rivers with elsewhere in the world has occurred (see Finlayson and McMahon 1988; Puckridge *et al.* 1998; McMahon *et al.* 2007 a, b, c;) but has not been extended to a similar comprehensive analysis within Australia. Nevertheless, some large-scale studies have been undertaken within Australia. For example, McMahon and Finlayson (2003) provided a map of the continent divided into the various seasonality regimes identified by Haines *et al.* (1988) (Figure 2.4).

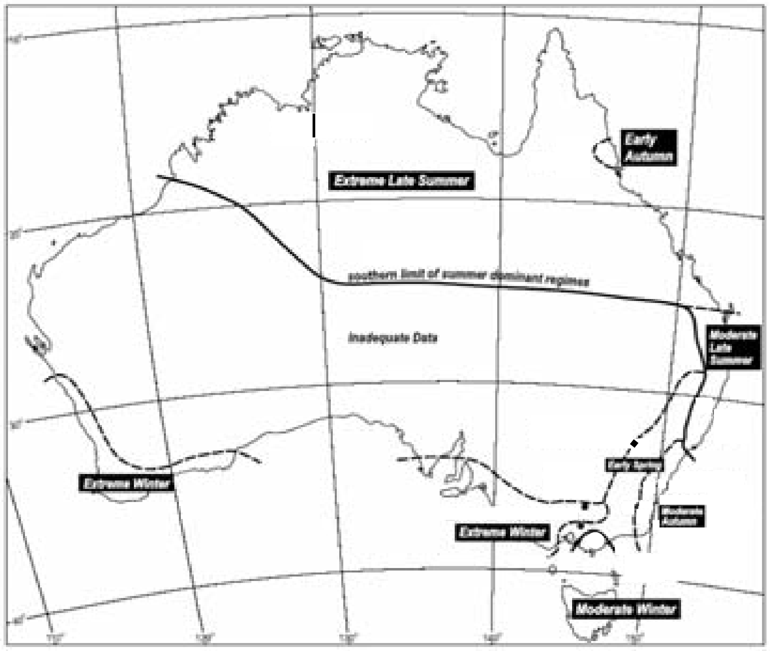

Figure 2.4. Application of the Haines *et al.* (1988) discharge regime seasonality classification to Australia (from McMahon and Finlayson 2003).

Zoppou *et al.* (2002) used modeled daily discharge data at 286 gauges distributed throughout the continent but heavily concentrated in south-eastern Australia (only four gauges in the Northern Territory, 10 in south-western Western Australia and domination of Queensland gauges by those from the Burdekin River) to examine discharge regime signatures across a range of time scales. They employed wavelet transformations to decompose the discharge regime into variation at different time scales (1,2,4 days….64 days…~1 year, 2 years, 3 years….90 years) and then employed k-means clustering to group gauges according to the energy spectrum of the wavelets. Twelve classification types were identified and in which random variations were the dominant signal. One group (3) was characterised by a dominant annual signature and many stations within this group were located in south-western WA or Victoria (i.e. a Mediterranean signal). Another group with a dominant annual signature (10) was distributed across Victoria, NSW and Queensland. The outcomes of this classification, whilst apparently mathematically elegant, are difficult to interpret and harder still to attribute ecological significance.

2.6 Conclusion

A number of conclusions may be drawn from the Australian examples of hydrological classification described in this short review.

- First, despite a comparatively long history during which some basin-wide and regional classifications have been produced, an interpretable, ecologically relevant and quantitatively objective continent-wide classification of hydrologic regimes has not been produced.
- Second, a variety of techniques have been employed in regional and basin-centred classifications of stream discharge but all have had drawbacks associated with metric redundancy, comprehensiveness of hydrologic metrics used, standardisation of metrics and methodological approaches. In part, this reflects the original intent of the studies and the period in which they were undertaken.
- Third, no Australian studies have formally addressed the implications of record length and period of record overlap for estimation of hydrologic metrics.
- Fourth, hydrologists have, not surprisingly, and until recently, tended to be more interested in classification as a means of extending insights gained into ungauged catchments than they are in the ecological relevance of the spatial variation in regime. However, regionalisation exercises for the purposes of extension into ungauged catchments have revealed that a relatively small group of landscape and climatic attributes are capable of predicting many individual aspects of hydrology and by extension, may be used to model or predict hydrologic regime (Laut *et al.* 1985; McMahon *et al.* 2005; Ransley *et al.* 2007).

Clearly, the most effective way in which a continent wide classification incorporating hydrologic rigor and ecological relevance can be progressed is by the production of a classification based on similarities in hydrologic metrics (an empirical approach) following the protocol outlined above, in tandem with the development of regionalisations based on landscape and climatic attributes (a deductive approach).

2.7 References

Abdulla, F.A. and Lettenmaier, D.P. (1997). Development of regional parameter estimation equations for a macroscale hydrologic model. *Journal of Hydrology* 197: 203–257.

Arnell, N.W., Brown, R.P.C. and Reynard, N.S. (1990). *Impact of Climatic Variability and Change on River Flow Regimes in the UK*. Institute of Hydrology Report 107, Wallingford.

Arthington, A.H., Bunn, S.E., Poff, N.L. and Naiman, R.J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16: 1311–1318.

Assani, A.A. and Tardif, S. (2005). Classification and characterization of natural flow regimes in Quebec (Canada). Factors of spatial variability – an eco-geographical approach. *Revue Des Sciences De L'Eua* 18: 247–266.

Baeza Sanz, D. and Garcia del Jalon, D. (2005). Characterisation of streamflow regimes in central Spain, based on relevant hydrobiological parameters. *Journal of Hydrology* 310: 266–279.

Bates, B.C. (1994). *Regionalisation of hydrological data: a review*. Report as part of Project D2: regionalisation and scaling of hydrologic data. Cooperative Research Centre for Catchment Hydrology, Monash University, Melbourne. 61 pp.

Bower, D., Hannah, D.M. and McGregor G.R. (2004). Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrological Processes* 18: 2515–2543.

Braaten, R. and Gates, G. (2002). Groundwater-surface water interaction in inland NSW: a scoping study. *Water Science and Technology* 48: 215–224.

Brizga, S.O., Arthington, A.H., Pusey, B.J., Kennard, M.J., Mackay, S.J., Werren, G.L., Craigie, N.M. and Choy, S.J. (2002). Benchmarking, a 'top-down' methodology for assessing environmental flows in Australian rivers. In *Proceedings of International Conference on Environmental Flows for Rivers*, Cape Town, SA.

Bunn, S.E. and Arthington, A.H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30: 492–507.

Burn, D.H. and Arnell, N.W. (1993). Synchronicity in global flood responses. *Journal of Hydrology* 144: 381–404.

Cheeseman, P. and Stutz, J. (1996). Bayesian classification (Autoclass): theory and results. Pp. 153–180. In Fayyad, U. *et al.* (eds), *Advances in knowledge discovery and data mining*. AAAI Press and MIT Press.

Chiang, S-M., Tsay, T-K. and Nix, S.J. (2002a). Hydrologic Regionalisation of Watersheds. I: Methodology Development. *Journal of Water Resource Planning and Management* 128: 3–11.

Chiang, S-M., Tsay, T-K. and Nix, S.J. (2002b). Hydrologic Regionalisation of Watersheds. II: Applications. *Journal of Water Resource Planning and Management* 128: 12–20.

Clausen, B. and Biggs, B.J.F. (2000). Flow variables for ecological studies in temperate streams: groupings based on covariance. *Journal of Hydrology* 237: 184–197.

Detenbeck, N.E., Batterman, S.L., Brady, V.L., *et al.* (2000). A test of watershed classification systems for ecological risk assessment. *Environmental Toxicology and Chemistry* 19: 1174–1181.

Dettinger, M.D. and Diaz, H.F. (2000). Global characteristics of stream flow seasonality and variability. *Journal of Hydrometeorology* 1: 289–310.

Dollar, E.S.J., James, C.S., Rogers, K.H. and Thoms, M.C. (2007). A framework for interdisciplinary understanding of rivers as ecosystems. *Geomorphology* 89: 147–162.

Finlayson, B.L. and McMahon, T.A. (1988). Australia vs. the World: A comparative analysis of streamflow characteristics. Pp. 17–40. In Robin F Werner (ed), *Fluvial Geomorphology of Australia*. Academic Press, Sydney.

Gelman, A., Carlin, J.B., Stern, H.S. and Rubin, D.B. (2004). *Bayesian Data Analysis*. 2nd edition. Chapman and Hall/CRC Press, Boca Raton, Florida.

Gordon, A. (1987). A review of hierarchical classification. *Journal of the Royal Statistical Society. Series A (General)* 150:119–137

Gottschalk, L., Lundager, J., Lundquist, D., Solantie, R. and Tollan, A. (1979). Hydrologic regions in the Nordic countries. *Nordic Hydrology* 10: 273–286.

Gottschalk, L. (1985). Hydrological regionalisation of Sweden. *Hydrological Science* 30: 65–83.

Growns, J. and Marsh, N. (2000). Characterisation of flow in regulated and unregulated streams in eastern Australia. Technical Report, Cooperative Research Centre for Freshwater Ecology. 66 pp.

Haines, A.T., Findlayson, B.L. and McMahon, T.A. (1988). A global classification of river regimes. *Applied Geography* 8: 255–272.

Hannah, D.M., Smith, B.P.G., Gurnell, A.M. and McGregor, G.R. (2000). An approach to hydrograph classification. *Hydrological Processes* 14: 317–338.

Hannah, D.M., Kansakar, S.R., Gerrard, A.J. and Rees, G. (2005). Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns. *Journal of Hydrology* 308: 18–32.

Harris, N.M., Gurnell, A.M., Hannah, D.M. and Petts, G.E. (2000). Classification of river regimes: a context for hydroecology. *Hydrological Processes* 14: 2831–2848.

Henriksen J.A., Heasley J., Kennen J.G. and Nieswand S. (2006). *Users' Manual for the hydroecological Integrity Assessment Process Software (including the New Jersey Assessment Tools).* Open-File Report 2006–1093. U.S. Geological Survey, Fort Collins Science Center, Colorado, USA.

Hughes, J.M.R. (1987). Hydrological characteristics and classification of Tasmanian rivers. *Australian Geographical Studies* 25: 61–82.

Hughes, J. M. R. and James, B. (1989). A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. *Australian Journal of Marine and Freshwater Resources* 40:303–326.

Hughes, D.A. and Hannart, P. (2003). A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology* 270: 167–181.

Jowett, I.G. and Duncan, M.J. (1990). Flow variability in New Zealand rivers and its relationship to in-stream habitat and biota. *New Zealand Journal of Marine and Freshwater Research* 24: 305–317.

Kachroo, R.K. and Mkhandi, S.H. (2000). Flood frequency analysis of southern Africa: I. Delineation of homogeneous regions. *Hydrological Science* 45: 437–447.

Kahya, E., Demirel, M.C. and Piechota, T.C. (2007). Spatial grouping of annual streamflow patterns in Turkey. Paper presented at Hydrology Days, Colorado State Univ. (Available at: http://hydrologydays.colostate.edu/Papers_2007/Demirel_Kahya_paper.pdf).

King, J.M., Brown, C.A. and Sabet, H. (2003). A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications* 19: 619–640.

Kohonen, T. (1982). Self-organized formation of topologically correct feature maps. *Biological Cybernetics* 43: 59–63.

Kohonen, T. (2000). *Self organizing maps*. 3rd edition. Springer-Verlag, Berlin. 521 pp.

Kondolf, G.M. (1995). Cases studies and reviews. Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations. *Aquatic Conservation: Marine and Freshwater Ecosystems* 5: 127–141.

Kondolf, G.M., Montgomery, D.R., Piégay, H. and Schmitt, L. (2003). Geomorphic classification of rivers and streams. Pp 169–202. In Kondolf, G.M. and Piégay, H. (eds), *Tools in Fluvial Geomorphology*. Wiley, New York.

Krasovskaia, I. and Gottschalk, L. (1992). Stability of river flow regimes. *Nordic Hydrology*. 23: 137–154.

Krasovskaia, I., Arnell, N. W. and Gottschalk, L. (1994). Flow regimes in northern and western Europe: development and application of procedures for classifying flow regimes. Pp. 185–193. In Seuna, P., Gustard, A., Arnell, N.W. and Cole, G.A. (eds), *FRIEND: Flow Regimes from International Experimental and Network Data* (Proc. 2nd Int. FRIEND Conf., UNESCO, Braunschweig, Germany, October 1993). IAHS Publ. no. 221.

Krasovskaia, I. (1995). Quantification of the stability of river flow regimes. *Hydrological Science* 40: 587–598.

Krasovskaia, I., Gottschalk, L. and Kundzewicz, Z.W. (1999). Dimensionality of Scandinavian river flow regimes. *Hydrological Science* 44: 705–723.

Krasovskaia, I. (1997). Entropy-based grouping of river flow regimes. *Journal of Hydrology* 202: 173–191.

Krasovskaia, I. and Gottschalk, L. (2002). River flow regimes in a changing climate. *Hydrological Science* 47: 597–609.

Laaha, G. and Blöschl, G. (2006a). Seasonality indices for regionalising low flows. *Hydrological Process* 20: 3851–3878.

Laaha, G. and Blöschl, G. (2006b). A comparison of low flow regionalisation methods—catchment grouping. *Journal of Hydrology* 323: 193–214.

Laut, P., Austin, M.P., Body, D.N., Faith, D.P., Goodspeed, M.J. and Paine, T. (1985). *Hydrologic classification of sub-basins in the Macelay Valley, New South Wales.* Division of Water and Land Resources Technical Paper No. 45. CSIRO, Melbourne. 64 pp.

Legendre, P. and Legendre, L. (1998). *Numerical Ecology*, 2nd edition. Elsevier Scientific, Amsterdam, The Netherlands. 870 pp.

Leigh C. and Sheldon F. (2008). Hydrological changes and ecological impacts associated with water resource development in large floodplain rivers in the Australian tropics. *River Research and Applications* 24: 1251–1270.

Lin, G-F. and Wang, C-M. (2006). Performing cluster analysis and discrimination analysis of hydrological factors in one step. *Advances Water Research* 29: 1573–1585.

Lins, H. (1985). Streamflow variability in the United States: 1931–78. *Journal of Climate Applications and Meteorology* 24: 463–471.

Lvovich, M.I. 1973. *The World's Water*. Mir, Moscow. 213 pp.

McMahon, T.A. and Finlayson, B.C. (2003). Droughts and anti-droughts: the low flow hydrology of Australian rivers. *Freshwater Biology* 48: 1147–1160.

McMahon, T., Murphy, R., Little, P., Costelloe, J.F., Peel, M.C., Chiew, F.H., Hayes, S., Nathan, R. and Kandel, D.D. (2005). *Hydrology of Lake Eyre Basin*. Report prepared by the Department of Civil and Environmental Engineering, Melbourne University and SKM for the Natural Heritage Trust. 131 pp.

McMahon, T.A., Vogel, R.M., Peel, M.C. and Pegram, G.G.S. (2007a). Global streamflows – Part 1: Characteristics of annual stream flows. *Journal of Hydrology* 347: 243–259.

McMahon, T.A., Vogel, R.M., Pegram, G.G.S., Peel, M.C. and Etkin, D. (2007b). Global streamflows – Part 2: Reservoir storage-yield performance. *Journal of Hydrology* 347: 260–271.

McMahon, T.A., Vogel, R.M., Peel, M.C. and Pegram, G.G.S. (2007c). Global streamflows – Part 3: Country and climate zone characteristics. *Journal of Hydrology* 347: 272–291.

Meigh, J.R., Farquharson, F.A.K. and Sutcliffe, J.V. (1997). A worldwide comparison of regional flood estimation methods and climate. *Hydrology Science*. 42: 225–244.

Merz, B. and Bloeschl, G. (2004). Regionalisation of catchment model parameters. *Journal of Hydrology* 287: 95–123.

Mkhandi, S.H. and Kachroo, R.K. (1996). Regional flood frequency analysis for southern Africa. Xiièmes Journées Hydrologiques De L'orstom. Montpellier, 10–11 October, 1996.

Milly, P.C.D., Dunne, K.A. and Vecchia, A.V. (2005). Global patterns of trends in streamflow and water availability in a changing climate. *Nature* 438: 347–350.

Moilanen, A., Leathwick, J. R. and Elith, J. (2008). A method for spatial freshwater conservation prioritization. *Freshwater Biology* 53: 577–592.

Moliere, D.R. (2006). Preliminary analysis of streamflow characteristics of the Tropical Rivers Region, Internal Report 5**, June, Supervising Scientist, Darwin. Unpublished paper.

Moliere, D., Lowry, J., Staben, G. and Humphrey, C. (2006). Flow characteristics of streams in the tropical rivers region. In *Proceedings of the 30th Hydrology and Water Resources Symposium*, 4–7 December 2006, Launceston, Tasmania.

Monk, W.A., Wood, P.J., Hannah, D.M., Wilson, D.A., Extence, C.A. and Chadd, R.P. (2006). Flow variability and macroinvertebrate community response within riverine systems. *River Research and Applications* 22: 595–615.

Monk, W.A., Wood, P.J., Hannah, D.M. and Wilson, D.A. (2007). Selection of river flow indices for the assessment of hydroecological change. *River Research and Applications* 23: 113–122.

Mosley, M.P. (1981). Delimitation of New Zealand hydrologic regions. *Journal of Hydrology* 49: 179–192.

Nathan, R.J. and McMahon, T.A. (1990). Idenification of homogeneous regions for the purposes of regionalisation. *Journal of Hydrology* 121: 217–238.

Nel, J.L., Roux, D.J., Maree, G., Kleynhans, C.J., Moolman, J., Reyers, B., Rouget, M. and Cowling, R.M. (2007). Rivers in peril inside and outside protected areas: a systematic approach to conservation assessment of river ecosystems. *Diversity and Distributions* 13: 341–352.

Olden, J.D. and Poff, N.L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19: 101–121.

Olden, J.D., Lawler, J.J. and Poff, N.L. (2008). Machine learning methods without tears: a primer for ecologists. *The Quarterly Review in Biology* 83: 171–193.

Parde, M. (1955). *Fleuves et rivieres*. Collection Armand Colin, Paris. 224 pp.

Pegg, M.A. and C.L. Pierce. (2002). Classification of reaches in the Missouri and lower Yellowstone rivers based on flow characteristics. *River Research and Applications* 18: 31–42.

Poff, N. (1996). A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology* 36: 71–91.

Poff, N.L. and Ward, J.V. (1989). Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* 46: 1805–1818.

Poff, N.L., Allan, D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997). The natural flow regime: a paradigm for river conservation and restoration. *Bioscience* 47: 769–784.

Poff, N.L. and Allan, J.D. (1995). Functional organization of stream fish assemblages in relation to hydrological variability. *Ecology* 76: 606–627.

Poff, N.L., Olden, J.D., Merritt, D.M. and Pepin, D.M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences, USA* 104: 5732–5737.

Poff, N.L., Olden, J.D., Pepin, D.M. and Bledsoe, B.P. (2006). Placing global stream flow variability in geographic and geomorphic contexts. *River Research and Applications* 22: 149–166.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M., Henriksen, J., Jacobson, R.B., Kennen, K., Merritt, D.M., O'Keeffe, J., Olden, J.D., Rogers, K.H., Tharme, R.E. and Warner, A.T. (In review). Ecological limits of hydrologic alteration: a new framework for developing regional environmental flow standards. *Freshwater Biology*.

Puckridge, J.T., Sheldon, F., Walker, K.F. and Boulton, A.J. (1998). Flow variability and the ecology of large rivers. *Marine and Freshwater Research* 49: 55–72.

Pusey, B.J. and Arthington, A.H. (1996). Streamflow variability within the Burdekin River. *Proceedings of the 23rd Hydrology and Water Resources Symposium*. Pp. 213–220. Australian Institute of Engineers, Barton.

Pusey,B.J., Arthington,A.H. and Read,M.G. (1998). Freshwater fishes of the Burdekin River, Australia: bigeography, history and spatial variation in community structure. *Environmental Biology of Fishes* 53: 303-318.

Pusey, B.J., Kennard, M.J. and Arthington, H. (2000). Discharge variability and the development of predictive models relating stream fish assemblage structure to habitat in northeastern Australia. *Ecology of Freshwater Fishes* 9: 30–50.

Ransley, T., Tottenham, R., Sundaram, B. and Brodie, R. (2007). *Development of a method to map potential stream-aquifer connectivity: a case study in the Border Rivers catchment.* Bureau of Rural Sciences, Canberra. 27 pp.

Rao, A.R. and Srinivas, V.V. (2003). Some problems in regionalisation of watersheds. Pp.301–308. In Franks,S., Bloschl, G., Kumagai, M., Musiake, K. and Rosbjerg, D. (eds), *Water Resources Systems – Water Availability and Global Change*. Proceedings of XXIII General Assembly of the International Union of Geodesy and Geophysics (IUGG), June 30–July 11, Sapporo, Japan. IAHS Publ. 280.

Rao, A.R. and Srinivas, V.V. (2006). Regionalisation of watersheds by hybrid-cluster analysis. *Journal of Hydrology* 318: 37–56.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10: 1163–1174.

Richter, B.D., Warner, A.T., Meyer, J.L. and Lutz, K. (2006). A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications* 22: 297–318.

Roberts, D.W. (1986). Ordination on the basis of fuzzy set theory. *Vegetatio* 66: 123–131.

Sauquet, E., Krasovskaia, I. and Leblois, E. (2000). Mapping mean monthly runoff pattern using EOF analysis. *Hydrology and Earth System Sciences* 4: 79–93.

Saunders, D.L., Meeuwig, J.J. and Vincent, A.C.J. (2002). Freshwater protected areas: strategies for conservation. *Conservation Biology* 16: 30–41.

Schmitt, L., Maire, G., Nobelis, P. and Humbert, J. (2007). Quantitative morphodynamic typology of rivers: a methodological study based on the French Upper Rhine basin. *Earth Surface Processes and Landforms* 32: 1726–1746.

Snelder, T.H. and Biggs, B.J.F. (2002). Multi-scale river environment classification for water resources management. *Journal of the American Water Resources Association* 38: 1225–1240.

Snelder, T.H., Biggs B.J.F. and Woods, R.A. (2005). Improved eco-hydrological classification of rivers. *River Research and Applications* 21: 609–628.

Snelder, T.H., Dey, K. and Leathwick, J.R. (2007). A procedure for making optimal selection of input variables for multivariate environmental classifications. *Conservation Biology* 21: 365–375.

Snelder, T.H., Weatherhead, M. and Biggs, B.J.F. (2004). Nutrient concentration criteria and characterization of patterns in trophic state for rivers in heterogeneous landscape. *Journal of the American Water Resources Association* 40: 1–13.

Srinivas, V.V., Rao, A.R. and Govindaraju, R.S. (2002). A Hybrid Cluster Analysis for Regionalisation. *Proceedings of ASCE Environmental and Water Resources Institute (EWRI) Conference on Water Resources Planning and Management* (CDROM), May 19–22, Roanoke, Virginia, USA.

Stahl, K. (2001). *Hydrological drought: a study across Europe*. PhD Dissertation, Albert Ludwig University, Freiburg, Germany.

Tasker, G.D. (1982). Comparing methods of hydrologic regionalisation. *Water Resources Bulletin* 18: 965–970.

Tharme, R.E. (2003). A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19: 397–441.

Thoms, M.C. and Parsons, M. (2003). Identifying spatial and temporal patterns in the hydrological character of the Conadmine-Balonne river, Australia, using multivariate statistics. *River Research and Applications* 19: 443–457.

Wagener, T., Sivapalan, M., Troch, P. and Woods, R. (2007). Catchment classification and hydrologic similarity. *Geography Compass* 1: 1–31.

Webb, J.A., Bond, N.R., Wealands, S.R., Mac Nally, R., Quinn, G.P., Vesk, P.A. and Grace, M.R. (2007). Bayesian clustering with AutoClass explicitly recognises uncertainties in landscape classification. *Ecography* 30: 526–536.

Whetton, P.H. (1988). A synoptic climatological analysis of rainfall variability in south-eastern Australia. *Journal of Climatology* 8: 155–177.

Winter, T.C. (2001). The concept of hydrologic landscapes. *Journal of the American Water Resources Association* 37: 335–349.

Wolock, D.M., Winter, T.C. and McMahon, G. (2004). Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. *Environmental Management* 34 (Suppl 1): S71–S88.

Yadav, M., Wagener, T. and Gupta, H. (2007). Regionalisation of constraints on expected watershed response behavior for improved predictions in ungauged basins. *Advances in Water Resources* 30: 1756–1774.

Zadeh, L.A. (1965). Fuzzy Sets. *Information and Control* 8: 338.

Zoppou, C., Nielsen, O.M. and Zhang, L. (2002). *Regionalisation of daily stream flow in Australia using wavelets and k-means analysis*. CMA Research Report MRR02-003, Australian National University, Canberra. Available at: http://wwwmaths.anu.edu.au/research.reports/mrr/02/003/

Appendix 3

Issues associated with classification of contemporary flow data: do contemporary flow regimes approximate the ‘natural flow regime’?

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Summary

The Natural Flows Paradigm has become an essential underpinning of how we view flow ecology relationships and the management of impacts associated with hydrologic change. In the present context, streamflow regime groups or classes derived from a continent-wide classification are assumed to approximate the Natural Flows condition given the steps taken to restrict the analyses to unregulated streams and to omit catchments that have been severely modified.

We place the contemporary flow regimes used in the classification presented in Appendix 5 in a historical context by reference to long-term (1000s of years), moderate (100s of years) and recent changes in climate and land use. Natural change over these time scales has been substantial and has not occurred at a uniform rate. For example, it is suggested that changes in climate over the last 10,000 years is as extreme as that which has occurred over the last 3 million years. In addition, changes in land use since European colonisation of Australia that are relevant to stream yield processes are reviewed. These include changes in vegetative cover, extent of large animal grazing, changes in fire regime, increasing construction of small farm dams, urbanisation and the construction of roads. Each impact may influence riverine flow regimes in different ways. Although some of the influences mentioned above may be limited in areal extent, their pervasiveness when examined collectively suggests that there are few streams not influenced to some extent by anthropogenic activities.

The ability to control for this anthropogenic influence is severely constrained by the typical length of record available for most of the nation’s stream gauge network. Accordingly, interpretation of the outcomes of the classification must be made in the context of how much contemporary flow regimes might potentially differ from that expected in the absence of recent anthropogenic change.

3.1 Introduction

Hydrological classification systems seek to arrange fluvial systems into groups based on similarities in flow regime. Ecohydrological classifications seek to go further by using hydrological attributes (metrics) hypothesised to describe ecologically important facets of the flow regime to group systems and ascribe ecological importance to those similarities or differences in hydrologic regime.

The importance of the hydrologic regime to the functioning of aquatic systems is sufficiently recognised for general principles (Bunn and Arthington 2002), holistic paradigms (Poff *et al.* 1997) and theory (Zalewksi *et al.* 1997) to be enunciated within the scientific field termed 'ecohydrology'. This field, although originally developed for environmental problem-solving, seeks to quantify and explain the multi-scaled relationships between hydrological, biogeochemical and ecological phenomena (Zalewski *et al.* 1997; Hannah *et al.* 2004; Newman *et al.* 2006). These functional relationships between hydrology and biota are described (Zalewski 2002) and provide the theoretical basis for predicting impacts of anthropogenic changes to hydrologic regimes. Hydrologic change due to human activities such as land use, water extraction and from projected global climate change (Sala *et al.* 2000; Vörösmarty *et al.* 2000, 2004; Postel and Richter 2003) are at the forefront of the many processes that threaten aquatic habitats and biota (McAllister *et al.* 1997; Cambray and Bianco 1998) and require effective management in order to curb or reverse associated impacts.

Environmental water management, including assessment of aquatic ecosystems to flow regime changes and water allocation, is a relatively new and rapidly developing field. Over the last three decades, the focus of environmental water allocations has shifted from concerns about single species, usually of some economic or recreational importance (e.g. freshwater fish), to entire communities, including species from a range of floral and faunal groups, and to entire ecosystems also. Spatial foci have evolved from in-stream habitat maintenance at the micro- or meso-scale (e.g. river reach) to that of the whole of catchment and thence to that of the catchment plus its adjacent ecosystems (e.g. marine receiving waters) (Arthington and Pusey 2003). These changes have paralleled those seen in riverine ecology in general, particularly the increasing recognition of the importance of the natural flow regime, especially hydrologic variability, as a template upon which patterns of distribution, life history and community organisation are based (e.g. Horwitz 1978; Poff and Ward 1989; Schlosser and Angermeier 1995; Poff and Allan 1995; Oberdorff *et al.* 1995; Pusey *et al.* 2000). Recognition of the links between terrestrial landscapes and riverine and marine ecosystems, and of the importance of the flow regime, led to the development of the Holistic Approach (Arthington *et al.* 1992) in the field of environmental water management and the enunciation of the Natural Flow Regime paradigm by Poff *et al.* (1997) in ecohydrology. These developments require that our view of the organisation and ecology of rivers, our assessment of the impacts associated with water use and infrastructural development and especially prescriptive remediation, be placed in the context of the natural flow regime and deviations away from it (Arthington and Pusey 2003).

A key foundation of the Natural Flows Paradigm (Poff *et al.* 1997), upon which ecohydrology is largely based, is that the long-term regime of natural environmental heterogeneity and hydrologic disturbance constitutes a physical habitat template that constrains local communities with respect to composition, assemblage level attributes and expression of ecological traits (Poff and Ward 1990; Lytle and Poff 2004) and that organisms, their traits and their role in the aquatic environment have evolved in response to the hydrologic regime in which they exist. Systems with similar hydrologic regimes, all other factors (e.g. biogeographic, geomorphic, evolutionary constraints, etc.) held constant, should contain species with similar relationships to that regime and similar expression of ecological traits. Evidence for this posit can be found in investigations of trait expression in stream fishes occurring across vast spatial scales (Poff and Allan 1995; Lamouroux *et al.* 2002; Hoeinghaus *et al.* 2007) and in investigations seeking to explain hydrologically-linked spatial variation in biodiversity of aquatic organisms (Oberdorff *et al.* 1995; Guégan *et al.* 1998; Kennard *et al.* 2007; Stewart-Koster *et al.* 2007).

3.2 Issues affecting the context of hydrological classifications

Quantitative description and classification of spatial variation in hydrologic regime is therefore a critical step in assessing the ecohydrological relationships that may exist within different rivers. We would argue however, that prior assessment of what constitutes the 'natural flow regime' and whether we can actually describe it in ways that are amenable to classification or future assessment of change is an equally, perhaps more, important step. While environmental flow methods such as benchmarking (Brizga *et al.* 2002) and the Holistic Approach (Arthington *et al.* 1992) acknowledge that the maintenance of flow-related evolutionary processes under modified flow conditions is a key desired end-point of flow management, the capacity to do so is constrained by an inability to fully define the historical flow record over an appropriate evolutionary time scale and imprecise knowledge of the time span over which evolutionary responses to changing flow occur. These issues, particularly the former, are of direct relevance to the process of ecohydrological classification as it requires consideration of the representativeness of the information used in the context of various historical times spans within which the flow record is placed.

3.2.1 Temporal context of available contemporary flow data

Given the huge number of water storages constructed on the world's rivers (approximately 800,000) and frequent and extensive manipulation of channel and floodplain characteristics (Rosenberg *et al.* 2000), it is increasingly difficult to find rivers exemplifying the natural flow regime. The idiosyncratic nature of a river's flow regime (Olden and Poff 2003) may also make it difficult to characterise the natural regime of a regulated river by reference to that of an unregulated river in close geographical proximity. Furthermore, myriad and pervasive effects of human presence in the landscape may alter stream yield processes (see below). Accordingly, the computation of meaningful and accurate hydrological metrics in a classification, or any other consideration of the ecological relevance of flow regime, is best done with data covering as long a time period as possible to, at least understand how such impacts have altered the natural hydrology, and at best to partial out these effects. Unfortunately, the duration of streamflow records worldwide is generally limited, often less than that needed for valid characterisation (Huh *et al.* 2005) and typically greatly less than 100 years in length. This is especially important in the Australian context. For example, the mean length of flow record for most Australian states and territories varies between about 25 and 36 years (many of which have missing periods of data). Although maximum years of record frequently exceed double this number, few of the country's gauges extend for more than 50 years (Table 3.1). Very few gauges approach the long period required to detect all but the grossest of human alterations to streamflow or to assess how natural climatic variation has altered flow regimes in recent history.

Moreover, not all longer-term records pertain to the same period, an important consideration in classification (see Appendix 4 for an expanded discussion of this latter point). In the classification exercise described in Appendix 5, 356 gauging stations with record lengths longer than 25 years were confined to the common period of 1966–2000 but only 64% of these covered to the period 1971–2000. Thus, the flow regimes being classified are concerned very much with recent history. It is appropriate to consider therefore how this period of record reflects flow regime over a short to medium time scale (i.e. last 100 yrs), a medium time scale (i.e. prior to European colonisation and institution of European land use practices) and a longer time frame (i.e. prehistoric).

Table 3.1. Summary of record lengths of gauged streamflow data for the Australian States and Territories (for records > 10years). N refers to the number of gauges for which data was available from the various State and Territory agencies. Mean record length is given, as is the length of record of the longest continually monitored gauge (notwithstanding some periods of missing data), for each jurisdiction. The record length approximating the 80th percentile is given for all gauges combined. Note – this analysis does not include data post 2000. Commonly used jurisdictional abbreviations are used.

Jurisdiction	**N**	**Mean record length (years)**	**Longest record length (years)**	**80th %ile**
ACT	10	29.8	48.8	
TAS	86	28.0	82.0	
SA	88	25.2	66.7	
NT	176	27.0	54.6	
VIC	180	28.2	76.2	
WA	357	26.1	54.7	
QLD	893	26.4	96.1	
NSW	1014	36.1	123.2	
Combined	2804	30.1	123.2	40.5

3.3 Implications of using short-term modern hydrological data

3.3.1 Long-term climate variation (1000s of years)

The Earth's climate is largely determined by its relationship to the Sun (i.e. its orbital pattern); a relationship that varies through time in a well-defined set of superimposed cycles. For example, orbital eccentricity results in a change of orbit of the Earth around the Sun from almost circular to almost elliptical with a periodicity varying between 100–400 Ka and this greatly affects the extent of intra-annual radiation received by the Earth's surface. The angle of tilt or obliquity of the Earth's axis varies with a periodicity of ~41Ka and this also results in long-term changes in the extent of seasonality. Finally, the small 'wobble' in the Earth's rotation around its axis causes differences in the extent of seasonality between Northern and Southern Hemispheres with a cycle periodicity of between 19 and 23 Ka (see McDowell *et al.* 1995) for an expanded discussion of these cycles). These regular and predictable variations in the Earth's orbital elements affect insolation intensity and collectively form the boundary conditions of climate change at time scales of 10^4 years or more. When coupled with the global extent of ice sheets, they form the boundary conditions at shorter time scales also (Williams *et al.* 2003).

Large-scale changes in effective precipitation due to these orbital variations have occurred throughout the Pleistocene (Ayliffe *et al.* 1998 and references therein). In the last 130–175 Ka period, full transition from a glacial to an interglacial period has occurred and on this, axis tilt and equinox processional cycles (Webb and Bartlein 1992) and El Nińo cycles (Tudhope *et al.* 2001) were also imposed. Climatic changes experienced in the last 20 Ka are suggested to be as large as any occurring over the preceding 3 Ma and are mostly limited to the last 8–15 Ka (Webb and Bartlein 1992). Whilst detailed paleohydrological regimes are not available, long-term changes in rainfall (Ayliffe *et al.* 1998) strongly indicate that riverine flow regimes would have undergone significant and frequent change.

The time-span of such profound and persistent change is well within the longevity of species as evolutionary units (Cronin 1985; McDowell *et al.* 1995; Avise *et al.* 1998) and accordingly most extant species of aquatic organisms have persisted over periods of great change in climate and hydrology. In contrast to terrestrial biota for which migration (albeit at a slow rate) is the most frequently reported response to changing environmental conditions over long time scales (see Webb and Bartlein 1992), many freshwater organisms are limited in the extent to which they are able to migrate by their dependency on freshwater as a sustaining habitat. Consequently, historical changes in climate, and hence hydrology, must be endured or adapted to, or otherwise be the cause of local and possibly global extinction.

How valid is the view that the characteristics of existing biotic communities (e.g. composition, diversity, functional traits or the nature and strength of interspecific relationships) represent some sort of end product of the prevailing flow regime, assuming it is in a natural state and notwithstanding any anthropogenic changes that may be imposed upon it (e.g. Poff *et al.* 1997; Lytle and Poff 2004)? Natural selection for the evolution of ecological traits is a process and hence occurs over some defined time period; not all traits evolve or vary at the same rate, however. Functional morphology, for example, is important in determining habitat use and trophic style but typically changes slowly over time (Foote 1997). In contrast, some aspects of life history may change very quickly (Stearn 1992; Hendry and Kinnison 1999) providing they are not canalised by phylogenetic constraints. As a consequence of such differences, the observed set of traits for any one species within a community represents a mosaic of traits, some that may be optimal for the existing environmental regime, others which may be in the process of changing under a selection regime imposed by existing circumstances, and yet others that may be essentially invariant as they are either fixed (canalised), not under selection or have evolved under previous environmental regimes and change so slowly as to appear invariant. Gorman (1992) suggests that the time frame for community assembly in stream fish communities cannot be viewed as relatively recent or the result of ongoing equilibrium phenomena. Rather, members of the assemblage have co-evolved together over a long period in the same environment and have 'fine-tuned' their ecological interrelationships. What is actually meant by the term 'same environment' is not actually defined by Gorman (1992). If it refers to an unchanging environment (i.e. it has remained the same), then clearly this is inappropriate given the profound environmental changes that have occurred over the last, say, 120,000 years. If it refers, as is more likely, to the fact that co-existing species have a similar and shared history with respect to environmental (i.e. hydrological) variation, then fine tuning is probably unlikely unless that process is relatively rapid.

If the rate of evolution in response to flow regime change remains an open question (Lytle and Poff 2004), there is little doubt that contemporary changes in flow regime (i.e. anthropogenic) have had negative impacts throughout the world. Presumably such changes are wrought by a mismatch between the new flow regime and the ecological traits of the constituent species. In the case of some species this may mean a decline in population size. Other, perhaps less abundant, species may experience an increase in dominance under the new regime state as a result of better match between regime and ecological traits, perhaps because their trait set, evolved under previous environmental conditions, is better matched to the new and altered conditions. If natural communities are composed of many species, each with a set of ecological traits which are differentially optimised to the prevailing flow regime, a range of responses may be observed to hydrological change. It is conceivable that if the direction of change is towards a state that has existed in the evolutionary past of the constituent species, then those that retain the traits associated with that past (i.e. those species for which evolutionary change in the ecological traits matrix has been slow) are likely to benefit, whereas those species having experienced rapid change in trait structure to better fit the contemporary regime, will be disadvantaged, unless they are able to rapidly evolve different traits.

3.3.2 Short-term climate variation (100–200 years)

Climatic variation in Australia, especially variation in rainfall, is pronounced and may be associated with phenomena with recurrence intervals of several years (e.g. the ENSO phenomena – Clewett and Stone 1994; Chiew *et al.* 1998), one to two decades (Willcocks and Young 1991) or even longer (Pittock 1975). For example, it is well recognised that major shifts in the Australian climate have occurred since the 1880s when reliable and continuous rainfall records began (Sturman and Tapper 1996). Mean annual rainfall, a significant determinant of annual streamflows, was relatively high between 1880 and 1910, particularly in northern and eastern parts of the continent. Not surprisingly, this period also corresponded with major extensions of agriculture into areas that are now considered marginal at best. A subsequent decrease in rainfall occurred over the period 1913–1945 and in some areas this decrease was between 50 and 75 mm per year (Gentili 1971; Pittock 1975). Contrastingly, rainfall in some areas of south-western Australia increased by up to 25 mm per year over this same period. Further changes in continental climate occurred after 1945 with increases in rainfall occurring over much of south-eastern Australia, the rate of change exceeding 100 mm per year in coastal New South Wales and between 0 and 50 mm per year in north-western Australia (Gentili 1971; Pittock 1975). Reductions in diurnal temperature ranges, an important determinant of the rate of evapotranspiration, of between 0.2 to 0.4°C per decade have occurred over much of the continent during the period 1951–1992 also (Plummer *et al.* 1995). Changes in rainfall are usually amplified in runoff (Chiew and McMahon 2002) and changes in rainfall would have strongly impacted on streamflow over much of the continent. For these reasons, Hughes and James (1989) chose not to use any flow data prior to 1950 in their hydrological classification of Victorian streams.

Flow records for Wide Bay Creek in the Mary River catchment (south-east Queensland) over a 90 year period illustrate the medium-term changes that may occur coincident with widespread changes in rainfall and temperature (Figure 3.1). The period 1915–1927 was distinguished by low discharge with extended periods of zero flow whereas the period 1933–1945, although typically with few very wet periods, contained periods of low flow within the months of September to December. Post 1945 to 1960, flow increased and few periods below 1 ML day^{-1} were recorded. Thereafter, the length of periods of flow <1 ML day^{-1} increased (1960–1970) and again declined (1970–1978). The frequency and duration of low flows has increased after 1978 until the present, possibly in response to increased riparian extraction. These data clearly illustrate the changes in hydrology that have occurred in a medium-term time frame, and notwithstanding any changes in the last decade that may be attributed to potential effects of global climate change (Chiew 2006), it is difficult to say what is the natural or typical flow regime of this system, other than to say that it varies in time and there are comparatively wetter and comparatively drier periods.

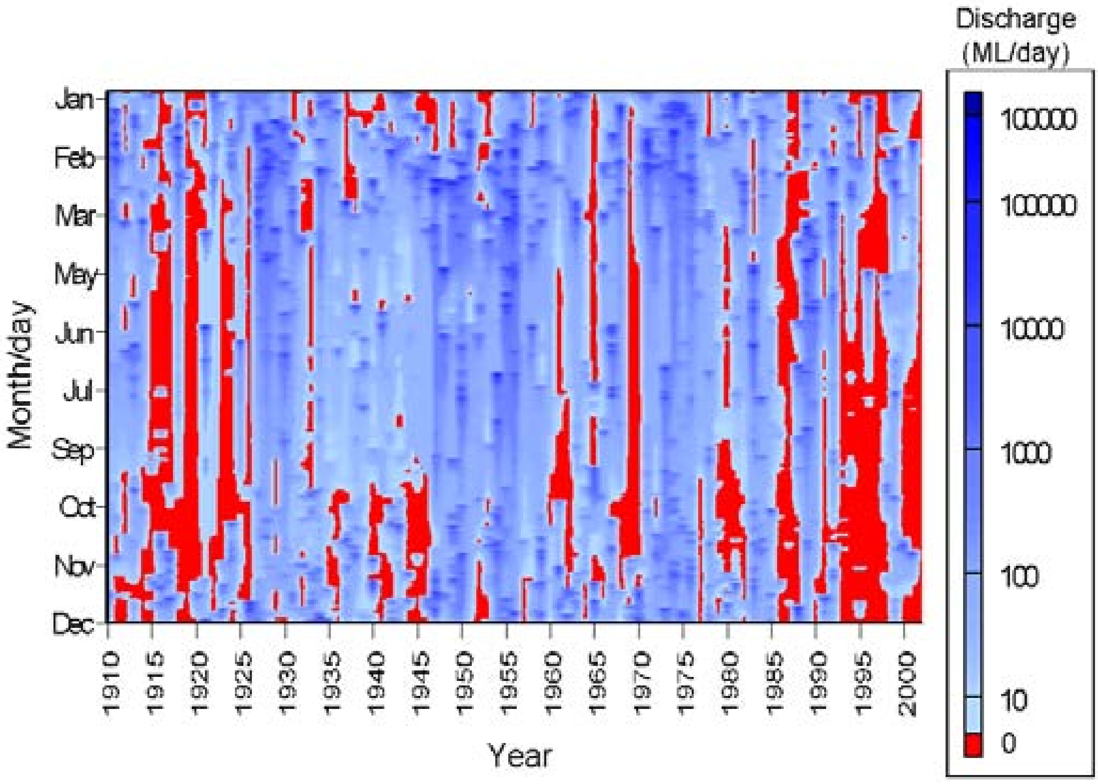


Figure 3.1. Variation in daily discharge (ML/day) over a 90 year period in Wide Bay Creek, Mary River (gauge # 138002). Note that although this stream is unregulated there are several points at which riparian offtake occur and the flow record is therefore subject to minor modifications in low flow magnitude, particularly in the last two decades.

A common approach to overcome the problems relating to the absence of long-term discharge data is to use rainfall data, which often spans a much greater period, to model streamflow and thus construct a historical flow record. In eastern Australia, the Integrated Quantity and Quality Model (IQQM) is frequently used to achieve this and is the model used in Queensland environmental water studies (e.g. Water Resource Management Plans). The underlying basis of the IQQM is a Sacramento Model, a 16 parameter simulation system that apportions precipitation into evapotranspiration, direct runoff, surface runoff, interflow and baseflow to model streamflow (Simons *et al.* 1996). Typically, the model is calibrated against some short period of discharge data and then, using rainfall records, is used to simulate a long period of streamflow able to be analysed in order to define the boundaries and conditions of the flow regime (i.e. low flow spell incidence and duration, flood frequency, etc.). Notwithstanding the problem such models have in estimating very low flow and very high flow conditions (an issue with gauged data also) two factors are of importance in this regard. First, is whether the period of discharge used to calibrate the model is capable of defining the natural flow regime given the long-term variation described above. Second, and more important, is the assumption that the simulated pattern of streamflow represents those conditions existing prior to European occupation of the catchment in question. In all fairness, users of the IQQM refer to the simulated discharge data as the 'no development' case rather than the 'natural flow regime'. Nonetheless, the issue of how well such simulations approximate the natural case is identical to the issue of how well do short to medium-term (25–100 years) contemporary flow records approximate the natural flow regime under which biota have adapted and evolved.

3.3.3 Recent anthropogenic changes to hydrology – catchment clearing

The processes governing stream yield and flood behaviour are unlikely to have remained unchanged over the last 200 years given the profound change in the way the landscape has been modified by human land use. Anthropogenic impacts on stream hydrology associated with European land use are to be expected, foremost among which are those associated with land clearing or deforestation. The extent of change in the natural vegetation of the Australian continent is profound (Figure 3.2a) and Sahin and Hall (1996) refer to changes in landcover as the hydrological problem 'that will not go away'. Loss of transpirative capacity of the landscape and changes in the speed at which water moves across the landscape alters the rates at which rainfall enters the subsoil and groundwater reservoirs in a complex dynamic (Caspary 1990; Borg and Stoneman 1991; Potter 1991; Trimble and Mendel 1995). Stream responsiveness to local rainfall can be greatly altered (Pearce 1990) resulting in changes in the frequency of spates and the rates of rise and fall of such events. Siriwardena *et al.* (2006) report a 40% increase in annual runoff (after accounting for increases in rainfall) associated with the conversion of *Acacia harpophylla* woodlands to grasslands in the Comet River of Central Queensland. In addition, aforestation (e.g. replacement of cleared land by silviculture) has implications for stream yield also (Swank and Douglas 1974; Sahin and Hall 1996). Clearly, natural flow regimes are likely have altered greatly, especially in south-eastern, south-western and north eastern Australia where crop-based agriculture is extensive (Figure 3.2b).

3.3.4 Recent anthropogenic changes to hydrology – grazing

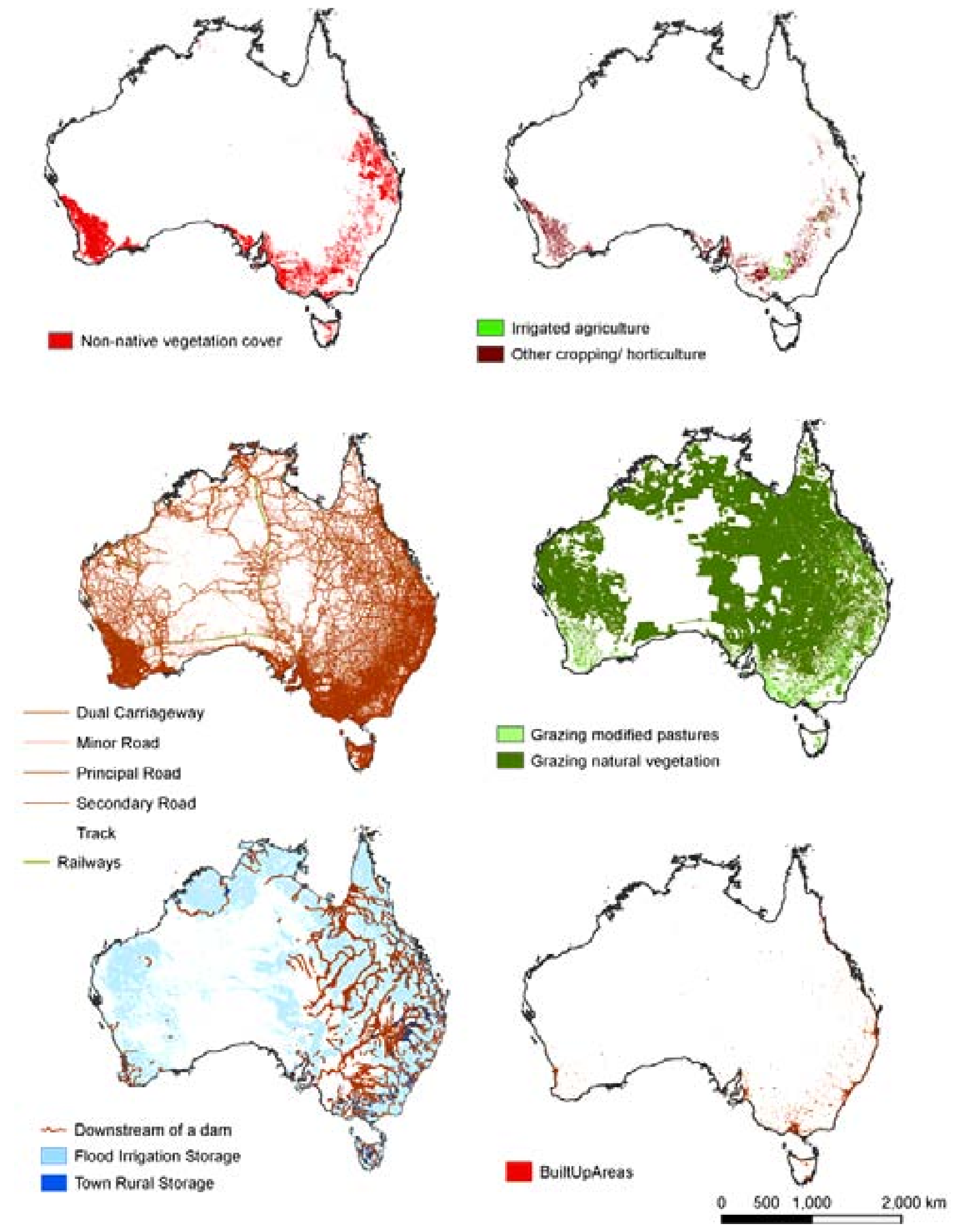
McCulloch *et al.* (2003) demonstrate a five to tenfold increase in sediment delivered by the Burdekin River to the Great Barrier Reef since European settlement. They attribute this change to a rapid increase in cattle grazing in the catchment and note that increases in sediment delivery were detectable within 20 years of the commencement of grazing. Cattle, by virtue of their large size and behaviour, are powerful geomorphic agents and may influence stream yield by compacting soil and reducing groundcover in rangelands and by the formation of ramps and trails through the riparian zone (Trimble and Mendel 1995; Greenwood and McKenzie 2001). These impacts greatly reduce the infiltration capacity of the soil and the extent to which rainfall is able to enter the stream as interflow or baseflow, and increases the amount of rainfall moving into stream systems as overland flow (Trimble and Mendel 1995). In addition, cattle may spend a significant portion of their day within the stream channel or sheltering in the shade of riparian vegetation (Platts 1991), especially in semi-arid regions. There is ample anecdotal evidence that this behaviour has resulted in the trampling, plugging (poaching) and loss of function of hundreds of springs in the upper Burdekin catchment. Indeed, the loss of springs coincident with European settlement has been reported for large areas of northern Queensland and is great cause for concern (Fairfax and Fensham 2002).

Such impacts are likely to change the natural hydrograph in at least three significant ways. First, increased rates of runoff lead to an increase in the frequency of flood events, and second, such events will have steeper rising and falling arms of the flood hydrograph (Trimble and Mendel 1995). Wohl (1992), using carbon dating of slackwater deposits in the Burdekin Gorge, estimated that floods of about 20,000 $m^3.sec^{-1}$ had occurred only four times in the last millennium. Independent corroboration of at least one of these floods using coral coring techniques in the Great Barrier Reef has been reported (Isdale 1996). Floods of this magnitude have occurred at least 10 times in the period 1921–2002 (Department of Natural Resources, Mines and Energy stream gauge 120101, *unpublished data*). Third, reductions in infiltration capacity and groundwater inputs, coupled with the loss of spring water inputs will lead to reduced dry season flows and greater distinction between wet and dry seasons. Thus, in the period of European occupation of the Burdekin River catchment the flow regime, in all likelihood, has become more flood-dominated and the seasonal signal of flow much more accentuated. Such impacts are highly likely to have been experienced over much of northern Australia and indeed the continent as a whole given the widespread nature of the cattle grazing industry (Figure 3.2d).

3.3.5 Recent anthropogenic changes to hydrology – fire regimes

Fire has been a widespread and persistent feature of the Australian landscape and available evidence suggests that Aboriginal use of fire as a management tool has a very long history (~40,000 yrs) (Kershaw 1986). Frequent burning has declined over much of southern Australia since European colonisation however. For example, the frequency of forest fires in south-western Australia has declined from a return interval of approximately three years to more than eight years over the last two centuries (Ward *et al.* 2001). Changes in vegetation thickness are hypothesised to have occurred as a result (Ward *et al.* 2001) and are likely to have impacted on stream yield process over this period (Wondzell and King 2003). Dense overstorey and understorey vegetation combined with well-developed litter layers protect the soil surface from rain splash and reduce Hortonian flow. A six-fold reduction in recurrence interval (from 30 yr to 5 yr) of the threshold at which overland flow occurs has been attributed to the effects of changes in fire regime (Miller *et al.* 2003). Intense fire can increase soil hydrophobicity (DeBano 2000) and such changes can persist for up to six years (Dyrness 1976). Moreover, regeneration after wildfire can alter local hydrology due to increased transpiration rates of regenerating seedlings, suckers and lignotubers (Langford 1976).

Figure 3.2. Spatial extent across the Australian continent of selected anthropogenic factors with direct impacts on stream hydrology.



Changes in burn frequency have not been so dramatic across much of northern Australia because of continued, albeit reduced, maintenance of Aboriginal contact with country and the adoption of much the same management strategies by pastoralists (Crowley and Garnett 2000). However, the introduction of fire-dependent grass species across northern Australia may greatly increase the extent to which fire changes the vegetative aspect of the landscape (D'Antonio and Vitousek 1992) and changes stream yield processes. Gamba grass (*Andropogon gayanus*), an alien pasture grass introduced into northern Australia, can develop dry season fuel loads up to seven times greater than native grasses and sustain fires up to eight times as intense (Rossiter *et al.* 2003). Intense fires are able to burn the crowns of tree species and result in the transformation of woodlands to open grasslands (Williams *et al.* 1999) with potentially the same hydrological impacts as those associated with clearing. Similarly, the grass *Cenchrus ciliarus* is capable of invading riparian zones and watercourses of arid Australia and transforming these areas from fire barriers to wicks (D'Antonio and Vitousek 1992). Loss of riparian integrity can greatly alter stream yield processes (Herron and Hairsine 1998). Changes in fire regime and intensity are likely to have resulted in deviation of hydrological regimes from that existing prior to European colonisation.

3.3.6 Recent anthropogenic changes to hydrology – large impoundments and regulatory structures

Water control structures were constructed almost immediately upon European colonisation to secure reliable water supplies for settlements, mining and irrigated agriculture. Many and varied flow regulation structures, including many thousands of weirs (3600 in the Murray-Darling Basin alone), locks and floodplain levee banks, 446 large dams (>10 m crest height) and over 50 intra- and inter- basin water transfer schemes have been built. Australia now has the highest per capita water storage capacity in the world with 79% of this stored water used for irrigation purposes, the highest proportional usage of all OECD countries (SEAC 1996). Most of this water is held in a few, very large storages, the ten largest holding about 50% of total capacity. Impacts from this era of dam construction and floodplain modifications include highly modified flow regimes and degraded rivers. Total river flows and their temporal patterns are fundamentally altered in many of Australia's great rivers, including the River Murray, the major headwater tributaries of the Darling in New South Wales, the Burdekin, Fitzroy, Proserpine, Pioneer, Burnett, Mary, Brisbane and Logan rivers of Queensland, many coastal rivers in New South Wales, the Snowy River in Victoria, the Ord River in Western Australia, the Gordon and other Tasmanian rivers, as well as many small stream systems throughout the continent (Arthington and Pusey 2003).

3.3.7 Recent anthropogenic changes to hydrology – small scale impoundments and abstraction

Many Australian rivers are impounded or regulated by dams or have their flows supplemented by interbasin transfers (Figure 3.2e). We are not concerned here with these large changes as regulated or modified streams were excluded from the classification exercise described in Appendix 5. However, farm dams, too small to be registered as major impoundments and thus not 'captured' in analyses of natural flow regimes such as the classification described in Appendix 5, are increasingly numerous and widespread and do deserve consideration. Impacts on streamflow, especially in small to medium-sized catchments, may be substantial (see review by Beavis and Howden 1996). Savadamathu (2002) reported a 24% reduction in the magnitude of the median runoff as a result of farm dam impoundments in the Upper Marne catchment, a small (240 km^2) tributary system of the lower Murray River. Associated with this change was a reduction in the duration of low and medium flow events but minimal impact on high flow events (>10 ML day^{-1}). Thus, farms dams in this catchment reduced the provision of low flows and accentuate the seasonal signal of flow. Not surprisingly, the extent of impact of farms dams on local hydrology is related to the number of farm dams present within a catchment (Schreider *et al.* 2002) and given the increasing rate of farm dam construction, it is likely that impacts on hydrology will continue to be manifest. Similarly, small-scale riparian abstraction is likely to have altered flow regimes in those areas where crop irrigation is practiced. Natural riverine flows are an important source of water supply for stock, and domestic and agricultural uses throughout many catchments in Australia. Private riparian abstractions generally occur at times of low rainfall and hence at times of low to medium flow.

3.3.8 Recent anthropogenic changes to hydrology – other factors

A host of other anthropogenic factors may influence local hydrology. Urbanisation, principally due to the creation of extensive areas of impervious surface, greatly alters flood hydrographs (Walsh 2000, 2004; Walsh *et al.* 2005; Booth 1990). While the areal extent of urban areas in Australia remains small (Figure 3.2), the continent has a high-density road network (Figure 3.2.) which may impact on streamflow. The presence of small roads, even in forested catchments, may alter the flood hydrograph. For example, Bren and Leitch (1986) estimated that a single road, comprising only 2% of a small forested catchment, increased storm flow by about 10%; but more importantly, doubled the peak flow generated.

This document is not intended to be an exhaustive review of anthropogenic changes to hydrology but rather is intended to highlight the current and antecedent conditions present across Australia. It seems that there are probably very few areas of Australia that are not, in some way, affected by human activities and the likely impact that these activities might have on hydrology. This is a fact of life.

3.4 Relevance of the late 20th century time period in ecohydrological classification

Given that hydrologic regimes have varied over different time scales prior to European colonisation of Australia and in many places have altered subsequent to this period, can we validly describe the state of the natural flow regime and how it varies across the continent? By sheer necessity the classification scheme based on hydrological data presented here (Appendix 5) is based upon contemporary flow data confined to a very recent time period (i.e. between 1965 and 2000). This is largely unavoidable given the nature of the exercise; i.e. to construct a continent wide ecohydrological classification based on empirically derived flow data. It is accepted that as a result of human influences, flow regimes may have altered, typically to some unknown extent, from that existing prior to European colonisation. Whilst this may be perceived as problematic, several factors need to be considered before an empirically derived classification based on contemporary data is rejected. First, some form of baseline is needed and the definition of that baseline is dependent not only on considerations about record length and metric computation, temporal concordance of flow records and relevance of the contemporary flow regime in the context of short-, medium- and long-term flow regime change, but also upon simple pragmatic decisions largely governed by data availability. Second, it is within the contemporary flow regime that aquatic organisms exist, although very long-lived organisms may still be adjusting to historical change. Assessments of ecological change associated with further changes in land use, flow manipulation and global climate change can only be based on comparison between the existing and projected future states unless there is data on pre-existing conditions, which in most cases we do not.

3.5 References

Arthington, A.H., King, J.M., O'Keefe, J.H., Bunn, S.E., Day, J.A., Pusey, B.J., Bluhdorn, D.R. and Tharme, R. (1992). Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems. Pp. 69–76. In Pigram, J.J. and B.Hooper, B. (eds.), *Water Allocation for the Environment.* Proceedings of an international seminar and workshop. Centre for Water Policy Research, University of New England, Armidale, NSW.

Arthington,A.H. and Pusey,B.J. (1993). In-stream flow management in Australia: methods, deficiencies and future directions. In Arthington, A.H. (ed), *Water: An Endangered National Resource. Australian Biologist* 6: 52–60.

Arthington, A.H. and Pusey, B.J. (2003). Flow restoration and protection in Australian rivers. River Research and Applications 19: 1–19.

Avise, J.C., Walker, D. and Johns, G.C. (1998). Species durations and Pleistocene effects on vertebrate phylogeny. *Proceedings of the Royal Society of London B* 265: 1707–1712.

Ayliffe, L.K., Marianelli, P.C., Moriarty, K.C., Wells, R.T., McCulloch, M.T., Mortimer, G.E. and Hellstrom, J.C. (1998). 500 ka precipitation record from south-eastern Australia; evidence for interglacial aridity. *Geology* 26: 147–150.

Beavis, S.G. and Howden, M. (1996). *National Landcare Program (NLP) Project: Effects of farm dams on water resources*. Report to the Bureau of Resource Sciences, Canberra. 65 pp.

Booth, D.B. (1990). Stream channel incision following drainage basin urbanisation. *Water Resources Bulletin* 26: 407–417.

Borg, H. and Stoneman, G.L. (1991). Long-term implications for streamflow of changes in vegetation cover and stand height of regenerating karri stands in south-west Western Australia. *Forest Ecology and Management* 40: 65–73.

Brizga S.O., Arthington A.H., Pusey B.J., Kennard M.J., Mackay S.J., Werren G.L., Craigie N.M. and Choy S.J. (2002). Benchmarking, a 'top-down' methodology for assessing environmental flows in Australian rivers. In King, J. And Petts, G. (eds), *Environmental Flow Management – A World Perspective*. Proceedings of an International Conference held in Johannesburg, South Africa, March 2002.

Bren, L.J. and Leitch, C.J. (1986). Rainfall and water yields of three small forested catchments in north-east Victoria, and relation to flow of local rivers. *Proceedings of the Royal Society of Victoria* 98: 19–29.

Bunn, S.E. and Arthington, A.H. (2002). Basic principles and consequences of altered hydrological regimes for aquatic biodiversity. *Environmental Management* 30: 492–507.

Cambray, J.A. and Bianco, P.G. (1998). Freshwater fish in crisis, a Blue Planet perspective. *Italian Journal of Zoology* 65 (Suppl.): 345–356.

Caspary, H.J. (1990). An ecohydrological framework for water yield changes of forested catchments due to forest decline and soil acidification. *Water Resources Research* 26: 1121–1131.

Chiew, F.H.S. and McMahon, T.A. (2002). Modelling the impacts of climate change on Australian streamflow. *Hydrological Processes* 16: 1235–1245.

Chiew, F.H.S. (2006). An overview of methods for estimating climate change impact on runoff. *Proceedings of the 30th Hydrology and Water Resources Symposium*, Launceston, Tasmania.

Chiew, F.H.S., Piechota, T.C., Dracup, J.A. and McMahon, T.A. (1998). El Niño/Southern Oscillation and Australian rainfall, streamflow and drought: links and potential for forecasting. *Journal of Hydrology* 204: 138–149

Clewett, J.F. and Stone, R.C. (1994). The weather and the SOI. Pp. 22–30. In Partridge, I.J. (ed), *Will it rain?* Queensland Dept of Primary Industries, Brisbane.

Cronin, T.M. (1985). Speciation and stasis in marine Ostracoda: climatic modulations of evolution. *Science* 227: 60–63.

Crowley, G.M. and Garnett, S.T. (2000). Changing fire management in the pastoral lands of Cape York Peninsula of northern Australia, 1623 to 1996. *Australian Geographical Studies* 38: 10–25.

D'Antonio, C.M. and Vitousek, P.M. (1992). Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics* 23: 63–87.

DeBano, L.F. (2000). The role of fire and soil heating on water repellancy in wildland environments. *Journal of Hydrology* 231: 113–122.

Dyrness, C.T. (1976). *Effect of wildfire on soil wettability in the high Cascades of Oregon.* Research Paper PNW-202, USDA Forest Service, Portland, Oregon.

Fairfax, R.J. and Fensham, R.J. 2002. In the footsteps of J. Alfred Griffiths: a Cataclysmic history of Great Artesian Basin springs in Queensland. *Australian Geographical Studies* 40: 210–230.

Foote, M. (1997). The evolution of morphological diversity. *Annual Review of Ecology and Systematics* 28: 129–152.

Gentili, J. (1971). Climate fluctuations. Pp. 189–211. In *Climates of Australia and New Zealand,* World survey of Climatology Vol 13. Elsevier, Amsterdam.

Gorman, O.T. (1992). Evolutionary ecology and historical ecology: assembly, structure, and organization of stream fish communities. Pp 659-688 In *systematics, Historical Ecology and North American Freshwater Fishes.* (Ed. R.L. Mayden). Stanford University Press, Stanford, California.

Gorman, T.O. (1992). Evolutionary ecology and historical ecology: assembly, structure, and organization of stream fish assemblages. Pp. 659–688. In Mayden, R.L. (ed), *Systematics, Historical Ecology, and North American Freshwater Fishes.* Stanford University Press, Stanford.

Greenwood K.L. and McKenzie B.M. (2001). Grazing effects on soil physical properties and the consequences for pastures: a review. *Australian Journal of Experimental Agriculture* 41: 1231–1250.

Guégan, J.F., Lek, S. and Oberdorff, T. (1998). Energy availability and habitat heterogeneity predict global riverine fish diversity. *Nature* 391: 382–384.

Hannah, D.M., Wood, P.J. and Sadler, J.P. (2004). Ecohydrology and hydroecology: a "new paradigm"? *Hydrological Processes* 18: 3439–3445.

Hendry, A.P. and Kinnison, M.T. (1999). The pace of modern life: measuring rates of contemporary microevolution. *Evolution* 53: 1637–1653.

Herron N.F. and Hairsine P.B. (1998). A scheme for evaluating the effectiveness of riparian zones in reducing overland flow to streams. *Australian Journal of Soil Research* 36: 683–698.

Hoeinghaus, D.J., Winemiller, K.O. and Burnbaum,J.S. (2007). Local and regional determinants of stream fish assemblage structure: inferences based on taxonomic and functional groups. *Journal of Biogeography* 34: 324–338.

Horwitz, R.J. (1978). Temporal variability patterns and the distributional patterns of stream fishes. *Ecological Monographs* 48, 307–321.

Huh, S., Dicky, D.A., Meador, M.R. and Ruhl, K.E. (2005). Temporal analysis of the frequency and duration of low and high streamflow: years of record needed to characterise streamflow variablility. *Journal of Hydrology* 310: 78–94.

Hughes, J.M.R. and James, B. (1989). A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. *Australian Journal of Marine and Freshwater Research* 40: 303–326.

Isdale, P.J. (1996). Coral rain gauges – the fluorescence proxy record in coral reefs. Pp. 51–59. In *Proceedings of the IGBP – PAGES/PEP-II Symposium on Paleoclimate and Environmental variability in the Austral-Asia Transect during the past 2000 years.* IAHS Nagoya University, Japan.

Kennard, M.J., Olden, J.D., Arthington, A.H., Pusey, B.J. and Poff, N.L. (2007). Multi-scale effects of flow regime, habitat, and their interaction on fish assemblage structure in eastern Australia. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 1346–1359.

Kershaw, A.P. (1986). Climatic change and Aboriginal burning in north-eastern Australia during the last two glacial/interglacial cycles. *Nature* 322: 47–49.

Lamouroux, N., Poff, N.L. and Angermeier, P.L. (2002). Intercontinental convergence of stream fish community traits along geomorphic and hydraulic gradients. *Ecology* 83: 1792–1807.

Langford, K.J. (1976). Changes in yield of water following a bushfire in a forest of *Eucalyptus regnans*. *Journal of Hydrology* 29: 87–114.

Lytle, D.A. and Poff, N.L. (2004). Adaptation to natural flow regimes. *Trends in Ecology & Evolution* 19: 94–100.

McAllister, D.E., Hamilton, A.L. and Harvey, B. (1997). Global freshwater biodiversity: striving for the integrity of freshwater systems. *Sea Wind* 11: 1–140.

McCulloch,M., Fallon, S., Wyndham, T., Hendy, E., Lough, J. and Barners, D. (2003). Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. *Nature* 421: 727–730.

McDowell, P.F., Webb, T. III and Bartlein, P.J. (1995). Long-term environmental change. Pp. 327–370. In Powell, T.M. and Steele, J.H. (eds), *Ecological Time Series.* Chapman and Hall, New York.

Miller, D.J., Luce, C.H. and Benda, L.E. (2003). Time, space, and episodicity of physical disturbance in streams. *Forest Ecology and Management* 178: 121–140.

Newman, B.D., Wilcox, B.P., Archer, S.R., Breshears, D.D., Dahm, C.N., Duffy, C.J., McDowell, N.G., Phillips, F.M., Scanlon, B.R. and Vivoni E.R. (2006). Ecohydrology of water-limited environments: a scientific vision. *Water Resources Research* 42: W06302.

Oberdorff, T., Guegan, J.F. and Hugueny, B. (1995). Global scale patterns of fish species richness in rivers. *Ecography* 18: 345–352.

Olden, J.D. and Poff, N.L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19: 101–121.

Pittock, A.B. (1975). Climate change and the patterns of variation in Australian rainfall. *Search* 6: 498–504.

Platts, W.S. (1991). Livestock grazing. Pp. 389–423. In Meehan, W.R. (ed), *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats.* American Fisheries Society Special Publication 19, Bethesda, Maryland.

Pearce, A.J. (1990). Streamflow generation processes – an Austral view. *Water Resources Research* 26: 3037–3047.

Plummer, N., Lin, Z. and Torok, S. (1995). Trends in diurnal temperature range over Australia since 1951. *Atmospheric Research* 37: 79–86.

Poff, N.L and Ward, J.V. (1989). Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* 46: 1805–1818

Poff, N.L. and Allan, J.D. (1995). Functional organization of stream fish assemblages in relation to hydrologic variability. Ecology 76: 606–627

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997). The natural flow regime: a paradigm for river conservation and restoration. *BioScience* 47: 769–84.

Postel, S. and Richter, B. (2003). *Rivers for life: Managing water for people and nature*. Island Press, Washington, DC.

Potter, K.W. (1991). Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. *Water Resources Research* 27: 845–855.

Pusey, B.J., Kennard. M.J. and Arthington, A.H. (2000). Discharge variability and the development of predictive models relating stream fish assemblage structure to habitat in north-eastern Australia. *Ecology of Freshwater Fish* 9: 30–50.

Rosenberg, D.M., McCully, P. and Pringle, C.M. (2000). Global-scale environmental effects of hydrological alterations – introduction. *BioScience* 50: 746–751.

Rossiter, N.A., Setterfield, S.A., Douglas, M.M. and Hutley, L.B. (2003). Testing the grass-fire cycle: alien grass invasion in the tropical savannas of northern Australia. *Diversity and Distributions* 9: 169–178.

Sahin, V. and Hall, M.T. (1996). The effects of aforestation and deforestation on water yield. *Journal of Hydrology* 178: 293–309.

Sala, O.E., Chapin, F.S.I., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.R., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M. and Wall, D.H. (2000). Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.

Savadamathu, K. (2002). Impact of farm dams on streamflow in the upper Marne Catchment. South Australia Department of Water Resources. Report DWR 02/01/003. 34 pp.

Schreider, S.Y., Jakeman, A.J., Letcher, R.A., Nathan, R.J., Neal, B.P. and Beavis, S.G. (2002). Detecting changes in streamflow responses to changes in non-climatic catchment conditions: farm dam development in the Murray-Darling basin, Australia. *Journal of Hydrology* 262: 84–98.

Schlosser, I.J. and Angermeier, P.L. (1995). Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. *American Fisheries Society Symposium* 17: 392–401

SEAC (State of the Environment Advisory Council). (1996). *State of the Environment Australia 1996*. CSIRO Publishing: Melbourne.

Simons, M., Podger, G. and Cooke, R. (1996). IQQM – a hydrological modelling tool for water resource and salinity management. *Environmental Software* 11: 185–192.

Siriwardena, L., Finlayson, B.L. and McMahon, T.A. (2006). The impact of land use change on catchment hydrology in large catchments: the Comet River, Central Queensland, Australia. *Journal of Hydrology* 326: 199–214.

Stearn, S.C. (1992). *The Evolution of Life Histories.* Oxford University Press, Oxford. 249 pp.

Stewart-Koster, B., Kennard, M.J., Harch, B.D., Sheldon, F., Pusey, B.J. and Arthington, A.H. (2007). Partitioning the variation in stream fish assemblages in a spatio-temporal hierarchy. *Marine and Freshwater Research*. 58: 675–686.

Sturman, A. and Tapper, N. (1996). *The weather and climate of Australia and New Zealand*. Oxford University Press, Oxford. 476 pp.

Swank, W.T. and Douglas, J.E. (1974). Streamflow greatly reduced by converting hardwood stands to pineforests. *Science* 185: 857–859.

Trimble, S.W. and Mendel A.C. (1995). The cow as geomorphic agent – a critical review. *Geomorphology* 13: 233–253.

Tudhope, A.W., Chilcot, C.P., McCulloch, Cook, E.R., Chappell, J., Ellam, R.M., Lea, D.W., Lough, J.M. and Shimmield, G.B. (2001). Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle. *Science* 291: 1511–1517.

Vörösmarty, C.J., Green, P. Salisbury, J. and Lammers, R.B. (2000). Global water resources: vulnerability from climate changes and population growth. *Science* 289: 284–288.

Vörösmarty, C.J., Lettenmaier, D., Leveque, C., Meybeck, M., Pahl-Wostl, C., Alcamo, J., Cosgrove, H., Grassl, H., Hoff, H., Kabat, P., Lansigan, P., Lawford, R. & Naiman, R. (2004). Humans transforming the global water system. *EOS* 85: 509–514.

Walsh C. J., Fletcher T. D. and Ladson A. R. (2005). Stream restoration in urban catchments through re-designing stormwater systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society* 24: 690–705.

Walsh, C. J. (2000). Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration. *Hydrobiologia* 431(2): 107–114.

Walsh, C. J. (2004). Protection of in-stream biota from urban impacts: minimise catchment imperviousness or improve drainage design? *Marine and Freshwater Research* 55: 317–326.

Ward, D.J., Lamont, B.B. and Burrows, C.L. (2001). Grasstrees reveal contrasting fire regimes in eucalypt forest before and after European settlement of south-western Australia. *Forest Ecology and Management* 150: 323–329.

Webb, T. and Bartlein, P.T. (1992). Global climate changes during the last 3 million years: climatic controls and biotic responses. *Annual Review in Ecology and Systematics* 23: 141–173.

Whitlow, J.R. and Gregory, K.J. (1989). Changes in urban stream channels in Zimbabwe. *Regulated Rivers: Research and Management* 4: 27–42.

Willcocks, J. and Young, P (1991). *Queensland's rainfall history: Graphs of rainfall averages 1880–1998*. Queensland Department of Primary Industries, Brisbane. 290 pp.

Williams, L.R., Taylor, C.M., Warren, M.L. and Clingenpeel, J.A. (2003). Environmental variability, historical contingency, and the structure of regional fish and macroinvertebrate faunas in Ouachita Mountain stream systems. *Environmental Biology of Fishes* 67: 203–216.

Williams, M., Dunkerley, D., De Decker, P., Kershaw, P. and Chappell, J. (1998). *Quaternary Environments*, 2nd edition. Arnold, London. 329 pp.

Williams, R.J., Cook, G.D., Gill, A.M. and Moore, P.H.R. (1999). Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Austral Ecology* 24: 50–59.

Wohl, E.E. (1992). Bedrock benches and boulder bars: floods in the Burdekin Gorge of Australia. *Geological Society of America Bulletin* 104: 770–778.

Wondzell, S.M. and King, J.G. (2003). Post-wildfire erosional processes in the Pacific northwest and Rocky Mountain regions. *Forest Ecology and Management* 178: 75–87.

Zalewski, M., Janauer, G.A. and Jolankai, G. (1997). *Ecohydrology. A new paradigm for the sustainable use of aquatic resources*. UNESCO IHP Technical Document in Hydrology 7. IHP – V Projects 2.3/2.4. UNESCO, Paris. 58 pp.

Zalewski, M. (2002). Ecohydrology – the use of ecological and hydrological processes for sustainable management of water resources. *Hydrological Sciences Journal* 47:825–834.

Appendix 4

Quantifying uncertainty in estimation of hydrologic metrics – implications of discharge record length and record period

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Summary

Hydrologic metrics have been used extensively in ecology and hydrology to summarise the characteristics of riverine flow regimes at various temporal scales but there has been limited evaluation of the sources and magnitude of uncertainty involved in their computation. Variation in bias, precision and overall accuracy of these metrics influences the ability to correctly describe flow regimes, detect meaningful differences in hydrologic characteristics through time and space, and define flow-ecological response relationships. Here, we examine the effects of two primary factors – discharge record length and time period of record – on uncertainty in the estimation of 120 separate hydrologic metrics commonly used by researchers to describe ecologically relevant components of the hydrologic regime. These analyses are intended to inform the ecohydrological classification analyses presented in Appendix 5.

Our study was based on six stream gauges with 75 years of continuous daily discharge data and the gauges were situated in a variety of climatic zones, represented a range of catchment sizes and had varying hydrologic regime types. When compared to hydrologic metrics estimated from 75 years of discharge record, bootstrapped resampling results revealed that metric bias rapidly decreased and precision and overall accuracy markedly increased with increasing record length, but tended to stabilise >15 years and did not change substantially >30 years. The most biased metrics for a given record length were those describing skewness in annual and maximum flows, low flow duration, timing of minimum and maximum flows, and variability in the number of flow reversals. The relative magnitude of bias between metrics tended to remain similar irrespective of record length. Variation in the precision and overall accuracy of metric estimates with increasing record length showed similar trends to that observed for bias. The use of at least 15 years of discharge data was sufficient to detect a 10% difference in the mean of estimates of most hydrologic metrics with statistical power ($1-\beta$) greater than 0.80 and all metrics had a power greater than 0.95 when calculated using 30 years of record. Overall, relatively few stream gauges (i.e. < 20 when based on 15 year records, <10 when based on 30 year records) needed to be sampled to achieve a half width of the confidence interval within close proximity to the true population mean.

We found a strong positive relationship between the degree of overlap of discharge record and similarity in hydrologic metrics when based on 15-year and 30-year discharge periods calculated within a 36-year temporal window (1965–2000), although hydrologic metrics calculated for a given stream gauge tended to vary only within a restricted range through time. The hydrologic metrics most sensitive to the degree of record overlap were similar to those showing the highest sensitivity to length of record used in their calculation. Cluster analyses revealed that hydrologic metrics were slightly more sensitive to short discharge records than longer records, however differences overall were very minor.

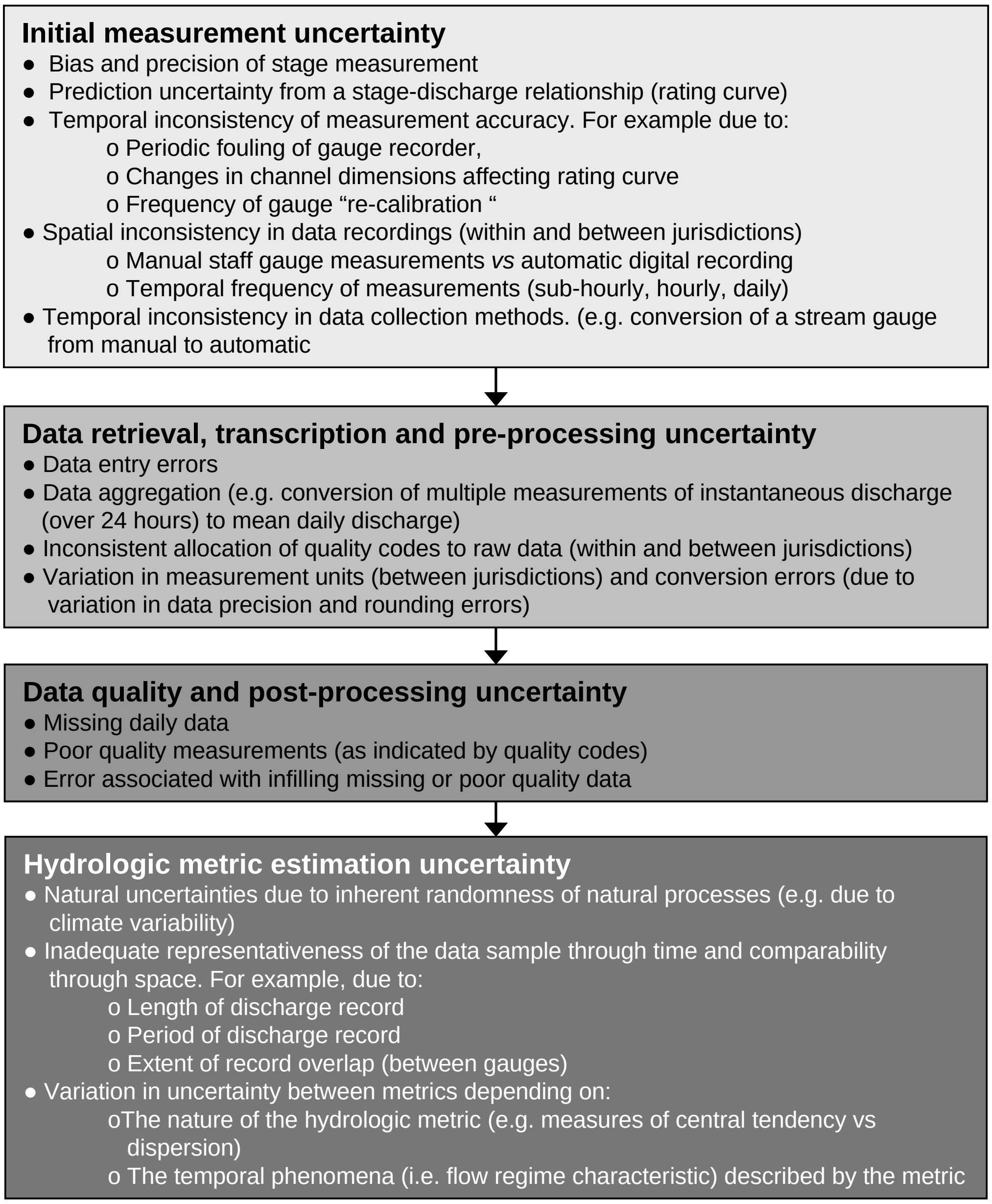
Our study provides critical guidance for selecting an appropriate record length and temporal period of record given a degree of metric bias and precision deemed acceptable by a researcher. We conclude that: (1) estimation of hydrologic metrics based on at least 15 years of discharge record is suitable for use in hydrologic analyses that aim to detect important spatial variation in hydrologic characteristics; (2) metric estimation should be based on overlapping discharge records contained within a discrete temporal window (ideally > 50% overlap among records); and (3) metric uncertainty varies greatly and should be accounted for in future analyses.

4.1 Introduction

The importance of flow variability for shaping the biophysical attributes and functioning of river systems is well recognised (Naiman *et al.* 2008). The natural flow-regime paradigm proposes that the structure and function of riverine ecosystems, and the adaptations of their constituent riparian and aquatic species, are dictated by patterns of intra- and inter-annual variation in river flows (Poff *et al.* 1997). Researchers often describe the components of the hydrograph (i.e. magnitude, frequency, seasonal timing, duration and rate of change of flow) using hydrologic metrics (also termed indices or statistics) that characterise statistical properties of the long-term hydrologic regime of rivers based on multi-year time series of discharge data. Hydrologic metrics have been used extensively throughout the scientific literature for the evaluation of spatial variation in flow regime characteristics (Puckridge *et al.* 1998; McMahon *et al.* 2007), flood frequency estimation (Micevski *et al.* 2006; Ribatet *et al.* 2007), hydrologic classification (Hughes and James 1989; Poff 1996) and regionalisation (Nathan and McMahon 1990; Wilkinson *et al.* 2006), hydrologic trend detection (Chiew and McMahon 1993; Huh *et al.* 2005), hydrologic model calibration and validation (Simons *et al.* 1996; Thyer *et al.* 2006), detection of anthropogenic hydrological alteration (Richter *et al.* 1996; Mathews and Richter 2007), environmental flow assessments (see reviews by Tharme 2003; Arthington *et al.* 2006), and in studies investigating the influence of hydrology on biological communities and ecological processes (Poff and Allan 1995; Clausen and Biggs 1997; Monk *et al.* 2007; Kennard *et al.* 2007).

Despite the diverse and extensive application of hydrologic metrics to address hydrological, ecological and management questions, there have been surprisingly few systematic evaluations of the sources and magnitude of uncertainty involved in metric estimation. Assessment of uncertainty is a critical step in the data acquisition and analysis phases of any environmental modelling and prediction exercise (Pielke and Conant 2003; Jakeman *et al.* 2006) and failure to do so can lead to biases in model structure, parameter estimation, hypothesis testing and, ultimately result in underestimation of prediction uncertainty (Hanafi *et al.* 2007). This is especially relevant for ecohydrological studies where an inability to accurately define hydrological characteristics and predict ecological responses can have significant economic and ecological consequences (e.g. determining environmental flow allocations, Stewardson and Rutherford 2006).

Uncertainties in hydrologic data analysis reflect both an inability to quantify the phenomena and underlying processes, and the variable nature of hydrologic events (Kundzewicz 1995; Yen 2002; Figure 4.1). For example, uncertainty commonly arises at multiple phases during the collection and subsequent processing of raw stream stage and discharge data (Shiklomanov *et al.* 2006). This will ultimately contribute to uncertainty in the estimation of summary hydrologic metrics, however the manner in which uncertainty is propagated through these phases (i.e. additively, multiplicatively) is not well understood. Uncertainty associated with collection of stage height data is the province of hydrographers and is largely beyond the control of many end-users of hydrologic data. In contrast, quantifying uncertainty associated with the estimation of hydrologic metrics from time series of available discharge data is both feasible and warranted. In this context, uncertainty can be quantified in terms of bias (the difference between an estimate and the true value) and precision (the degree of variation in an estimate) (Walther and Moore 2005; Wheaton *et al.* 2008). Variation in hydrologic metric bias and precision influences the ability to characterise and detect meaningful variation in hydrologic characteristics through space and time. The most important considerations for metric calculations are the magnitude of uncertainty associated with the length of discharge record (i.e. sample size), the temporal period of record (i.e. sample period) and the extent of temporal similarity between periods of record (i.e. sample overlap among stream gauge records) (Figure 4.1). The magnitude of uncertainty also may vary depending on the nature of the hydrologic metric (e.g. measures of central tendency versus dispersion) and the temporal phenomena (i.e. particular flow regime characteristic) it seeks to describe.



Initial measurement uncertainty

- Bias and precision of stage measurement
- Prediction uncertainty from a stage-discharge relationship (rating curve)
- Temporal inconsistency of measurement accuracy. For example due to:
    - Periodic fouling of gauge recorder,
    - Changes in channel dimensions affecting rating curve
    - Frequency of gauge "re-calibration "
- Spatial inconsistency in data recordings (within and between jurisdictions)
    - Manual staff gauge measurements *vs* automatic digital recording
    - Temporal frequency of measurements (sub-hourly, hourly, daily)
- Temporal inconsistency in data collection methods. (e.g. conversion of a stream gauge from manual to automatic

Data retrieval, transcription and pre-processing uncertainty

- Data entry errors
- Data aggregation (e.g. conversion of multiple measurements of instantaneous discharge (over 24 hours) to mean daily discharge)
- Inconsistent allocation of quality codes to raw data (within and between jurisdictions)
- Variation in measurement units (between jurisdictions) and conversion errors (due to variation in data precision and rounding errors)

Data quality and post-processing uncertainty

- Missing daily data
- Poor quality measurements (as indicated by quality codes)
- Error associated with infilling missing or poor quality data

Hydrologic metric estimation uncertainty

- Natural uncertainties due to inherent randomness of natural processes (e.g. due to climate variability)
- Inadequate representativeness of the data sample through time and comparability through space. For example, due to:
    - Length of discharge record
    - Period of discharge record
    - Extent of record overlap (between gauges)
- Variation in uncertainty between metrics depending on:
    - The nature of the hydrologic metric (e.g. measures of central tendency vs dispersion)
    - The temporal phenomena (i.e. flow regime characteristic) described by the metric

Figure 4.1. Potential sources of uncertainty in estimating summary hydrological metrics from gauged discharge data.

Limited investigations of a small number of hydrologic metrics, including measures of flood magnitude, seasonality, spell frequency and duration, and discharge predictability, constancy and contingency, indicate anywhere between 10 and 60 years of continuous discharge data are required for estimates of some metrics to stabilise (e.g. Gan *et al.* 1991; Richter *et al.* 1997; Cunderlik *et al.* 2004; Huh *et al.* 2005; Ribatet *et al.* 2007). This wide range of record lengths no doubt reflects differences among studies in the type of metric examined, the time-step of the raw discharge data used to derive the metric (i.e. daily, monthly, yearly), the criteria used to define estimate stabilisation, geographic differences in discharge variability, and differences in the subjective choice of researchers (McMahon *et al.* 2007). Increasing the length of discharge record examined should minimise the bias and maximise the precision of estimates of hydrologic metrics and therefore increase the statistical power to detect spatial and temporal variation in hydrologic characteristics. In practice however, the length of discharge record used to calculate hydrologic metrics is often limited by pragmatic constraints of data availability and quality (Cunderlik and Burn 2002; Wilkinson *et al.* 2006) rather than being informed by a quantitative evaluation of changes in metric estimates with increasing record length (but see previously cited examples).

Many hydrologic analyses presented in the scientific literature use concurrent periods of record (i.e. identical start and end dates for all gauges) to control for potential climatic effects that vary over time. However, if the criteria for determining the optimum period of record are too restrictive many available stream gauges may be excluded unnecessarily, because stream gauges often vary in their periods of operation. An alternative approach is to use gauges that share a common period of record without being concurrent, i.e. periods of record overlap but do not necessarily share start and end dates, or use hydrologic data from non-overlapping time periods. Although this approach potentially increases the geographic coverage of stream gauges, it also increases the likelihood of evaluating hydrologic characteristics from time periods with different climatic conditions (McMahon and Finlayson 1992; Micevski *et al.* 2006). However, the extent to which this influences the comparability of a broad range of hydrologic metrics calculated from multiple stream gauges has not yet been formally evaluated (but see Cunderlik and Burn 2002, who examined the sensitivity of an index of flood seasonality to the temporal period of record).

In this Appendix, we examine the effects of discharge record length and temporal period of record on uncertainty (referring to bias, precision and overall accuracy) in the estimation of 120 hydrologic metrics commonly used to describe various ecologically relevant components of the hydrologic regime (Olden and Poff 2003). We address the following questions: (1) what is the sensitivity of the hydrologic metrics to variations in discharge record length; (2) how does variation in discharge record length affect the statistical power and sample size (number of stream gauges) required to detect spatial differences in hydrologic characteristics; and 3) what is the sensitivity of the hydrologic metrics to variations in the period of discharge record? Precise, unbiased estimates of streamflow characteristics are required to best inform future water management and planning, and investigations of ecological responses to water stress at a time of overexploitation of global water resources and increasing conflict between societal and environmental needs. The aim of the present study was therefore to quantify uncertainty in the estimation of a wide range of hydrological metrics frequently used in ecohydrological studies and to inform the ecohydrological classification analyses presented in Appendix 5.

4.2 Methods

4.2.1 Location and hydrologic characteristics of test streams

Six stream gauges were used to evaluate hydrologic metric sensitivity to discharge record length and period of record (Figure 4.2). These gauges were situated in a variety of climatic zones (ranging from tropical to temperate Australia), and represent a range of catchment sizes (28–3634 km^2). All had 75 years of continuous mean daily discharge data for the period between 1 January 1926 and 31 December 2000.

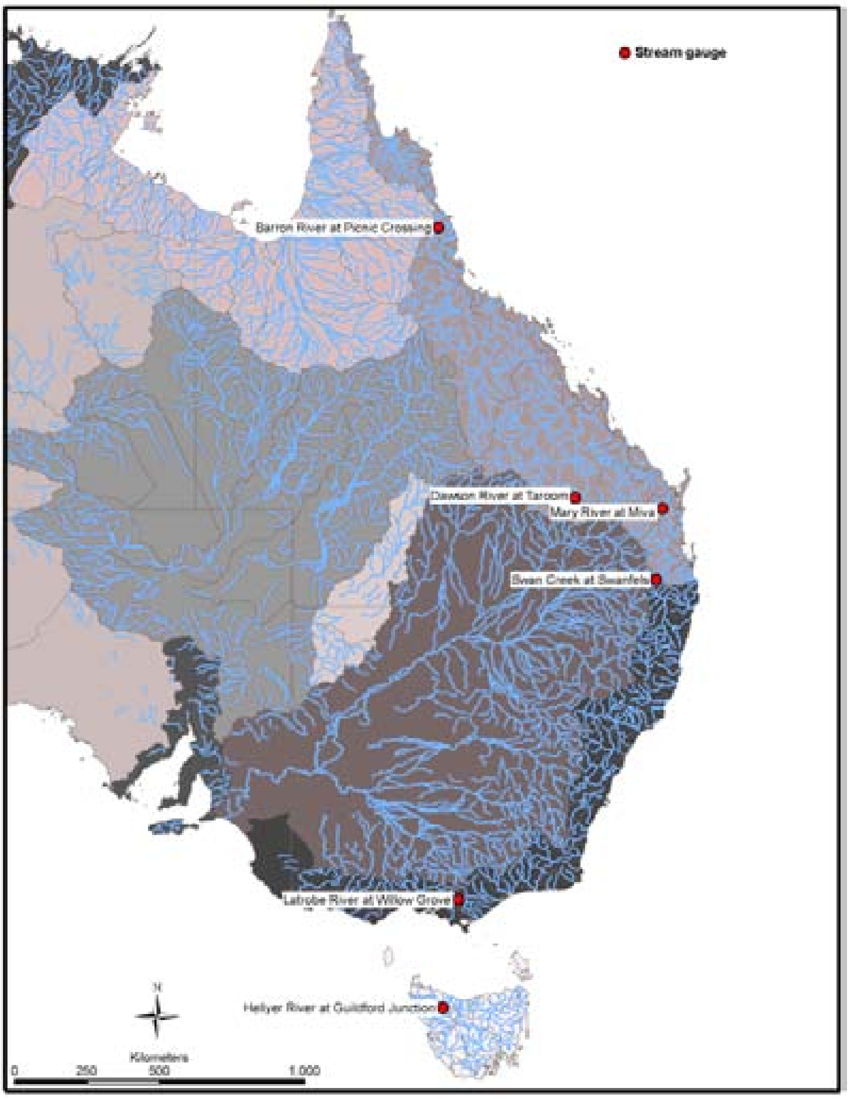


Figure 4.2. Location of the six stream gauges used for record length and period of overlap analyses.[1]

Long-term cyclic variation in discharge is evident in the six stream gauges; however, the relative magnitude of this variation differs between gauges (Figure 4.3). Inter-annual variation in mean daily discharge (MDF, as a proportion of the long-term MDF) was most pronounced in the Dawson River, Mary River and Swan Creek in central eastern Australia (± 85–100% of MDF) but was not as great for the Barron River in north-eastern Australia (± 80%), Latrobe River in south-eastern Australia (± 50%) and Hellyer River in northern Tasmania (± 35%) (Figure 4.3). Fifteen- and thirty-year moving averages for MDF show that several gauges were subject to distinct periods of above- and below-average discharge but that the timing of these cycles varied between climatic zones and stream gauges. For example, a dry period ending in the mid 1940s is evident for the Dawson and Mary rivers and Swan Creek but not the Barron, LaTrobe or Hellyer rivers (Figure 4.3). The latter three rivers are characterised by prolonged high baseflows due to significant groundwater contributions (see Appendix 5).

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[1] This figure incorporate Data which is © Commonwealth of Australia (Geoscience Australia) 2006. The Data has been used with the permission of the Commonwealth. The Commonwealth has not evaluated the Data as altered and incorporated within this figure, and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose.

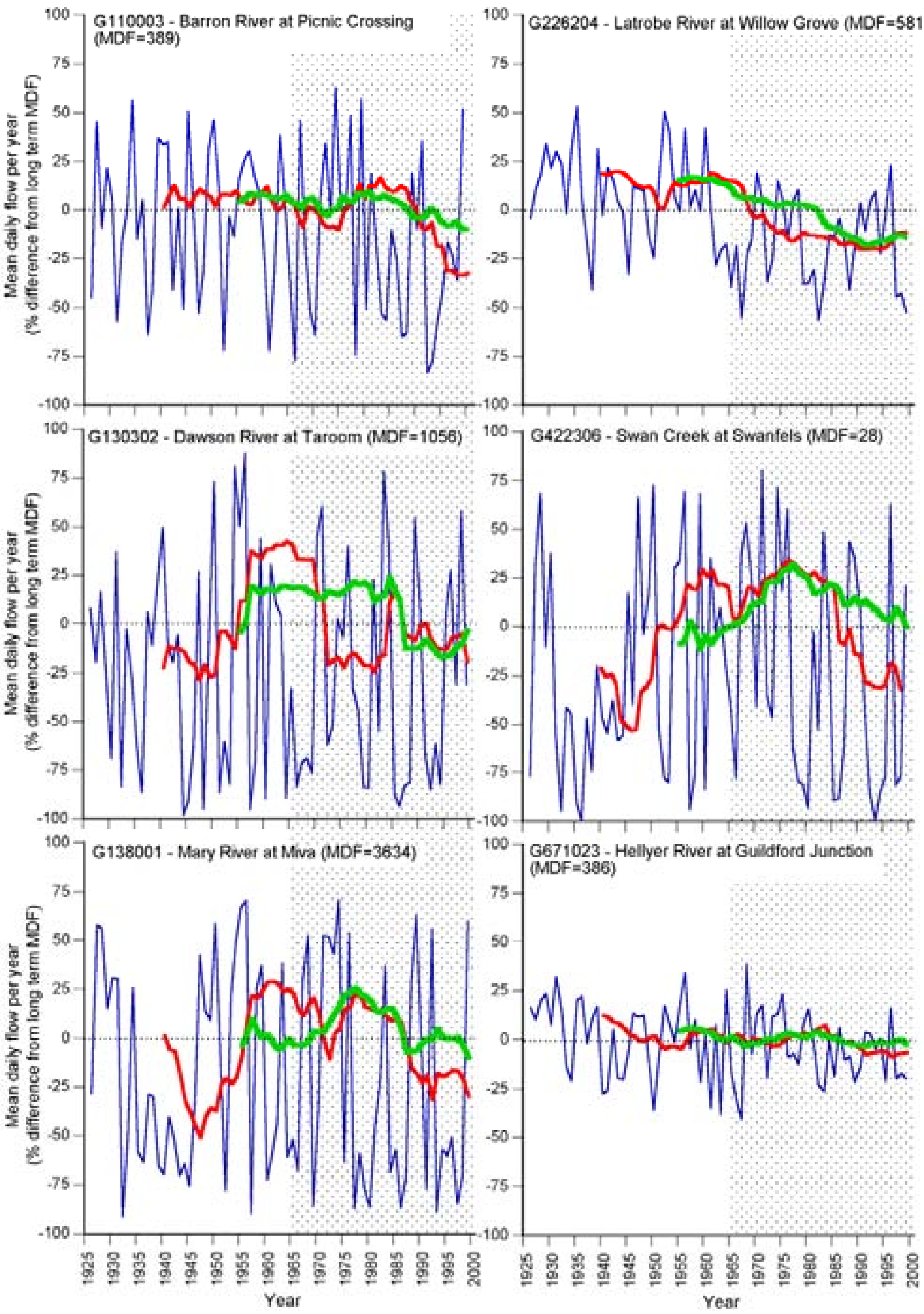


Figure 4.3. Annual variation in mean daily discharge at six stream gauges (thin blue line) expressed as a percentage difference from the mean daily discharge (MDF) calculated over the entire 75 year record (1 January 1926 to 31 December 2000). Fifteen year (medium red line) and 30 year (thick green line) moving averages fitted to the annual data are also shown. The mean daily discharge (MDF; ML day^{-1}) for each stream gauge is shown in parentheses and the study period used for the ecohydrological classification (1 January 1965 – 31 December 2000) is indicated by stippling.

4.2.2 Hydrologic metrics

We selected 120 metrics (listed in Appendix 5) commonly used to describe ecologically relevant components of the hydrologic regime relating to the magnitude, frequency, duration, timing and rate of change in discharge events and the temporal variability and predictability in these measures (e.g. see Richter *et al.* 1996; Olden and Poff 2003; and references therein). Following Olden and Poff (2003), we grouped our final set of 120 individual hydrologic metrics (see Appendix 5.1 for methods of calculation) into five major categories describing different major facets of the flow regime. These included measures of central tendency (mean) and dispersion (variance) in the magnitude (n = 54 metrics), frequency (n = 14), duration (n = 34), timing (n = 12) and rate of change (n = 6) in flow events.

4.2.3 Effects of discharge record length

For each of the six stream gauges, we evaluated changes in the uncertainty associated with each hydrologic metric as the length of the discharge record used in their estimation increased. We quantified uncertainty using a measure of *bias* (the difference between an estimate and the true value), *precision* (the degree of variation in an estimate) and *accuracy* (a measure of overall performance combining bias and precision) (Walther and Moore 2005). We incrementally constructed hypothetical time series of daily discharge data using a Monte-Carlo resampling procedure where one, then two, then three (etc.) consecutive years of daily discharge data were randomly selected up to the maximum of 75 years. For each increment of sampling effort (one year), daily discharge data were pooled and each hydrologic metric calculated. This resampling procedure was repeated 100 times for each annual increment. Bias for each annual increment was calculated as the mean absolute percentage difference between the estimated metric values generated over the 100 randomisations and the 'true' value calculated over the entire 75-year record. Note that the 'true' value is unknowable for time series of hydrologic data so our approximation based on 75 years of data is also subject to uncertainty (Wheaton *et al.* 2008). Precision for each annual increment was represented by the coefficient of variation (standard deviation/mean generated over the 100 randomisations). Accuracy (mean square error; MSE) for each annual increment was calculated as the mean of the squared differences between the estimated values (again generated over the 100 randomisations) and the true value calculated over the entire 75-year record. The lower the MSE value, the lower the bias and higher the precision associated with the estimate, and hence higher the accuracy. MSE values calculated for each metric at each stream gauge were scaled (divided by the range of observed values, hereafter termed sMSE) to allow direct comparison between stream gauges of varying discharge magnitudes and hydrological metrics quantified on different scales (Walther and Moore 2005).

We examined relationships between discharge record length and statistical power ($1-\beta$) to detect a 10% difference in the mean (effect size, δ) for each of the 120 hydrologic metrics. For each cumulative number of years of discharge record, we used the pooled mean and standard deviation from all six stream gauges for power calculations and set the Type I error rate (α) to 0.05. We used a two-sided test and substituted a range of values of δ (10–100% in increments of 10%) in these analyses but report only for δ = 10% as the trends for each hydrologic metric with increasing numbers of years of discharge record were similar for each level of $1-\beta$ and δ. We also calculated the sample sizes (i.e. number of stream gauges) required to achieve a half width of the confidence interval (Zar 1996) within specified percentages (10–100% in increments of 10%) of the estimated true population mean for each hydrologic metric. The confidence interval is a measure of the range of values (i.e. interval) within which the estimated true population mean lies with a specified probability (confidence level). For these analyses we used a one-sample test based on the pooled mean and standard deviation from all six stream gauges and set the confidence level (1-α) to 0.95. We report results for hydrologic metrics calculated using 15 years and 30 years of discharge data, respectively, as this represents the range of discharge record lengths most commonly used in ecohydrological studies and corresponds to the range of record lengths used in the hydrologic classification analyses (Appendix 5).

4.2.4 Effects of the discharge record period

We examined the extent to which the degree of overlap in two periods of discharge record for a given stream gauge influenced the degree of similarity in individual hydrologic metrics calculated from these two time series. We evaluated this for two discharge record lengths (15 and 30 years of continuous mean daily discharge data) calculated within a 36-year period spanning 1 January 1965 to 31 December 2000 as this was the period from which hydrologic data was summarised for the ecohydrologic classification analyses (Appendix 5). We hypothesised that the greater the degree of overlap in two periods of discharge record, the higher the similarity in hydrologic metrics calculated from the two time series. We also hypothesised that hydrologic metrics calculated from comparatively longer periods of discharge record will be less sensitive to the extent of record overlap than hydrologic metrics calculated from shorter discharge records.

For these analyses we first divided the total 36-year discharge record (for the period 1 January 1965 to 31 December 2000) into 15-year and 30-year periods moving forward in time at 1 year increments (resulting in 22 individual 15-year discharge series and seven 30-year discharge series). For each of the 15-year and 30-year discharge series, we calculated the hydrologic metric and then calculated the absolute percentage similarity in the resultant hydrologic metric between all possible pairwise combinations of time periods (n = 231 and 21 pairwise comparisons for the 15-year and 30-year discharge series, respectively). We conducted these analyses for each of 120 hydrologic metrics (listed in Appendix 5) and for each of the six stream gauges. Finally, we plotted the percentage similarity in hydrologic metrics versus the percentage overlap in period of discharge.

We also used cluster analyses to evaluate the sensitivity of hydrologic metrics to period of record. We hypothesised that if hydrologic metrics were not sensitive to the period of record used in their calculation then individual discharge records from a particular stream gauge should belong in the same cluster group and not form groups of discharge records derived from different gauges. The underlying assumption here is that, in the absence of metric sensitivity to degree of record overlap, each individual gauge is sufficiently distinctive that all discharge series for that gauge would cluster together. This analysis was performed on a Euclidean distance matrix generated from each stream gauge record using the 120 hydrologic metrics (range standardised) and an agglomerative hierarchical fusion technique (unweighted pairwise group arithmetic averaging). We conducted separate cluster analyses for the 15-year discharge records (22 discharge records from each of the six stream gauges, n = 132) and the 30-year discharge records (seven discharge records from each stream gauge, n = 42).

Differences in multivariate hydrological character between sets of discharge records from each stream gauge were tested using Analysis of Similarity (ANOSIM) based on the normalised Euclidian distance coefficient. ANOSIM compares rank similarities within *a priori*-defined groups (i.e. stream gauges) against rank similarities between groups and computes a statistic, R, which is scaled to lie between –1 and +1. Here, a value of +1 indicates that all discharge records within a stream gauge are more similar to one another than any discharge record from different stream gauges, a value of 0 indicates that there is no difference among gauges (i.e. representing the null hypothesis), and a value of –1 indicates that all discharge records within gauges are less similar to one another than any records from different gauges. Statistical significance was assessed using a permutation test where gauge membership is randomly permutated 999 times and R calculated for each permutation. Separate ANOSIMs were conducted for 15-year and 30-year datasets. Hydrologic metric calculations and Monte-Carlo simulations were undertaken using the Time Series Analysis Module of the River Analysis Package (Marsh *et al.* 2003). ANOSIM and cluster analyses were conducted using PRIMER software (Clarke and Gorley 2001). All other statistical analyses were performed using S-Plus 2000 (Statistical Sciences 1999).

4.3 Results

4.3.1 Effects of discharge record length

4.3.1.1 Bias, precision and accuracy in estimation of hydrologic metrics

Bias in the estimation of hydrologic metrics was generally high when calculated for short periods of discharge record (e.g. less than 5 years) but rapidly diminished as record length increased (Figure 4.4a). The majority of hydrologic metrics (i.e. 90% of metrics) were within 30% of the true values when calculated using 15 years of discharge data and were within 20% of the true values when calculated using 30 years of discharge data (Figure 4.4a). Examination of the magnitude of bias in hydrologic metrics for a given record length (e.g. 15 years – Figure 4.5a) indicated that the most biased metrics (i.e. those that differed from the true values by > 30%) were those describing skewness in annual and maximum flows, low flow duration (e.g. duration and variability of low flows < 99th percentile and zero flow days per year), timing of minimum and maximum flows (e.g. Julian date of annual minimum, predictability of minimum and maximum flows), and variability in the number of flow reversals. These metrics also tended to exhibit the greatest spatial variation in bias (i.e. variation between the six stream gauges), as judged by the magnitude of the standard deviations for these metrics (Figure 4.5a). The relative magnitude of bias between metrics tended to remain similar irrespective of record length. For example, metric bias estimated for 15 years, 30 years and 75 years were strongly correlated (Pearson's r = 0.94, 0.63 and 0.75, for comparisons of 15 years versus 30 years, 15 years versus 75 years, and 30 years versus 75 years, respectively).

We found similar patterns of variation in metric precision with increasing discharge record length (Figure 4.5b). Hydrologic metrics were less precise when calculated for short periods of discharge record but precision rapidly improved as record length increased (Figure 4.4b). Precision for metrics calculated using 15 years of discharge was usually less than 0.25 and did not decrease appreciably with increasing record length beyond this point. Hydrologic metrics that were the most biased (listed above) also tended to be the least precise (i.e. CV values > 0.3); in particular those metrics describing skewness (particularly skewness in annual flows) and low flow magnitude, duration and timing (Figure 4.5b). These metrics also tended to exhibit the greatest spatial variation in precision (i.e. between the six stream gauges), as judged by the magnitude of the standard deviations for these metrics (Figure 4.5b). The relative magnitude of precision between metrics tended to remain similar irrespective of record length (Pearson's r > 0.81 for all pairwise comparisons of metric precision estimated for 15, 30 and 75 years).

Given the rapid improvements in hydrologic metric bias and precision with increasing discharge record length described above, it is not surprising that overall accuracy in the estimation of hydrologic metrics also increased significantly as record length increased (as indicated by decreasing sMSE values; Figure 4.4c). Metric accuracy improved, though not substantially, beyond 15 years of record (Figure 4.4c). For example, 80% of hydrologic metrics had accuracy (sMSE) values < 0.1 after 15 years of discharge record and 90% of metrics were below this threshold after 30 years (Figure 4.4c). The relative magnitude of accuracy between metrics was similar to that observed for bias and precision (Figure 4.5c) and tended to remain similar irrespective of record length (Pearson's *r* > 0.85 for all pairwise comparisons of metric accuracy estimated for 15, 30 and 75 years).

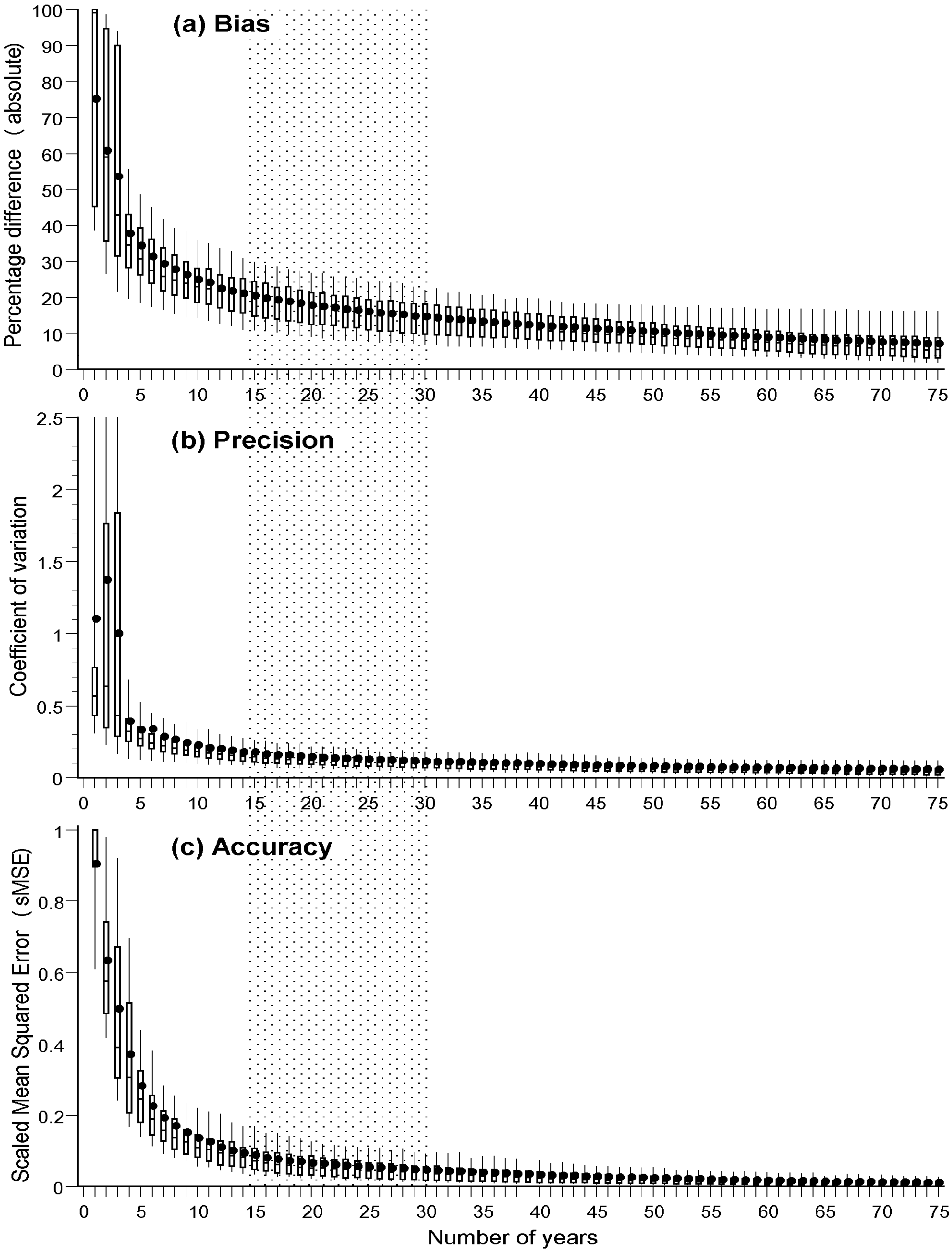


Figure 4.4. Changes in (a) bias, (b) precision and (c) accuracy in the estimation of all hydrologic metrics with increasing number of years used in their calculation. For each yearly increment, the distribution of values of all 120 hydrological metrics (averaged across the six stream gauges) is indicated using box-and whisker plots. The focal record length of stream gauges (15–30 years) is indicated by stippling. Note that the lines at the top, middle and bottom of each box represent the 75th percentile, median and 25th percentile of index values respectively. Upper and lower bars represent 90th and 10th percentiles and mean values are represented by symbols.

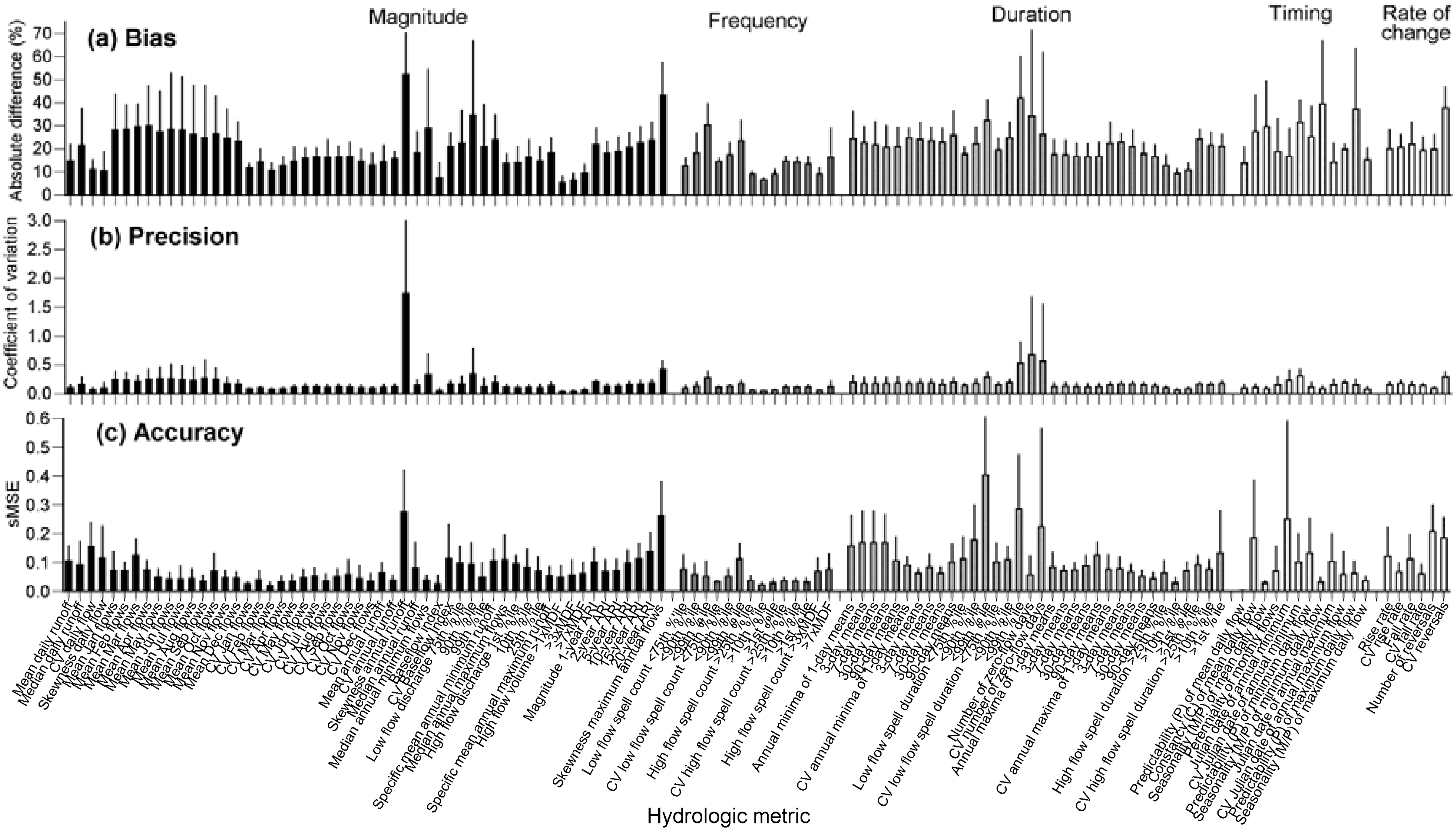


Figure 4.5. Variation between hydrologic metrics in (a) bias, (b) precision and (c) accuracy estimated using 15 years of discharge record. Data are averages (± 1 SD) across the six stream gauges.

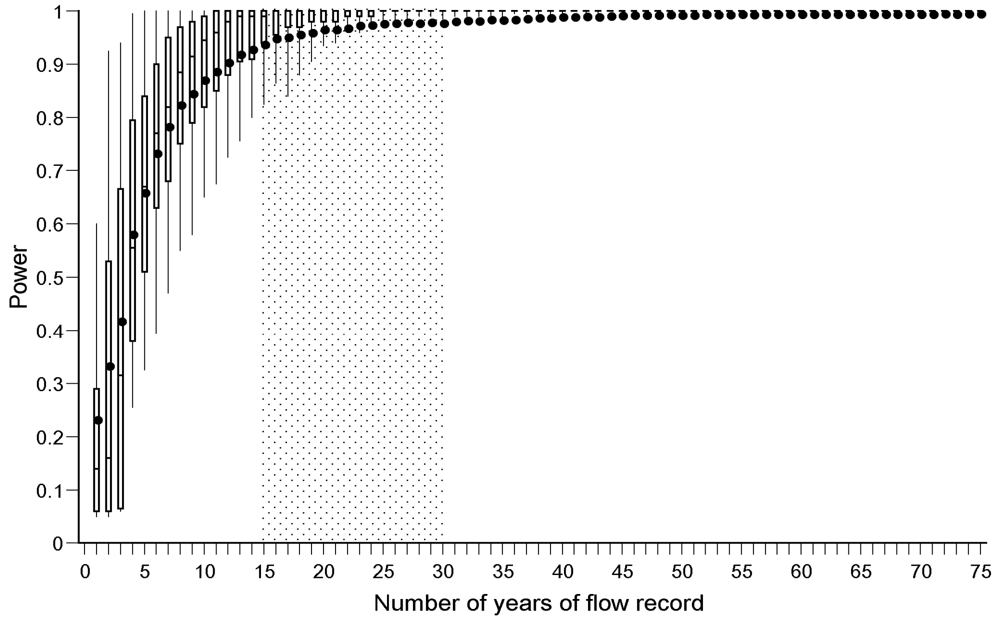
4.3.1.2 Power and sample size required to detect differences in hydrologic metrics

The statistical power to detect a 10% difference in the mean of estimates of hydrologic metrics increased rapidly with increasing length of discharge record used in their calculation (Figure 4.6a). Fifteen years of discharge record yielded a power (1-β) greater than 0.80 for most hydrologic metrics and all metrics had a power greater than 0.95 when calculated using 30 years of record.

Overall, relatively few stream gauges needed to be sampled to estimate the true population mean with a high degree of confidence (Figure 4.6b). Hydrologic metrics calculated using longer periods of discharge record yielded more precise estimates and so fewer stream gauges needed to be sampled, although this did not vary appreciably. For example, up to 20 stream gauges were required to achieve a half width of the confidence interval within 10% of the mean for most hydrologic metrics calculated using 15 years of discharge data (Figure 4.6b). In comparison, less than 10 gauges were required to achieve an equivalent percentage of the mean for most hydrologic metrics when calculated using 30 years of discharge data (Figure 4.6c). Importantly, the difference in sample sizes required for hydrologic metrics based on the entire 75-year record was minimal for percentages greater than 10% of the mean.

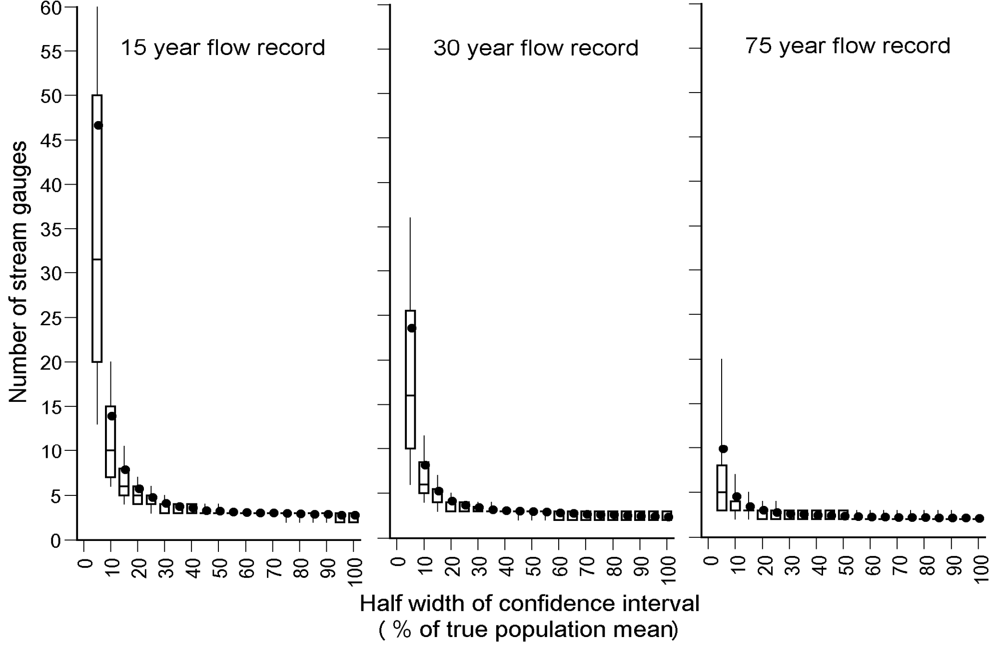
4.3.2 Effects of the discharge record period

There was a strong positive relationship between the degree of discharge record overlap and similarity in hydrologic metrics when calculated using 15-year and 30-year discharge records that were contained within a 36-year temporal window (Figure 4.7a, b). However, even metrics calculated from short (15-year) minimally-overlapping discharge records were generally similar. For example, 75% of hydrologic metric comparisons exceeded 70% similarity for non-overlapping records (i.e. 0% overlap) and 90% of metric comparisons exceeded 70% similarity for records that overlapped by 50% (Figure 4.7a). Hydrologic metrics calculated using 30-year periods were more robust to the extent of discharge period overlap (most metrics had > 90% similarity; Figure 4.7b), indicating that comparatively longer periods of discharge record are less sensitive to the extent of record overlap than shorter discharge records.



(a) Statistical power

(δ = 10%, α = 0.05)



(b) Sample size

(1-α = 0.95)

Figure 4.6. Statistical power (1-β) to detect a 10% difference (δ) in the mean of estimates of hydrologic metrics with increasing number of years used in their calculation (α = 0.05). For each yearly increment, the distribution of values for all 120 hydrological metrics is indicated using box-and whisker plots. The focal record length of stream gauges (15–30 years) is indicated by stippling. (b) The sample sizes (number of stream gauges) required to achieve a half width of the confidence interval within given percentages of the true population mean for hydrologic metrics (1-*α* = 0.95), based on 15 years, 30 years and 75 years of discharge record, respectively. For each percentage increment, the distribution of values for all 120 hydrological metrics is indicated using box-and whisker plots. Note that the lines at the top, middle and bottom of each box represent the 75th percentile, median and 25th percentile of index values respectively. Upper and lower bars represent 90th and 10th percentiles and mean values are represented by symbols.

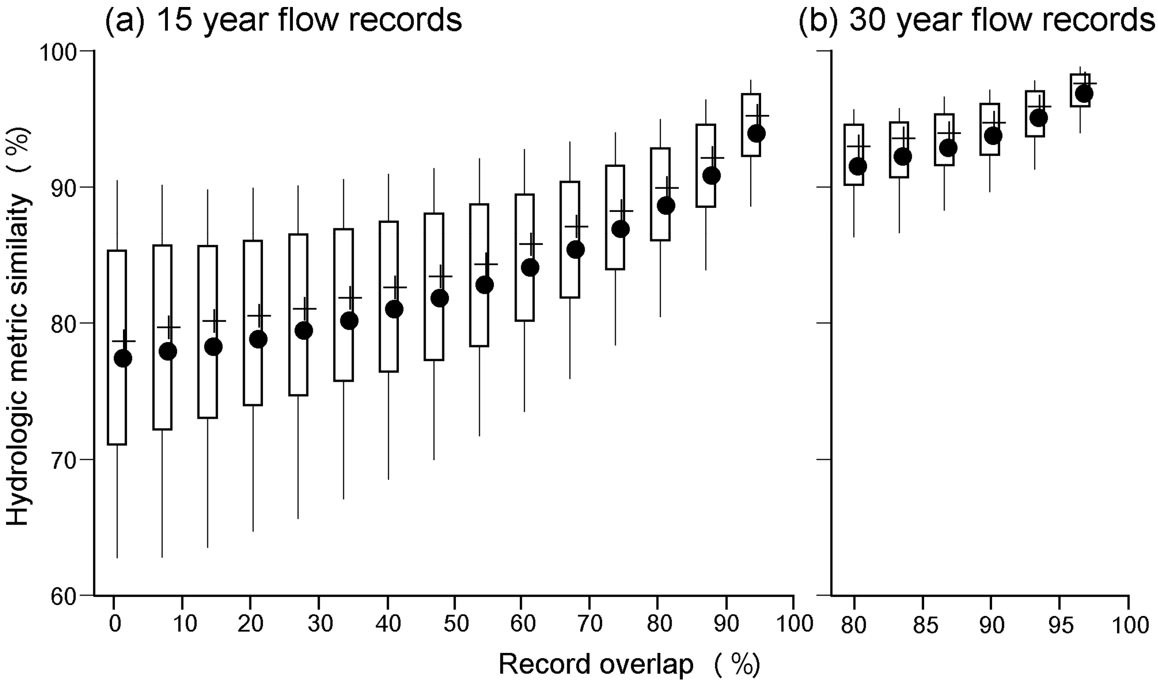


Figure 4.7. Relationships between the degree of record overlap (%) and degree of similarity (%) in individual hydrologic metrics when calculated using (a) 15-year discharge records (n = 22) and (b) 30-year discharge records (n = 7) (calculated within the period 1 January 1965 to 31 December 2000). For each increment in percentage record overlap, the distribution of percentage similarity values of all possible pairwise comparisons for all 120 hydrological metrics (averaged across the six stream gauges) is indicated using box-and whisker plots. Note that the lines at the top and bottom of each box represent the 75th percentile and 25th percentile of index values respectively. Upper and lower bars represent 90th and 10th percentiles, median (cross) and mean (circle) values are represented by symbols.

The hydrologic metrics most sensitive to the degree of record overlap were similar to those showing the highest sensitivity to length of record used in their calculation (compare Figures 4.5 and 4.8). Thus, based on 15-year discharge records, the hydrologic metrics most sensitive to the degree of record overlap (i.e. lowest % similarity) were those describing mean monthly flows, skewness in annual and maximum flows, low flow duration (e.g. duration and variability of low flows < 99th percentile and zero flow days per year), timing of minimum and maximum flows (e.g. Julian date of annual minimum, predictability of minimum and maximum flows), and variability in the number of flow reversals (Figure 4.8a). Not surprisingly, hydrologic metric similarity between 30-year discharge records was markedly higher (usually >90%) compared with metric similarity for 15 year records (Figure 4.8b). The major exceptions were for metrics describing mean August flows, skewness in annual flows, magnitude of 1-year average recurrence interval floods and variability in low flow duration.

Cluster analyses revealed that hydrologic metrics were slightly more sensitive to short discharge records than longer records. Overall, 94.7% of 15-year discharge records from all stream gauges were correctly classified into groups defined by their stream gauge origin (Table 4.1). All 22 discharge records from five of the six stream gauges clustered together with one another in separate groups (Table 4.1). Discharge records from one gauge (G422306 – Swan Creek) were split into two separate groups with seven 15-year records (i.e. those ending before 1986) clustering with all 22 records from G130302 – Dawson River. The cluster analysis based on 30-year records correctly classified all seven discharge records from each stream gauge into groups defined by their stream gauge origin (overall correct classification rate = 100%. Analysis of Similarity (ANOSIM) revealed there were significant differences ($P<0.001$) between sets of stream discharge records defined by stream gauge membership. Based on 15-year and 30-year discharge records, both had high Global R values (0.948 and 1.000, respectively) using stream gauge number to distinguish discharge records.

Table 4.1. Results of UPGMA classification of 15-year (n = 132) and 30-year (n = 42) discharge records at each stream gauge based on 120 hydrologic metrics. For each record length dataset, results are the number of individual discharge records from each stream gauged classified in each of 6 groups. The % correct classification rate for each gauge and overall % correct classification rate for each analysis is also shown.

	Stream gauge						
	G110003 Barron River	**G130302 Dawson River**	**G138001 Mary River**	**G226204 Latrobe River**	**G422306 Swan Creek**	**G671023 Hellyer River**	**Overall % correct**
Cluster group				**15 year records**			
1	**22**						
2		**22**			7		
3			**22**				
4				**22**			
5					**15**		
6						**22**	
% correct	100.0	100	100.0	100.0	68.2	100.0	**94.7**
Cluster group				**30 year records**			
1	**7**						
2		**7**					
3			**7**				
4				**7**			
5					**7**		
6						**7**	
% correct	100	100	100	100	100	100	**100**

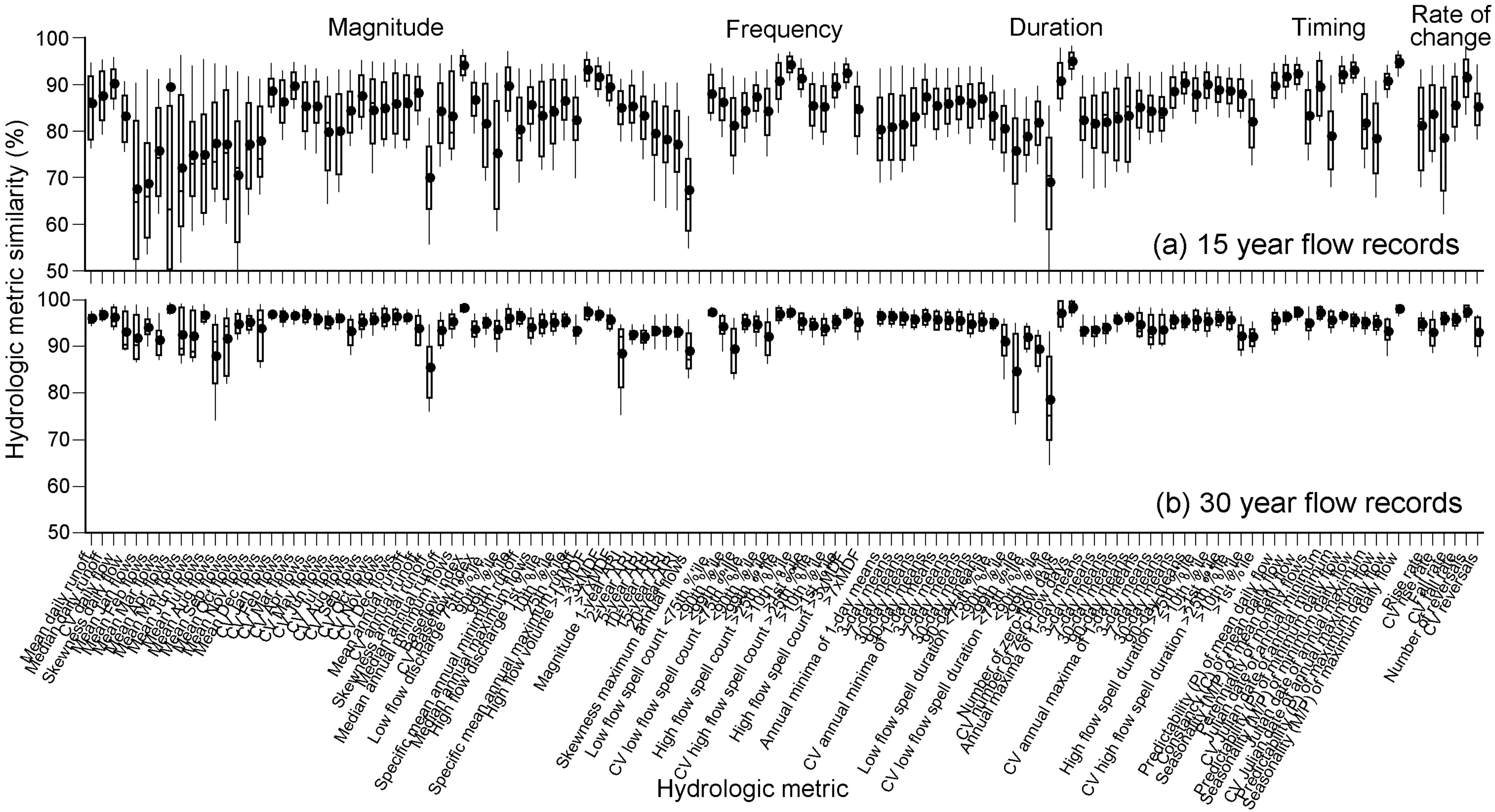


Figure 4.8. Variation between hydrologic metrics in their sensitivity (% similarity) to changes in the degree of record overlap when calculated using (a) 15-year discharge records and (b) 30-year discharge records (calculated within the period 1 January 1965 to 31 December 2000). For each metric, the distribution of hydrologic similarity values of all possible pairwise comparisons between 15-year time periods (231 comparisons) and 30-year time periods (21 comparisons), respectively, (averaged across the six stream gauges) is indicated using box-and whisker plots. Note that the lines at the top, middle and bottom of each box represent the 75th percentile, median and 25th percentile of index values respectively. Upper and lower bars represent 90th and 10th percentiles and mean values are represented by symbols.

4.4 Discussion

The utility of hydrologic metrics for describing various aspects of riverine flow regimes has resulted in their increased application in ecohydrological research and water management. However, the underlying relationships between metric uncertainty and discharge record length and comparability of record period have yet to be systematically examined. We provide the first comprehensive evaluation of the effects of discharge record length and period of record on uncertainty in the estimation of a large suite of hydrologic metrics commonly used to describe the major ecologically relevant components of the hydrologic regime. We also provide an example of the implications of variation in record length and period of record for hydrological classification analyses. Our results provide a researcher with the ability to make decisions based on trade-offs between minimising metric uncertainty and maximising sample size and geographic coverage. Based on our findings we recommend that whilst metric bias, precision and accuracy all improve with increasing record length, that: (1) estimation of hydrologic metrics based on at least 15 years of discharge record is suitable for use in hydrologic analyses that aim to detect important spatial variation in hydrologic regimes; (2) metric estimation in comparative studies should be based on hydrologic records contained within a moderately discrete temporal window with, ideally, 50% overlap or more among records; and (3) metric uncertainty varies greatly and should be accounted for in future analyses whenever possible.

The ability to identify and quantify sources of uncertainty in estimation of hydrologic metrics has a number of clear benefits. First, it allows managers to more fully understand the risks associated with their decisions and to strategically minimise the major sources of uncertainty in decision-making (Stewardson and Rutherford 2006). Economic and societal risks due to inaccurate flood forecasting are an obvious outcome of failing to understand the uncertainty associated with hydrologic estimation (Pielke and Conant 2003). Second, an inability to accurately define hydrological characteristics and predict ecological responses can have significant economic and ecological consequences, and this is especially relevant to ecohydrological applications such as the determination of environmental water needs (Arthington *et al.* 2006). In this context, failure to accurately estimate hydrological metrics can lead to errors in flow regime classification, characterisation of existing hydrological disturbance gradients and characterisation of projected flow regime changes under scenarios of flow management or climate change. Third, the difficulty in developing predictive relationships between discharge characteristics and ecological responses may be due in part to the uncertainty in the estimation of hydrologic metrics used as model predictors and lead to inaccurate predictions of ecological responses. Such relationships may be compromised by uncertainty in the measurement of both independent and dependent variables; consequently steps to minimise uncertainty in at least the independent variables are likely to result in better detection of ecological responses to different aspects of the flow regime. All these sources of uncertainty may collectively lead to costly failures to recommend appropriate flow management and restorative strategies (e.g. failure to define ecologically important hydrologic thresholds, or to predict the ecological outcomes of flow regime alteration and/or restoration, Arthington and Pusey 2003; Arthington *et al.* 2003; Stewardson and Rutherford 2006). Future studies using hydrological metrics can also 'embrace' uncertainty (*sensu* Wheaton *et al.* 2008) by explicitly incorporating uncertainty estimates for each metric in subsequent analyses (e.g. Stewardson and Rutherford 2006; Appendix 5).

The importance of discharge record length in influencing metric accuracy varies among hydrologic metrics. Our study showed that the least accurately estimated hydrologic metrics were those describing skewness (particularly skewness in annual flows) and low flow magnitude, duration and timing. This is perhaps not surprising given that skewness estimates would be expected to be highly influenced by individual years with unusually high peak or total annual discharges (see also MDBC 2004). Skewness is essentially a property of rare events which are, by definition, difficult to detect unless the sample size is large (Shaw 1988; Ribatet *et al.* 2007). Similarly, low flow metrics are influenced by both seasonal reductions in discharge and extended drought periods. Droughts are also, almost by definition, rare phenomena, and longer time periods are required to fully characterise their duration and frequency. In addition, the extent of spatial variation within our set of test streams was greatest for the low flow end of the annual hydrological spectrum. Test streams ranged from highly perennial to highly variable even to the extent that two gauges (Swan Creek and Dawson River) had years of zero flow within the period examined. Consequently, high dispersion around metrics associated with the annual low flow metrics was encountered and this resulted in reduced accuracy of metrics based on short discharge time series.

Maximising the length of record used in hydrologic analyses has clear benefits because the probability of capturing extreme discharge events is enhanced with longer periods of record (Shaw 1988). However, this study has shown that 15 years or more of discharge record for Australian rivers is sufficient to calculate a variety of hydrologic metrics with comparatively low bias, high precision, and high overall accuracy. Calculation of metrics from as little as 10 years of discharge record, whilst occasionally recommended under specific circumstances (i.e. providing the chosen discharge record is representative of the long-term rainfall regime), increases the risk of generating biased, imprecise results, especially in regions of high climatic variability (McMahon *et al.* 2007). Our results are broadly consistent with other published studies that have examined uncertainty in a reduced number of metrics (e.g. Richter *et al.* 1996; Gan *et al.* 1991; Cunderlik and Burn 2002; Cunderlik *et al.* 2004; Huh *et al.* 2005; Cunderlik and Burn 2006). All found that metric precision increased with increasing record length and that bias was greatest in those metrics associated with rare events (i.e. floods and droughts).

Time series long enough to capture rare events are typically uncommon and consequently compromises must frequently be made in which the benefits of increased accuracy are balanced against the availability or spatial coverage of such long-term data. The results of the present study suggest that improvements in accuracy generated by inclusion of records of increasing length typically decrease in magnitude after 15 years. Thus, no effective compromise is necessary if records are greater than 15 years in length. Difficulties in obtaining suitable discharge data (i.e. of sufficient spatial coverage for the spatial scale being examined) mean that researchers must sometimes also compromise the degree of discharge record overlap between stream gauges (Richter *et al.* 1996; Cunderlik and Burn 2002). In regions for which data availability is poor or limited, compromises between availability and record length or period overlap may simply not be possible because of the paucity of hydrological information. In such cases, and in the absence of modelled data, pragmatic choices are forced upon the investigator and best use of the available data must be made. However, the results of this study allow researchers to more fully understand the implications of variations in the length of discharge record and the degree of record overlap when choice is precluded by pragmatics.

The extent of both hydrologic variability and medium-term climatic variation (i.e. over a period of 20 to 50 years) varies spatially and this has substantial implications for hydrological comparisons made between regions of differing underlying variability or that have experienced different climatic variation. We recommend that at least 50% overlap between gauge samples is adequate to account for these potential sources of uncertainty. The streams used in the analyses reported here differ greatly in their hydrologic variability and the extent to which they have experienced climatic variation over the last 50 years. In addition, they cover a very large spatial area; indeed, Australian streams have been previously identified as among the most variables streams in the world (Puckridge *et al.* 1998;

Poff *et al.* 2006; McMahon *et al.* 2007). Consequently, the findings of the present study are probably conservative and should have application in many other regions of the world.

4.5 Conclusion

In conclusion, the world's water resources are increasingly under pressure in the struggle to balance societal and environmental needs and hydrological metrics are increasingly being used to define hydrological variation and compare rivers in efforts to minimise conflicts between these competing demands. The information upon which such metrics are based (i.e. time series of discharge data) is itself frequently of limited spatial and temporal extent. It is important to make the best use of such valuable data; consequently guidance for researchers and managers on the minimum amount of discharge data required to allow valid, relatively precise and unbiased estimates of hydrological variation is valuable. Based on comparisons of Australian streams differing in their inherent variability and covering a large spatial area in eastern Australia, we suggest that: (1) estimation of hydrologic metrics based on at least 15 years of discharge record is suitable for use in hydrologic analyses that aim to detect important spatial variation in hydrologic regimes; (2) metric estimation should be based on overlapping discharge records contained within a discrete temporal window (ideally > 50% overlap among records); and (3) metric uncertainty varies greatly and should be accounted for in future hydrological analyses.

4.6 References

Arthington, A.H. and Pusey, B.J. (2003). Flow restoration and protection in Australian rivers. *River Research and Applications* 19: 1–19.

Arthington, A.H., Bunn, S.E., Poff, N.L. and Naiman R.J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16: 1311–1318.

Arthington, A.H., Rall, J.L., Kennard, M.J. and Pusey, B.J. (2003). Environmental flow requirements of fish in Lesotho Rivers using the Drift Methodology. *River Research and Applications* 19: 641–666.

Chiew, F.S.H. and McMahon, T.A. (1993. Detection of trend or change in annual flow of Australian rivers. *International Journal of Climatology* 13: 643–653.

Clarke, K.R. and Gorley, R.N. (2001). *Primer v5: User Manual/Tutorial.* Primer-E Ltd., Plymouth.

Clausen, B. and Biggs, B.J.F. (1997). Relationships between benthic biota and hydrological indices in New Zealand streams. *Freshwater Biology* 38: 327–342.

Cunderlik, J.M. and Burn, D.H. (2002). The use of flood regime information in regional flood frequency analysis. *Hydrological Sciences* 47: 77–92.

Cunderlik, J.M., Ouarda, T.B.M.J. and Bobée, B. (2004). Determination of flood seasonality from hydrological records. *Hydrological Sciences* 49: 511–526.

Cunderlik, J.M. and Burn, D.H. (2006). Site-focused nonparametric test of regional homogeneity based on flood regime. *Journal of Hydrology* 318: 301–315.

Gan, K.C., McMahon, T.A. and Finlayson, B.L. (1991). Analysis in periodicity in streamflow and rainfall data by Colwell's indices. *Journal of Hydrology* 123: 105–118.

Cooperative Research Centre for Catchment Hydrology, Australia.

Hanafi, S., Grace, M., Webb, J.A. and Hart, B. (2007). Uncertainty in nutrient spiraling: sensitivity of spiraling indices to small errors in measured nutrient concentration. *Ecosystems* 10: 477–487.

Hughes, J.M.R. and James, B. (1989). A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. *Australian Journal of Marine and Freshwater Resources* 40: 303–326.

Huh, S., Dickey, D.A., Meador, M.R. and Ruhl, K.E. (2005). Temporal analysis of the frequency and duration of low and high streamflow: years of record needed to characterize streamflow variability. *Journal of Hydrology* 310: 78–94.

Jakeman, A.J., Letcher, R.A. and Norton, J.P. (2006). Ten iterative steps in development and evaluation of environmental models. *Environmental Modelling & Software* 21: 602–614.

Kennard, M.J., Olden, J.D., Arthington, A.H., Pusey, B.J. and Poff, N.L. (2007). Multi-scale effects of flow regime, habitat, and their interaction on fish assemblage structure in eastern Australia. *Canadian Journal of Fisheries and Aquatic Sciences*. 64: 1346–1359.

Kundzewicz, Z.W. (1995). Hydrological uncertainty in perspective. Pp 3–10. In Kundzewicz ZW (ed), *New Uncertainty Concepts in Hydrology and Water Resources*. International Hydrology Series, Cambridge University Press, Cambridge.

Marsh, N.A., Stewardson, M.J., Kennard, M.J. (2003). *River Analysis Package*. Cooperative Research Centre for Catchment Hydrology, Monash University: Melbourne. (http://www.toolkit.net.au).

Mathews, R. and Richter, B.D. (2007). Application of the indicators of hydrologic alteration software in environmental flow setting. *Journal of the American Water Resources Association* 43: 1400–1413.

McMahon, T.A. and Finlayson, B.L. (1992). Australian surface and groundwater hydrology – regional characteristics and implications. Pp 21–40. In Pigram, J.J. and Hooper, B.P. (eds), *Water Allocation for the Environment*. Centre for Water Policy Research, University of New England, Armidale.

McMahon, T.A., Vogel, R.M., Peel, M.C. and Pegram, G.G.S. (2007). Global streamflows – Part 1: Characteristics of annual streamflows. *Journal of Hydrology* 347: 243–259.

Micevski, T., Franks, S.W. and Kuczera, G. (2006). Multidecadal variability in coastal eastern Australian flood data. *Journal of Hydrology* 327: 219–225.

Monk, W.A., Wood, P.J., Hannah, D.M. and Wilson, D.A. (2007). Selection of river flow indices for the assessment of hydroecological change. *River Research and Applications* 23: 113–122.

MDBC (Murray-Darling Basin Commission). (2004). *Hydrology Theme Pilot Audit Technical Report – Sustainable Rivers Audit*. MDBC Publication 08/04.

Naiman, R.J., Latterell, J.J., Pettit, N.E. and Olden, J.D. (2008). Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience* 340: 629–643.

Nathan, R.J. and McMahon, T.A. (1990). Identification of homogeneous regions for the purposes of regionalisation. *Journal of Hydrology* 121: 217–238.

Olden, J.D. and Poff, N.L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19: 101–121.

Pielke, R.A. Jr. and Conant, R.T. (2003). Best practices in prediction for decision-making: lessons from the atmospheric and earth sciences. *Ecology* 84:1351–1358.

Poff, N.L. (1996). A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology* 36: 71–91.

Poff, N.L. and Allan, J.D. (1995). Functional organization of stream fish assemblages in relation to hydrologic variability. *Ecology* 76: 606–627.

Poff, N.L., Olden, J.D., Pepin, D.M. and Bledsoe, B.P. (2006). Placing global streamflow variability in geographic and geomorphic contexts. *River Research and Applications* 22: 149–166.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997). The natural flow regime: a paradigm for river conservation and restoration. *BioScience* 47: 769–84.

Puckridge, J.T., Sheldon, F., Walker, K.F. and Boulton, A.J. (1998). Flow variability and the ecology of large rivers. *Marine and Freshwater Research* 49: 55–72.

Ribatet, M., Sauquet, E., Grésillon, J-M. and Ouarda, T.B.M.J. (2007). A regional Bayesian POT model for flood frequency analysis. *Stochastic Environmental Research and Risk Assessment* 21: 327–339.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10: 1163–1174.

Richter, B.D., Baumgartner, J.V., Wigington, R. and Braun, D.P. (1997). How much water does a river need? *Freshwater Biology* 37: 231–249.

Shaw, E.M. (1988). *Hydrology in Practice*. VNR International, London.

Shiklomanov, A.I., Yakovleva, T.I., Lammers, R.B., Karasev, I.P., Vörösmarty, C.J. and Linder, E. (2006). Cold region river discharge uncertainty–estimates from large Russian rivers. *Journal of Hydrology* 326: 231–256.

Simons, M., Podger, G. and Cook, R. (1996). IQQM – A hydrologic modelling tool for water resources and salinity management. *Environmental Software* 11: 185–192.

Statistical Sciences. (1999). S-*PLUS, version 2000 for Windows*. Mathsoft Inc.: Seattle, WA.

Stewardson, M. and Rutherford, I. (2006). Quantifying uncertainty in environmental flow assessments. *Australian Journal of Water Resources*. 10: 151–159.

Tharme, R.E. (2003). A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19: 397–441.

Thyer, M., Frost, A.J. and Kuczera, G. (2006). Parameter estimation and model identification for stochastic models of annual hydrological data: is the observed record long enough? *Journal of Hydrology* 330: 313–328.

Walther, B.A. and Moore, J.L. (2005). The concepts of bias, precision and accuracy, and their use in testing the performance of species richness estimators, with a literature review of estimator performance. *Ecography* 28: 815–829.

Wheaton, J.M., Darby, S.E. and Sear, D.A. (2008). The scope of uncertainties in river restoration. Pp. 21–39. In Darby, S. and Sear, D. (eds), *River Restoration: Managing the Uncertainty in Restoring Physical Habitat*. John Wiley & Sons, Ltd, Hoboken, NJ.

Wilkinson, S.N., Young, W.J. and DeRose, R.C. (2006). Regionalizing mean annual flow and daily flow variability for basin-scale sediment and nutrient modelling. *Hydrological Processes* 20: 2769–2786.

Yen, B.C. (2002). System and component uncertainties in water resources. Pp. 133–142. In Bogardi, J.J. and Kundzewicz, Z.W. (eds), *Risk, Reliability, Uncertainty, and Robustness of Water Resources Systems*. International Hydrology Series, Cambridge University Press, Cambridge;

Zar, J.H. (1996). *Biostatistical Analysis*. Prentice-Hall, Englewood Cliffs, NJ.

Appendix 5

Ecohydrological classification of Australia's flow regimes

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Summary

The importance of the natural hydrologic regime to the functioning of freshwater ecosystems is increasingly well recognised. However, advances in scientific understanding of flow-ecology relationships and the ecologically sustainable management of aquatic ecosystems in Australia is hindered by a fundamental lack of knowledge of the nature and extent of spatial variation in ecologically important features of the natural flow regime. Hydrologic classification, the process of systematically arranging streams, rivers or catchments into groups that are most similar with respect to characteristics of their discharge regime, can aid in filling these knowledge gaps.

In this Appendix we present a multimetric ecohydrological classification of Australian flow regimes using discharge data from 830 minimally-disturbed stream gauges located throughout the country. The classification is based on 120 separate metrics describing ecologically important characteristics of the natural hydrologic regime in terms of the magnitude, frequency, duration and timing of discharge events, rate of change in discharge events and the temporal variability in these measures. Hydrologic metrics were calculated from continuous time series (15–30 years of record constrained within a 36-year period) of mean daily discharge data. Classification is undertaken using a fuzzy partitional method, Bayesian mixture modelling, implemented using the AutoClass C program. The approach is fully probabilistic and uncertainty is explicitly reported in terms of data specification, class specification and the final classification chosen. We attempt to gain insight into the mechanisms responsible for shaping broad-scale variation in the flow regimes by using combinations of environmental variables describing catchment topography, surficial geology and substrate, vegetative cover, and climate to explain and predict flow regime class membership of stream gauges. We also use an independent set of hydrologic metrics derived from a catchment water balance model as predictors of flow regime class membership to evaluate how well the water balance model predictions of hydrologic characteristics approximated the measured flow regime of each gauge. Finally, we evaluate the extent to which the flow regime classification developed here corresponds to other environmental and biophysical classifications available for Australia.

We classified 830 stream gauges based on 120 hydrologic metrics specifying variable uncertainty using estimates of metric accuracy based on 15 years of discharge data. The analysis resulted in the most likely classification having 12 classes of distinctive flow regime types differing in the seasonal pattern to discharge, degree of flow permanence (i.e. perennial versus varying degrees of intermittency), variations in flood magnitude and frequency and other aspects of flow predictability and variability. Geographic, climatic and some catchment topographic factors were generally strong discriminators of flow regime classes. The geographical distribution of flow regime classes showed varying degrees of spatial cohesion, with stream gauges from certain flow regime classes often being non-contiguously distributed across the continent. These results support the view that spatial variation in hydrology is determined by interactions between climate, geology, topography and vegetation at multiple spatial and temporal scales. We also found a generally low degree of concordance between the flow regime classification of stream gauges and their membership of other Australian environmental and biophysical classifications schemes. Decision trees were also developed to provide the ability to determine the natural flow regime class membership of new stream gauges based on their key environmental and/or hydrological characteristics.

The ecohydrological classification presented here represents the first continental-scale classification of hydrologic regimes undertaken for Australia. With certain provisos, we argue that an explicit spatial context such as is provided by the ecohydrological classification presented here should allow researchers to develop meaningful generalisations about the interaction between hydrology and ecology in Australia, and provide the benchmark against which the response of biological communities to hydrological alteration can be assessed.

5.1 Introduction

The importance of the flow (i.e. discharge) regime to the functioning of aquatic systems is well recognised (Zalewksi *et al.* 1997; Poff *et al.* 1997; Bunn and Arthington 2002). Hydrologic change due to changing land use, water extraction and from projected global climate change (Sala *et al.* 2000; Vörösmarty *et al.* 2000, 2004; Postel and Richter 2003) are at the forefront of the many processes that threaten aquatic habitats and biota (McAllister *et al.* 1997; Cambray and Bianco 1998) and require effective management in order to curb or reverse associated impacts. The flow regime, especially hydrologic variability, is seen as a template upon which patterns of distribution, life history and community organisation are based (e.g. Horwitz 1978; Poff and Ward 1989; Schlosser and Angermeir 1995; Poff and Allen 1995; Oberdorff *et al.* 1995; Pusey *et al.* 2000). These developments require that our view of the organisation and ecology of rivers, our assessment of the impacts associated with water use and infrastructural development and especially prescriptive remediation, be placed in the context of the natural flow regime and deviations away from it (Arthington and Pusey 2003). A key foundation of the Natural Flows Paradigm (Poff *et al.* 1997) is that the long-term regime of natural environmental heterogeneity and disturbance due to hydrologic variation constitutes a physical habitat template that constrains local communities with respect to composition, assemblage level attributes and expression of ecological traits (Poff and Ward 1990). Organisms, their traits and their role in the aquatic environment have evolved in response to the hydrologic regime in which they exist (Lytle and Poff 2004). Systems with similar hydrologic regimes, all other factors (e.g. biogeographic, geomorphic, evolutionary constraints, etc.) held constant, should contain species with similar relationships to that regime and similar expression of ecological traits.

Several ecologically important hydrologic characteristics constitute the natural flow regime. These include the seasonal pattern of flows; timing of extreme flows; the frequency, predictability, and duration of floods, droughts, and intermittent flows; daily, seasonal, and annual flow variability; and rates of change (Poff *et al.* 1997; Olden and Poff 2003). Natural spatial variation in these hydrologic characteristics is determined by variations in climate, geology, topography and vegetation (Knighton 1998). These factors interact at multiple spatial and temporal scales to influence physical habitat for aquatic biota (e.g. channel morphology, in-channel hydraulics, sediment transport, large woody debris recruitment, water quality and thermal regimes), the availability of refuges, the distribution of food resources, opportunities for movement and migration, and conditions suitable for reproduction and recruitment (Poff *et al.* 1997; Fausch *et al.* 2002; Biggs *et al.* 2005; Poff *et al.* 2006). In addition, temporal variation in the discharge regime, particularly in terms of the magnitude, timing, frequency and duration of high and low flow events, can constitute disturbance to some aquatic biota depending on the resistance and resilience of individual species and life stages to stressful conditions. Extreme discharge events may also drive the frequency and spatial extent of local colonisation and extinction events. Extreme high flows can cause habitat rearrangement and physical flushing of biota downstream (Lake 2000; Pearsons *et al.* 1992). Extended periods of low flow may result in loss of longitudinal connectivity and isolation of biota in residual pools (Lake 2000; 2003; Magoulick and Kobza 2003; Matthews and Marsh-Matthews 2003). Aquatic organisms may consequently be subjected to a deterioration of water quality as water levels subside (e.g. elevated temperature and salinity, low dissolved oxygen) and this also increases the potential for biotic interactions because of reduced habitat volume (e.g. competition for diminishing resources or decreased availability of refuges from avian and fish predators) (Zaret and Rand 1971; Kushlan 1976; Mittelbach 1986; Pusey and Bradshaw 1996). Ultimately, habitat desiccation and local species extinctions can occur (Lake 2000; 2003; Matthews and Marsh-Matthews 2003). Hydrologic variability is usually thought of as the two extremes of flood and drought, both of which may act as important sources of disturbance for freshwater biota (Horwitz 1978; Schlosser 1987; Resh *et al.* 1988; Grossman and Ratajczak 1998). Flow variability may also have a range of more subtle effects when viewed as being a continuum ranging from highly variable 'flashy' systems present in arid regions to more stable constant streams fed by spring outflows. It is important to note the distinction between hydrologic variability, which is insensitive to temporal pattern, and hydrologic predictability, a measure of temporal uncertainty in periodic phenomena. Both these aspects of the hydrologic regime are ecologically important (Poff and Ward 1990; Pusey *et al.* 2000).

The Natural Flow Paradigm has assumed a pivotal role in ecohydrologic investigations and the in the way we think about flow ecology relationships. As demonstrated in Appendix 3 however, it is increasingly difficult to define the natural flow regime in view of both long- and short-term natural variation in climate and rainfall-runoff processes, and more recent human impacts on flow regimes (e.g. land use, changing fire regimes, water use and flow regulation). Under ideal circumstances, the natural flow regime would be best described using flow data from a period prior to the imposition of these anthropogenic impacts. Unfortunately, these data do not exist for much of Australia, nor is widespread modelled streamflow data readily available. Given that long uninterrupted series of gauged flow records are limited in number and distribution (see Table 3.1 in Appendix 3), the choice of whether we are classifying the natural flow regime or the contemporary flow regime becomes largely secondary to statistical/methodological issues associated with how long a record is needed to adequately describe the long-term flow regime (see Appendix 4). Nonetheless, it must be emphasised that the flow regimes considered here are contemporary flow regimes and not necessarily the natural flow regime, although considerable effort has been taken to ensure that all stream gauges were minimally disturbed by human activities.

Hydrologic classification is the process of systematically arranging streams, rivers or catchments into groups that are most similar with respect to characteristics of their flow regime. This process has frequently been applied by hydrologists seeking to extend insights gained from well-gauged regions to ungauged or sparsely gauged regions or rivers (e.g. Bates 1994). Typically, only specific components of the flow regime are included (e.g. flood series) (e.g. Nathan and McMahon 1990; Bower *et al.* 2004, McMahon *et al.* 2007). Hydrologic classification is playing an increasing role in the ecological sciences for understanding riverine flow variability (e.g. Mosley 1981; Haines *et al.* 1988; Poff 1996; Harris *et al.* 2000), exploring the influence of streamflow on biological communities and ecological processes (e.g. Jowett and Duncan 1990; Poff and Allan 1995; Pusey *et al.* 2000; Monk *et al.* 2006, 2007), aiding hydrologic modelling in regionalisation analyses (Nathan and McMahon 1990), providing an inventory of hydrologic types for water resource management (e.g. Snelder and Biggs 2002; Snelder *et al.* 2005; Wolock *et al.* 2004; Arthington *et al.* 2006), and prioritising conservation efforts for freshwater ecosystems (e.g. Nel *et al.* 2007; Snelder and Dey 2007). Consequently, hydrologic classification has practical use as an organising framework for both river research and management purposes.

Hydrological classifications have previous been attempted in Australia at a variety of scales, and using a variety of methods. The Australian Water Resources Council (AWRC 1976) defined drainage divisions based largely on landform, climate and the distribution of aquatic habitat types. Although some of the watershed boundaries can be disputed (e.g. the distinction between drainage divisions I and II), the biogeography of Australia's native freshwater fishes strongly reflects these divisions (Unmack 2001; Allen *et al.* 2003; Pusey *et al.* 2004b). Finlayson and McMahon (1988) applied the Haines *et al.* (1988) classification of streamflow seasonality at a continental scale. Other continental-scale classifications of climate and other physical attributes with a direct relevance to hydrology have also been undertaken (e.g. Hutchinson *et al.* 2005). Classifications at smaller scales include examinations of streamflow at the regional level (Hughes 1987; Hughes and James 1989; Moliere *et al.* 2006), and those undertaken at the basin scale (Pusey and Arthington 1996; Thoms and Parsons 2003). A continental-scale multi-metric classification of ecologically relevant aspects of the flow regime has not yet been undertaken.

In this Appendix we present the first continental-scale classification of natural flow regimes for Australia. The classification is based on multiple hydrologic metrics describing the key ecologically relevant flow regime characteristics (hereafter termed an 'ecohydrological' classification) using discharge data from a large set of minimally disturbed stream gauges located throughout the country. We attempt to gain insight into the mechanisms responsible for shaping broad-scale variation in flow regimes by using combinations of environmental variables describing catchment topography, surficial geology and substrate, vegetative cover, and climate to explain and predict flow regime class membership of stream gauges. We also develop a decision tree to enable new stream gauges (i.e. not used in the present analyses) to be assigned to an individual flow regime class based on a subset of key discriminating hydrological characteristics. This facility is also important for predicting the type of flow regime existing prior to human impacts. We also used an independent set of hydrologic metrics derived from a catchment water balance model as predictors of flow regime class membership to evaluate how well the water balance model predictions of hydrologic characteristics approximated the measured flow regime of each gauge. Finally, we evaluated the extent to which the flow regime classification developed here corresponded to other environmental and biophysical classifications available for Australia. By addressing these objectives we aim to improve our understanding of spatial variation in natural flow regimes throughout Australia and provide the ability to determine the natural flow regime class membership of new stream gauges based on their key environmental and/or hydrological characteristics.

5.2 Methods

The process used to develop the hydrological classification of Australian flow regimes followed the protocols outlined in Appendix 2 (see in particular Section 2.4 and Figure 2.1). More specific details on the steps we used are provided below.

5.2.1 Study area – climate and geography

The Australian continent is notable for its generally low topography (average elevation = 330 m.a.s.l., maximum = 2745 m.a.s.l.), large inland arheic and endorheic river basins and low gradient coastal exorheic river basins (Bridgewater 1987). The climate is diverse (12 of the 30 Köppen-Geiger climate classes represented) but most of the continent is within two arid climate classes (Peel *et al.* 2007). The climate is dominated by the dry sinking air of the subtropical high pressure belt that moves north and south with the seasons such that most rainfall in the north occurs during the austral summer (i.e. monsoonal wet) whilst most rainfall in the south occurs in the austral winter (i.e. temperate wet) and is associated with complex low pressure weather systems originating in the Southern Ocean and South Pacific Ocean. Low rainfall (average = 451 mm yr^{-1}), high mean annual temperatures (21.5°C) and high rates of evaporation (typically in excess of rainfall) typically lead to low runoff (McMahon *et al.* 2007). Spatial variations in runoff separate the continent into two distinct areas, a humid coastline and an arid interior, with the greatest proportion of total runoff occurring in the northern and north-eastern coastal areas (88% from only 26% of the land area), and the least recorded in arid and semi-arid regions (75% of the continent receives <12.5mm of annual runoff). Extreme temporal variations in runoff are also characteristic of much, but not all of Australia, particularly by world standards (Puckridge *et al.* 1998).

5.2.2 Discharge data: criteria for inclusion

Mean daily discharge data for an initial set of 2686 gauges with >10 whole years of record were acquired from Australian state and territory water resources agencies. These gauges were screened and a subset fulfilling the following criteria were selected: 1) little or no hydrologic regulation; 2) little or no catchment urbanisation or intensive agriculture; 3) a period of hydrologic record $\geq$ 15 whole years within the period 1 January 1965 to 31 December 2000, preferably extending throughout a common year (i.e. 1980); and 4) continuous mean daily discharge data where possible. Our objective was to maximise the number and spatial coverage of gauges available for inclusion in subsequent analyses whilst ensuring that stream gauges were comparable in terms of data quality and quantity. In Appendix 4 it was shown that estimation of hydrologic metrics based on at least 15 years of discharge record was suitable for use in hydrologic classification analyses that aim to detect important spatial variation in hydrologic regimes, provided that the discharge records were contained within a discrete temporal window (i.e. preferably > 50% overlap between records). Stream gauges potentially subject to hydrologic modifications due to dams, weirs, interbasin transfers and water extraction were identified using available information on the location of major dams and weirs (e.g. ANCOLD 2002), discussion with colleagues from water resource management agencies and other institutions, as well as by examining GIS layers of the locations of major canals and pipelines (GeoSciences Australia 2006). Potential impacts on flow regimes were also evaluated using the Riverine Disturbance Index (RDI; Stein *et al.* 2002). This index comprises indirect measures of flow regime disturbance due to impoundments, flow diversions and levee banks, and catchment disturbance due to urbanisation, road infrastructure and land use activities. This information was summarised for the catchment upstream of each gauge and was used as a guide to identify and exclude gauges subject to intense human disturbances.

A total of 830 stream gauges fulfilled our initial screening criteria. While it is likely that the hydrologic regimes of some of these stream gauges are affected by human activities to some extent, this represents our best efforts to identify the subset of minimally-disturbed stream gauges in Australia. The majority of selected stream gauges (76%, 630 of 830 gauges) had continuous daily flow data. Only 8% of gauges had more than 1% of the entire record missing (maximum 22.8%) (Figure 5.1a) and only 3% of gauges had more than 10 individual periods of missing data (maximum 69 periods). Of the 200 gauges that contained periods of missing data, most missing periods (80%) were less than 30 days duration (maximum 261 days). The period of record for all gauges was within the years 1 January 1965 to 31 December 2000 and 85% included the year 1980 (Figure 5.1b). The majority of gauges (>60%) had at least 20 years of record and only 7% of gauges had 15 years of data (Figure 5.1c), the minimum length of record for inclusion in the classification. The degree of overlap between gauges in the period of flow record was greater than 75% for 50% of gauges and only 5% of gauges overlapped by less than 25% (Figure 5.1c). We conclude that the final set of 830 gauges were comparable with respect to period of record and record length, given that all gauges had at least 15 years of daily flow data contained within a restricted 36 year temporal window (see Appendix 4).

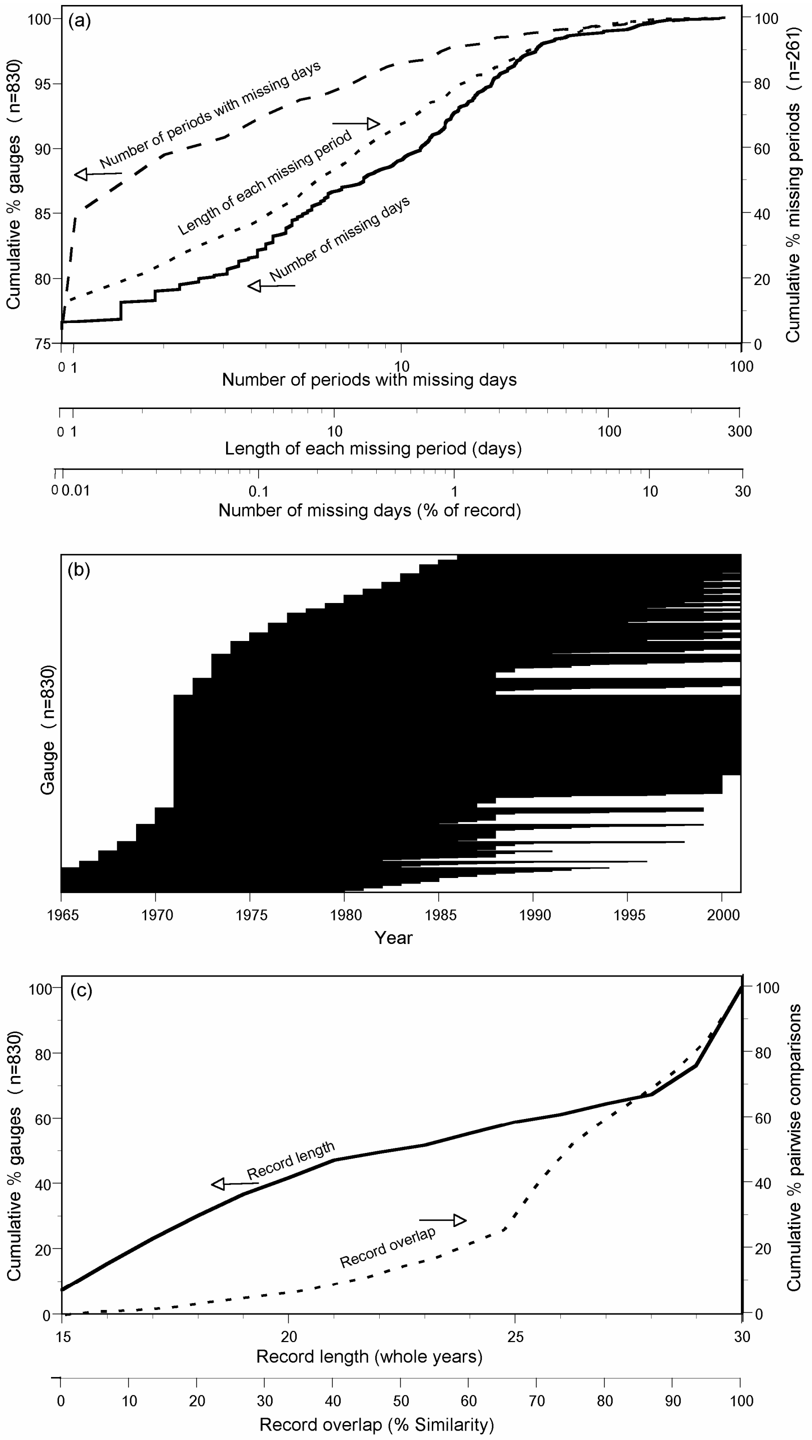

Figure 5.1. Characteristics of gauging stations used in the analysis (n=830) with respect to missing daily discharge data, period of discharge record and length of discharge record (number of whole years). (a) Cumulative frequency distributions of gauging stations showing the total number of missing

days (solid line, expressed as a percentage of the total record length), the number of periods with missing days (coarse dashed line), and the duration of each missing period for the 200 gauges with missing data (fine dashed line). (b) Period of record spanned by each gauge within the study period (1 January 1965 to 31 December 2000). (c) Cumulative frequency distributions of gauging stations showing the length of record (solid line) and the extent of overlap (% similarity) in period of record for all possible pairs of gauges (fine dashed line, n=344,035 comparisons). Arrows indicate vertical axis appropriate for each data series.

5.2.3 Missing periods of record: data infilling

Missing periods of record were infilled using linear interpolation or regression. The criteria for application of these techniques varied between drainage divisions due to variations in the density of the gauging network and the proportion of the discharge record for individual gauges that was missing. Thus, more stringent criteria were applied to drainage divisions with a relatively high number of gauges with good quality data (e.g. division I) than to drainage divisions with relatively poor quality data and/or relatively few gauges (divisions V, VI–XI).

Linear interpolation was used to infill missing periods of up to 20 days (Nature Conservancy 1997) where it was considered unlikely that a spate or flood had occurred during the missing period (as determined by comparison with nearby stream gauges and rainfall records). However, for poorly gauged divisions and/or divisions with poor quality discharge data, linear interpolation was used to infill gaps of up to 40 days, particularly where periods of zero or low discharge occurred immediately before and after the missing period (e.g. during the dry season). This approach was used for gauges that had few missing periods in the record and where no adjacent gauges were available for infilling by regression (see below). A small number of gauges (11) in several poorly gauged areas of tropical northern Australia (mostly from drainage divisions VIII and IX) each contained a single extended period of missing days (133–261), but these gauges were always on streams that rarely flowed during the study period, and so these data were infilled as zero daily flows.

Infilling by regression involved developing a regression equation to predict discharge for the missing period from one or more nearby stream gauges. Regression models were used to infill periods between 40 and 100 consecutive days of missing data. However, this criterion was relaxed for poorly gauged divisions (particularly divisions V, VII–XI) such that gaps of up to 130 days were infilled by regression. This was done where periods of low and stable discharge occurred immediately before and after the missing period and where little or no rainfall occurred during the missing period (as determined from the Bureau of Meteorology website). Regression models were developed with and without a zero intercept. Models without intercepts generally produced better estimates for periods of low flow (as determined by comparison of observed and predicted values, as well as successfully predicting zero discharge when it occurred), whereas models with constants different than zero generally produced better discharge estimates for periods of high flow.

The gauges were situated on streams with a wide range of catchment areas upstream (6–222,674 km^2) but with most (72%) being between 100 and 10,000 km^2 in area (Figure 5.2). The geographical location and length of discharge record for each of the 830 gauges is shown in Figure 5.3. Gauge density was greatest (> 0.4 $gauges.ha^{-1}$) for the eastern coastal region of Australia (i.e. drainage divisions I, II and III) and least (<0.02 $gauges.ha^{-1}$) for the two arid internally draining basins (divisions X and XI). The remainder spanned these extremes. The final set of 830 gauges covered most of the climatic (and hence potential flow regime) types throughout Australia.

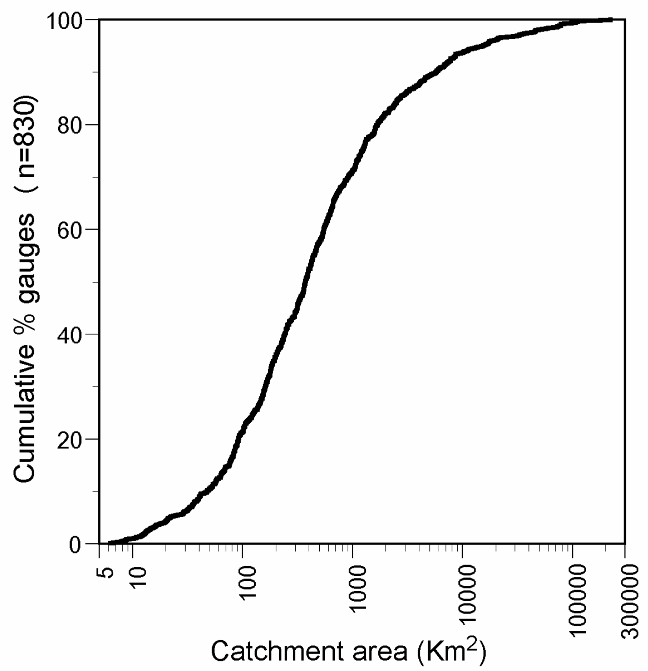

Figure 5.2. Cumulative frequency distribution of catchment areas (km^2) upstream of gauging stations (n=830).

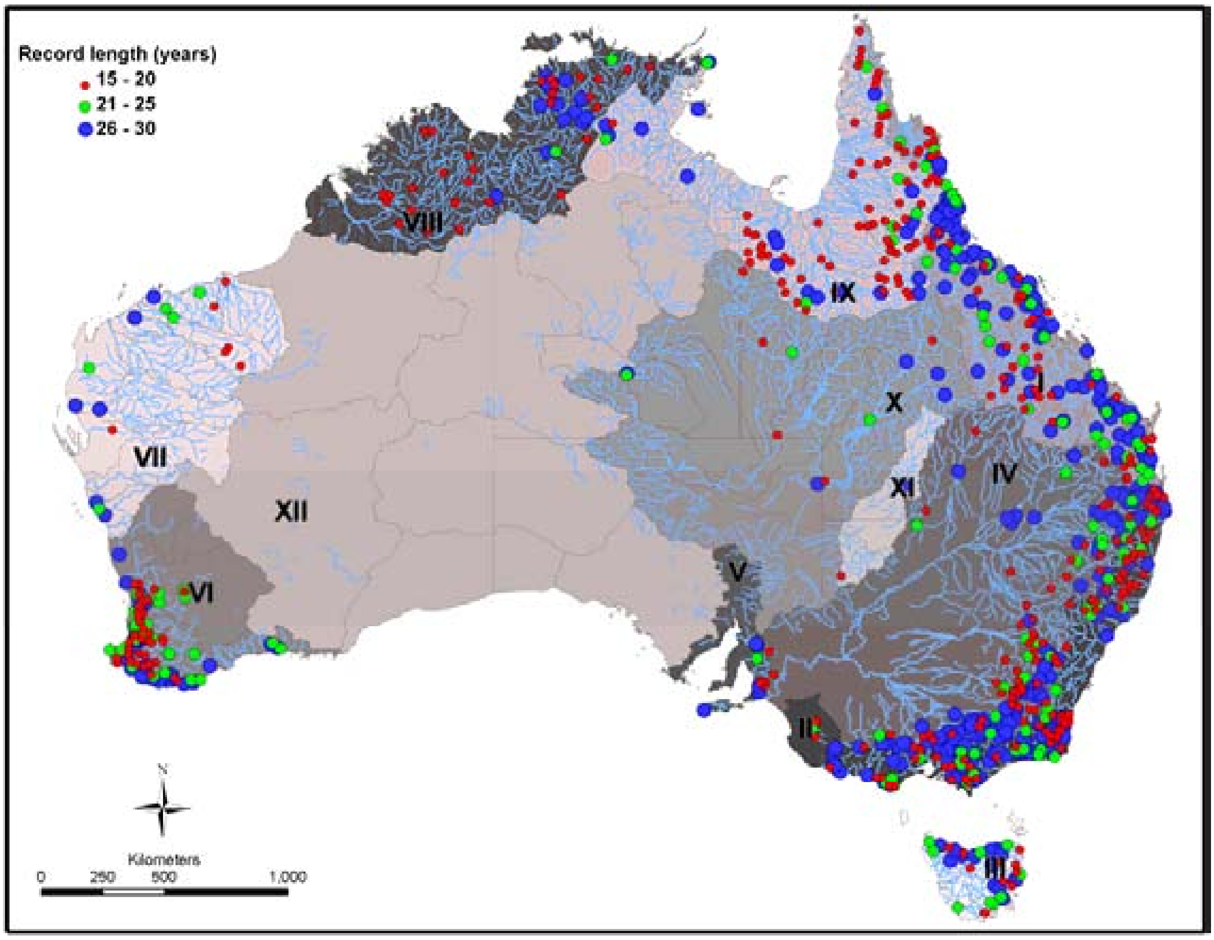

Figure 5.3. Length of flow record (years) for each stream gauge (n=830).[1]

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[1] This figure incorporate Data which is © Commonwealth of Australia (Geoscience Australia) 2006. The Data has been used with the permission of the Commonwealth. The Commonwealth has not evaluated the Data as altered and incorporated within this figure, and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose.

5.2.4 Hydrologic metrics

Several hundred hydrologic metrics can be used to describe the key ecologically relevant facets of the hydrologic regime (Richter *et al.* 1996; Poff *et al.* 1997) in terms of the magnitude, frequency, duration and timing of discharge events, rate of change in discharge events and the temporal variability in these measures (e.g. see Richter *et al.* 1996, Growns and Marsh 2000, Olden and Poff 2003, and references therein). However, hydrologic analyses based on a large suite of variables are computationally demanding and may statistically weaken models because of variable redundancy and multicollinearity (Olden and Poff 2003). A more desirable approach is to select a subset of high information, minimally redundant hydrologic metrics that describe the key facets of the hydrologic regime.

Olden and Poff (2003) examined patterns of redundancy amongst 171 hydrologic metrics derived from 13 published papers, and quantified their ability to describe the key ecologically relevant facets of hydrologic regimes in 420 stream gauges across the continental USA. They concluded that the 66 hydrologic metrics (including measures of central tendency and dispersion) calculated by the Indicators of Hydrologic Alteration (IHA) software package (Nature Conservancy 1997) could adequately describe most of the major flow regime components but recommended several additional metrics to describe the magnitude and frequency of high flow events (a shortcoming of IHA, Olden and Poff 2003). This reduced set of high information, minimally redundant metrics formed the basis for the selection of hydrological metrics for this study. To these, we added additional metrics which we considered to be of potential relevance for describing ecologically important aspects of flow regimes in Australia. We also attempted to 'balance' the number of metrics for each major facet of the flow regime to avoid one facet being dominant over others, although this was unavoidable in some instances (i.e. there are only a restricted number of ways in which to describe rates of change in flow events, in comparison to the numerous approaches to describing flow magnitude). Our final set of 120 individual hydrologic metrics (listed in Appendix 5.1) was grouped into five major categories (following Richter *et al.* 1996 and Poff *et al.* 1997). These included the magnitude ($n = 54$), frequency ($n = 14$), duration ($n = 34$), timing ($n = 12$) and rate of change ($n = 6$) in flow events, where magnitudes were subsequently divided into average ($n = 32$), low ($n = 7$) and high ($n = 15$) categories, frequency into low ($n = 6$) and high ($n = 8$) categories, and duration into low ($n = 18$) and high ($n = 16$) categories (after Olden and Poff 2003). This produced a total of nine subcategories of hydrologic metrics designed to describe different ecologically important components of the streamflow regime.

Hydrologic metrics were calculated using the Time Series Analysis module of the River Analysis Package (RAP, Marsh *et al.* 2003). RAP calculates all of the hydrologic metrics that IHA calculates but has greater flexibility in setting parameter options. Full details on the method of calculation of each hydrologic metric are given in Appendix 5.1. Prior to all subsequent analyses, standardisation of flow magnitude was considered essential in order to avoid such differences overwhelming the classification and overshadowing similarities due the temporal pattern of streamflow. In essence, this allowed small streams to be validly compared to larger streams. Except for six metrics specifically describing runoff (i.e. discharge volume per unit upstream catchment area – see Appendix 5.1), all metrics describing flow magnitude (expressed in ML day^{-1}) for each stream gauge were therefore normalised by dividing by the mean daily flow for the entire record. Mean daily flow was used as the denominator rather than median daily flow (as has often been used in other studies) because many gauges had a long-term median daily flow of zero.

5.2.5 Geospatial and environmental data

Geospatial and environmental data hypothesised to be important discriminators of flow regime types were used to interpret the ecohydrological classification (see section 5.2.6). These included variables describing the geographic location of each stream gauge (latitude and longitude) and environmental characteristics of the reach and/or catchment upstream of each gauge.

Environmental variables included catchment topography ($n = 13$ variables), surficial geology and substrate (11 variables), present day vegetative cover (2 variables) and climate (31 variables), summarised at the stream gauge location and/or the catchment upstream (see Appendix 7 for full description of environmental variables and their methods of derivation). We also used hydrologic metrics ($n = 35$ variables) derived from hydrologic data modelled at a monthly time step (using the water balance module of the GROWEST program – Nix 1981; Hutchinson *et al.* 2004) as predictors of flow regime class membership. We did this to evaluate how well the water balance model predictions of streamflows could approximate the measured flow regime of each gauge (see Appendix 7 for full description of the water balance model).

5.2.6 Statistical analyses

The extent of intercorrelations among hydrologic metrics was evaluated by examining cross-correlation matrices among all 120 metrics (using both Pearson's and Spearman's rank correlations). A series of threshold correlation coefficients were chosen and the numbers of pairs of metrics with cross correlation coefficients above the threshold coefficient were enumerated. Interrelationships among hydrologic metrics were also quantified using principal components analysis (PCA). The PCA was based on the Pearson's correlation matrix, and loadings of the original hydrologic metrics on each principal component were used to identify and explain the dominant patterns of hydrologic variation in the data set.

Hydrological classification was undertaken using a fuzzy partitional method, Bayesian mixture modelling, implemented using the AutoClass C program (v 3.3.4 – Hanson *et al.* 1991; Cheeseman and Stutz 1996). In Bayesian mixture modelling, the observed distribution of data is modelled as a mixture of a finite number of component distributions in order to determine the number of distributions, their parameters, and object memberships (Webb *et al.* 2007). The approach is fully probabilistic and uncertainty is explicitly reported in terms of data specification, class specification and the final classification chosen (Cheeseman and Stutz 1996; Webb *et al.* 2007). Multiple plausible classifications are produced, which are then ranked on their estimated marginal likelihoods to select the most parsimonious classification that is guaranteed to have the highest posterior probability; i.e. the probability of the model being correct given the data (Cheeseman and Stutz 1996; Gelman *et al.* 2004; Webb *et al.* 2007). Outputs from the analysis include: the probability of class membership for each object; class strength (the probability that the attribute distributions at the class level can be used to predict the class members, with strong classes tending to have tight distributions of attribute values); and the importance of the individual attributes for distinguishing each class. This is evaluated using the Kullback-Leibler distance, a measure of distance between data distributions, which accounts for the central tendency and variability of the data distribution. The summed Kullback-Leibler distances over all attributes provided an estimate of overall divergence of each class from the overall distribution of cases.

All 120 attributes (hydrologic metrics) were $\log_{10}(x+1)$ transformed prior to analysis and modelled as normally distributed continuous variables. Two or more continuous attributes can be specified as covarying using AutoClass, which leads to objects being classified by changes in the relationship between covarying attributes, rather than by the absolute differences between their values (Hanson *et al.* 2001; Webb *et al.* 2007). It is to be expected that certain aspects of the flow regime will covary with one another in certain circumstances. For example, the rate of change and duration of a high flow event might be expected to be a function of the peak magnitude of the event, and hence metrics describing these flow regime components may covary. However, the relationships among flow regime components (and between metrics used to describe individual flow components) are often complex and their nature and strength often vary between different flow regime types (e.g. see Results). We therefore chose to treat all attributes (hydrologic metrics) as independent for the analysis.

Bayesian classification using AutoClass requires the user to specify measurement uncertainty for each attribute and those attributes with lower uncertainty have more influence on the final classification (Webb *et al.* 2007). Uncertainty in the estimation of different hydrologic metrics is in part a function of the length of discharge record used to calculate them and varies between different metrics for a given length of record (see Appendix 4). We specified uncertainty for each hydrologic metric using estimates of mean accuracy (i.e. the scaled mean squared error, hereafter termed sMSE) based on the minimum discharge record length (15-years) (Appendix 4). We viewed the use of the 15-year sMSE as conservative but compared the classification based on the 15-year sMSE (C1) with a classification using the 30-year sMSE (C2). We also investigated the effects of including only the 334 stream gauges with $\geq$25 years of record (C3) and the effects of data order on clustering results. We re-ordered the data randomly 10 times, and re-ran the original classification (i.e. 15 year sMSE uncertainty for each metric). The most probable solutions for all 10 data orderings (C4–C13) were compared with the original classification (C1). Lastly, we undertook a ‘hard’ classification (C14) of the stream gauges in which individual objects are assigned to a single class only. We used an agglomerative hierarchical fusion technique (unweighted pairwise group arithmetic averaging) based on a Euclidean distance matrix (hydrologic metrics were range standardised prior to analyses) and set the number of groups to equal the number produced by the most likely Bayesian solution of C1 to provide a direct comparison of the two results.

The different clustering results were compared using the adjusted Rand index (ARI; Hubert and Arabie 1985). The ARI has been shown to be the most desirable index for measuring cluster recovery (e.g. Steinley 2004). The index is based on the relation of every pair of objects (gauges), and whether these relations differ between two cluster solutions. The index ranges between 0 (indicating agreement between two clustering solutions is no better than chance) and 1 (indicating perfect agreement). After assigning objects to their most probable classes (from the Bayesian classifications), we calculated the ARI comparing C1 with all other solutions (C2 – 14) and tested significance values for each comparison using a randomisation approach following Steinley (2004) and the mclust (v.3) package for R (Fraley and Raftery 2006). We also compared the relative influence of hydrologic metrics (based on Kullback-Leibler distances) on each classification (C1 – C13) using Pearson’s correlation to evaluate whether the classes defined in each classification were hydrologically similar. The relative influence of hydrologic metrics on the hard classification (C14) was defined by the magnitude of Kruskal-Wallace test statistics used to evaluate the ability of each hydrologic metric to discriminate between C14 classes. Variation in individual hydrologic metrics among flow regime classes (from C1) was also evaluated using graphical methods.

5.2.7 Explanation and prediction of flow regime classes using external environmental data

We explored the mechanisms responsible for shaping broad-scale variation in flow regimes by comparing the geospatial and environmental characteristics of stream gauges across flow regime classes. Differences in multivariate environmental characteristics between flow regime classes were tested using an Analysis of Similarity (ANOSIM) based on the normalised Euclidian distance coefficient (PRIMER software, v. 5.2.9). ANOSIM compares rank similarities within *a priori* defined groups (i.e. classification groups) against rank similarities between groups and calculates a statistic, R, which is scaled to lie between –1 and +1 (Clarke and Gorley 2001). In the context of our study, a value of 1 indicates that all gauges within flow classes are more similar to one another than any gauges from different classes, a value of 0 indicates that there is no difference among flow classes (i.e., representing the null hypothesis), and a value of –1 indicates that all gauges within classes are less similar to one another than any gauges from different classes. Statistical significance was assessed using a permutation test where group membership is randomly permutated 999 times and R calculated for each permutation. Separate ANOSIMs were conducted using different combinations of variables including: (1) geographic location; (2) climate; (3) catchment topography; (4), geology, substrate and vegetative cover; (5) combined environmental variables sets (2) – (4). We also used the water balance model hydrologic metrics as predictors of flow regime class membership to evaluate how well the water balance model approximated the measured flow regime of each gauge.

We also developed classification tree models (CART, Brieman *et al.* 1984) to predict the flow regime class membership of each stream gauge using each set of environmental data. This approach can identify those environmental variables important in discriminating between homogeneous groups of stream gauges, if indeed they do exist. Tree-based modelling provides a flexible non-parametric alternative to discriminant functions analysis for classification problems in that it can model nonlinear, non-additive relationships among mixed variable types, it is invariant to monotonic transformations of the explanatory variables and it facilitates the examination of collinear variables in the final model (De’ath and Fabricus 2000). The CART model implemented here was fitted by binary recursive partitioning, whereby the entire data set was successively divided into increasingly homogenous subsets. The partitioning process can also reveal interactions amongst environmental variables and examines increasingly smaller spatial scales of the data because each successive split is performed in the context of all previous splits (Venables and Ripley 1999). The splitting criterion was based on the Gini impurity index, and we selected the smallest tree within 1 standard error of the tree with the least classification error as determined using 10 fold cross-validation (Breiman *et al.* 1984). The values of the primary explanatory variable for each split defined the splitting thresholds and competing explanatory variables were also evaluated. We conducted separate analyses using the six different sets of environmental data described earlier for the ANOSIM analyses. Predictive performance of the classification trees was evaluated by calculating the percentage of stream gauges correctly allocated to their *a priori* defined flow regime class and comparing these classification rates to the probability of correct allocation due to random expectations (9.1%, assuming all groups have equal sample size, 9.6% if proportional to group size, and 15.1% probability of being allocated to the group with the largest sample size). Cohen's κ coefficient of agreement was also used to assess the predictive performance of the classification trees compared to random expectations (Fielding and Bell 1997). CART modelling was implemented using the rpart library of functions within S-PLUS 2000 (Statistical Sciences 1999).

5.2.8 Assigning new stream gauges to a flow regime class using hydrologic metrics

We developed a decision tree to enable new stream gauges (i.e. not used in the present analyses) to be assigned to an individual flow regime class based on their hydrological characteristics. The decision tree was constructed using a CART model in which the original 830 stream gauges were classified into groups using the 120 hydrological metrics as predictors of group membership.

5.2.9 Comparison with other continental environmental and biophysical classification schemes

We evaluated the extent to which the flow regime classification (C1) developed here corresponded to other environmental and biophysical classifications available for Australia. These included a modified Köppen climate classification (Stern *et al.* 2008), a global agro-climatic classification adapted for Australia (Hutchinson *et al.* 2005), a global classification of river flow regime seasonality (Haines *et al.* 1988), Australian drainage divisions (AWRC 1976), a terrestrial bioregional classification (Interim Bioregionalisation for Australia – IBRA version 6.1) and a freshwater ecoregionalisation (WWF 2008). We determined Haines' flow regime group membership of each stream gauge by visually inspecting mean monthly flows (expressed as a proportion of mean total annual runoff) and assigning it to the closest possible matching flow regime seasonality class. For all other classification systems, the geographical location of each stream gauge was used to assign group membership. The different classification systems were compared with the flow regime classification (C1) using the adjusted Rand index.

5.3 Results

5.3.1 Relationships among hydrological indices

The extent of multicollinearity among hydrologic metrics, as evaluated by examining cross-correlations between all 120 metrics, was generally low (Figure 5.4). The majority (i.e. > 70%) of between-metric comparisons had absolute correlation coefficients < 0.5 and fewer than 5% of between-metric comparisons had absolute correlation coefficients > 0.80. These observations were consistent when examining for linear (Pearson's correlation) and rank-order (Spearman's correlation) relationships among variables (Figure 5.4).

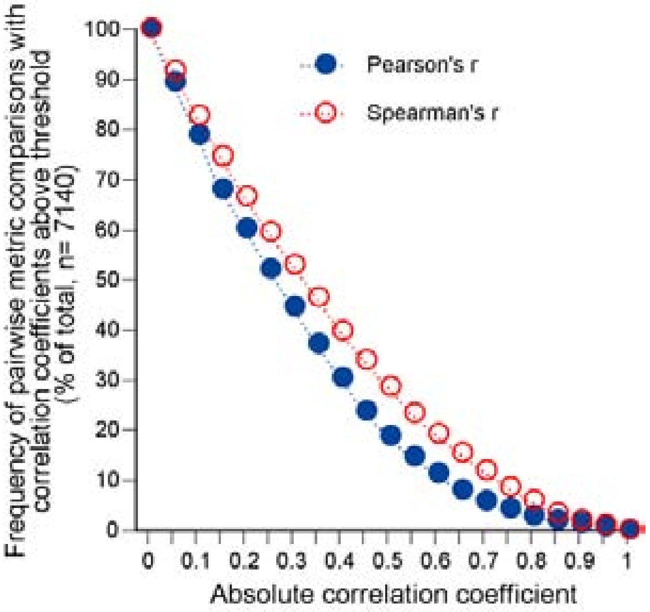


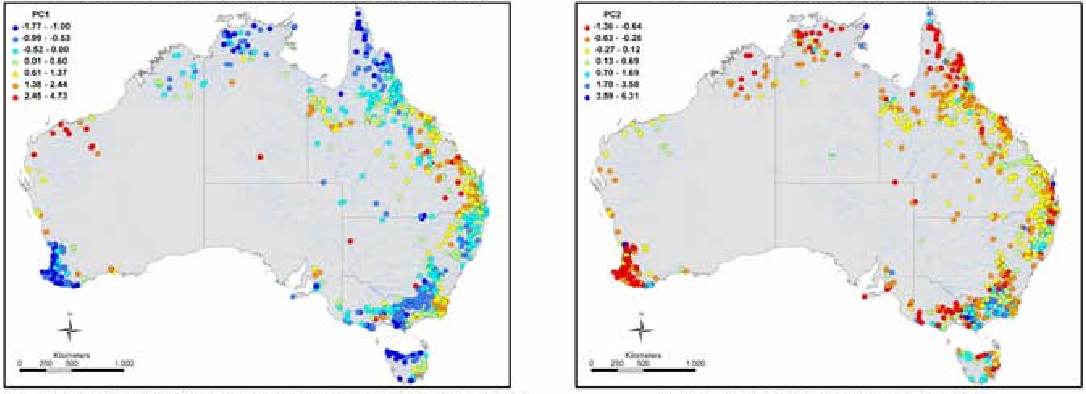
Figure 5.4. Cross-correlations for varying threshold values of the correlation coefficient.

Principal components analysis reduced the initial 120 hydrologic metrics to 16 components that collectively explained 83.4% of the total variation in the 830 stream gauge dataset. It is evident that from the principal component variable loadings (Appendix 5.1) that many metrics describing similar aspects of the flow regime were loaded with one another on individual components, however only 33% of metrics had absolute loading scores > 0.8. Together with the cross-correlation results presented above, these findings collectively suggest that the degree of overall multicollinearity and redundancy among the hydrologic metrics was not sufficiently high that we risked greatly weakening classification models by the inclusion of all 120 metrics.

Examining the dominant hydrological gradients identified by the principal components analysis revealed that groups of metrics that loaded together on the same component did not necessarily correspond to the nine subcategories of hydrologic metrics we initially used to describe the different ecologically important facets of the flow regime (see Section 5.2.3 and Appendix 5.1). Principal Component 1 (PC1), which accounted for 34.3% of the total variance, described a gradient of *increasing discharge variability and high discharge intensity*. It was positively loaded for metrics describing variability and skewness of daily and annual flows, variability in high flow duration, the magnitude and duration of high and flood flow events, and the rate of change and number of reversals in flow events. It was also negatively loaded for metrics describing the seasonality of mean and maximum flows. When PC1 scores for each stream gauge are plotted in geographical space (Figure 5.5), it is evident that streams situated across the central latitudes of the Australian continent, and in eastern coastal areas near to the New South Wales-Victoria border have the highest variability and intensity of high flows (i.e. in terms of magnitude and duration).

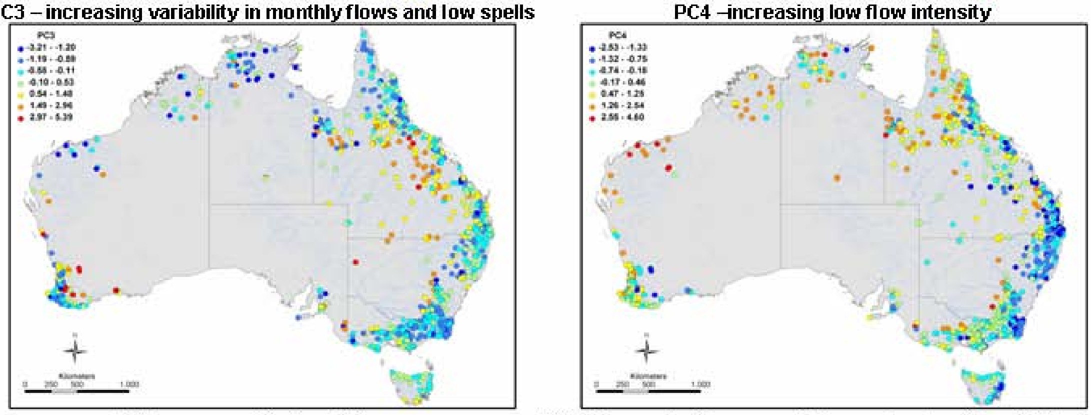
Scores on PC2 (which accounted for 9.1% of the variance) reflect a gradient in *increasing baseflow magnitude*, monthly flow perenniality, and magnitude of minimum annual flows of various durations. Regions of Australia with these flow regime characteristics (i.e. high PC2 scores) included the Wet Tropics region of north-eastern Queensland, north-eastern New South Wales, south-eastern Victoria, Tasmania and other localised areas scattered throughout the continent (Figure 5.5). Principal Component 3 (which accounted for 8.5% of the variance) described a gradient of *increasing variability in monthly flows,* and the frequency and variability in low flow spells. Areas of Australia with these flow regime characteristics included inland catchments (e.g. the Lake Eyre, Bulloo-Bancannia and Murray-Darling basins) and upland portions of coastal catchments in the southern Gulf of Carpentaria, and north-eastern Australia (Burdekin and Fitzroy Rivers). Principal Component 4, which accounted for 7.2% of the total variance, reflected a gradient in *increasing low flow intensity and predictability*. It was positively loaded for metrics describing the duration of very low flow spells and the duration and variability in the number of zero flow days. Colwell's measure of predictability (P) of mean, minimum and maximum flows was also positively loaded on this component, as was flow constancy (C). This indicates that predictability was derived from the constant nature of low flow spells rather than from a seasonal pattern to low flow spell occurrences (seasonality (M/P) of minimum flows was negatively loaded on this component). Regions of Australia with these flow regime characteristics included areas of central and northern Australia and inland catchments of southern Australia (Figure 5.5).

The next four principal components equated to gradients in: PC5 – *seasonal timing of flows* (e.g. magnitude monthly flows, Julian date of maximum and minimum flows), reflecting a basic north/south, tropical/temperate difference due to geographical variation in climate; PC6 – *increasing frequency and decreasing duration of high flows* (mostly in inland catchments); PC7 – *increasing runoff magnitude* (particularly in Cape York Peninsula, the Wet Tropics, small catchments of central and south-eastern Queensland and northern New South Wales, upland Victoria and Tasmania); and PC8 – *increasing variability in the magnitude of minimum annual flows* of various durations (not obvious strong geographic signal). Refer to Figure 5.5.



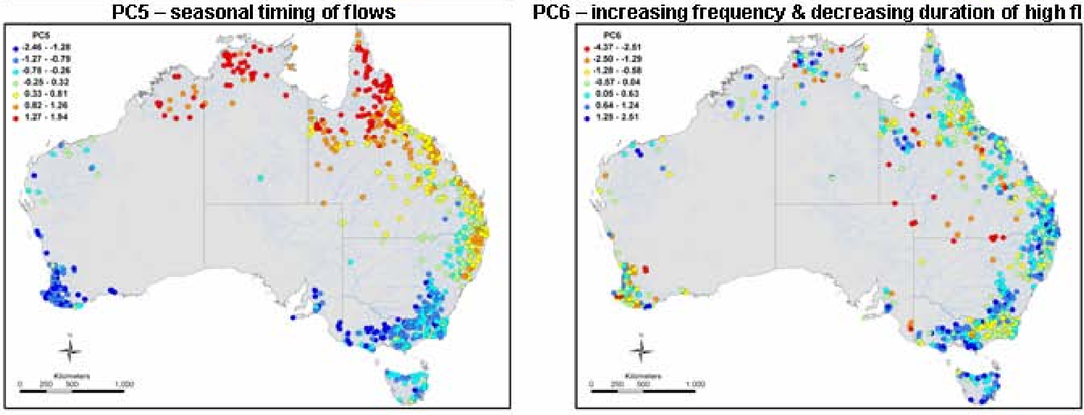
PC1 – increasing variability and high flow intensity

PC2 – increasing baseflow magnitude



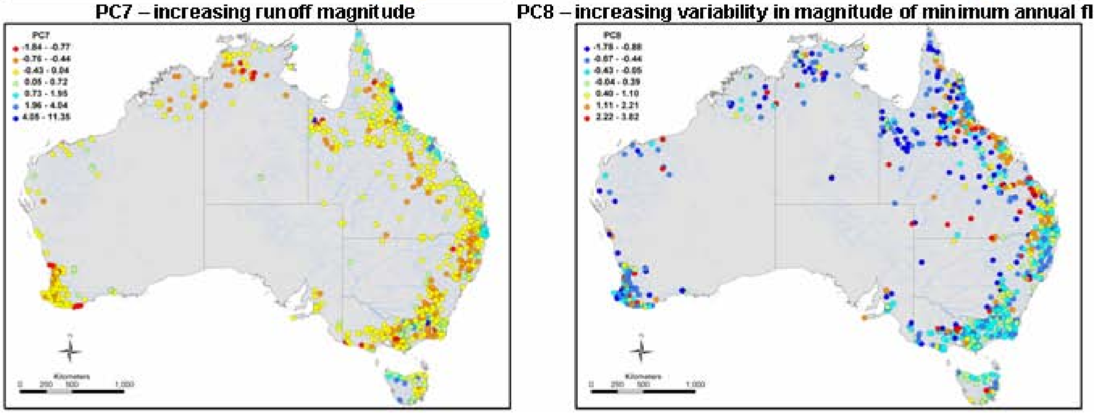
PC3 – increasing variability in monthly flows and low spells

PC4 –increasing low flow intensity



PC5 – seasonal timing of flows

PC6 – increasing frequency & decreasing duration of high flow



PC7 – increasing runoff magnitude

PC8 – increasing variability in magnitude of minimum annual flow

Figure 5.5. Map of stream gauge locations with symbols colour-coded according to loadings on the first eight principal components, respectively. Red implies increasingly harsh conditions for aquatic biota, whereas blue implies the opposite (except for PC5 – seasonal timing of flows) – see text for details and justification of principal component interpretations. [2]

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[2] This figure incorporate Data which is © Commonwealth of Australia (Geoscience Australia) 2006. The Data has been used with the permission of the Commonwealth. The Commonwealth has not evaluated the Data as altered and incorporated within this figure, and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose.

5.3.2 Hydrological classification

The most likely classification (C1) from the Bayesian clustering analysis produced 12 classes reflecting distinctive flow regime types. The majority (91%) of stream gauges had a 100% probability of belonging to only one class (Figure 5.6a). Only 12 of the 830 gauges exhibited a class membership probability of <0.990 for their most likely class and only one of these gauges had a probability (albeit low, p=0.002) of belonging to more than two classes. Classes varied in their divergence (i.e., hydrologic difference) from the global distribution. Classes 1, 9 and 12 exhibited the greatest class-level divergence with respect to the global class, while the remaining nine classes had generally equivalent divergence values (Figure 5.6b). Classes 2, 5 and 8 had the greatest class strength relative to the global distribution, indicating comparatively low within-class variation in hydrologic characteristics, whereas classes 1, 9 and 12 had the lowest class strength (Figure 5.6c). Inspection of the locations of stream gauges in each class when projected in ordination space defined by the first nine principal components tended to support these observations concerning class divergence and class strength (Figure 5.7). For example, members of classes 1, 2 and 12 tended to diverge from members of other classes in ordination space and classes 2, 5 and 8 formed comparatively tighter clumps of gauges in ordination space. Stream gauges in classes with the highest class strength also tended be geographically closer to one another than those with lower class strength (Figure 5.6d), implying that there is a reasonably strong geographic signal to flow regime variation between classes (Pearson's *r* for relationship between $\log_{10}$ mean class strength and mean Euclidean distance between all stream gauges within each class = -0.753).

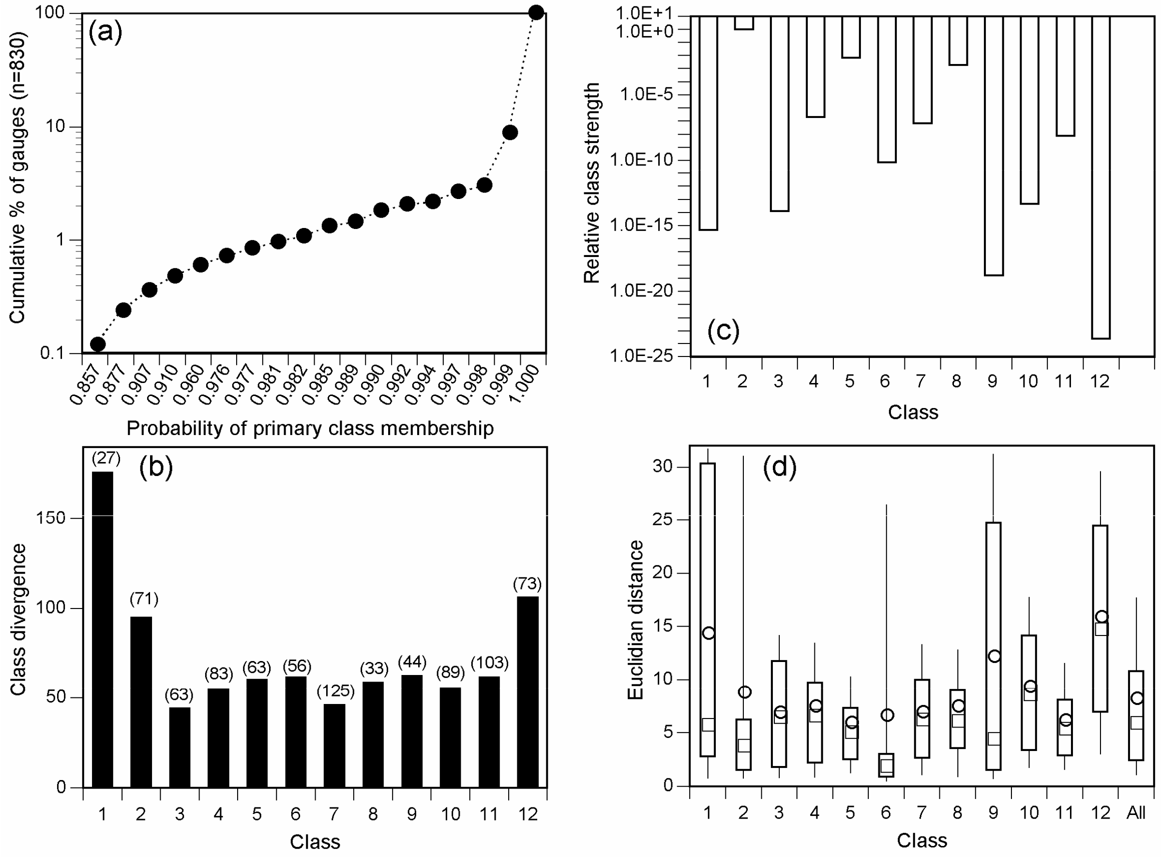

Figure 5.6. Results of Bayesian clustering (C1) of all 830 stream gauges showing (a) cumulative frequency distribution of the probability of each gauge belonging to its most likely class, (b) class divergence (number of stream gauges in each class shown in parentheses), (c) relative class strength and (d) variation in geographic (Euclidian) distance between all pairs of stream gauges within each flow regime class, and between all possible pairs of stream gauges (All). In (d) boxes define the 25th, 50th (median) and 75th percentile values and the vertical bars (whiskers) define the 10th and 90th percentile values. Median and mean values are represented by squares and circles, respectively.

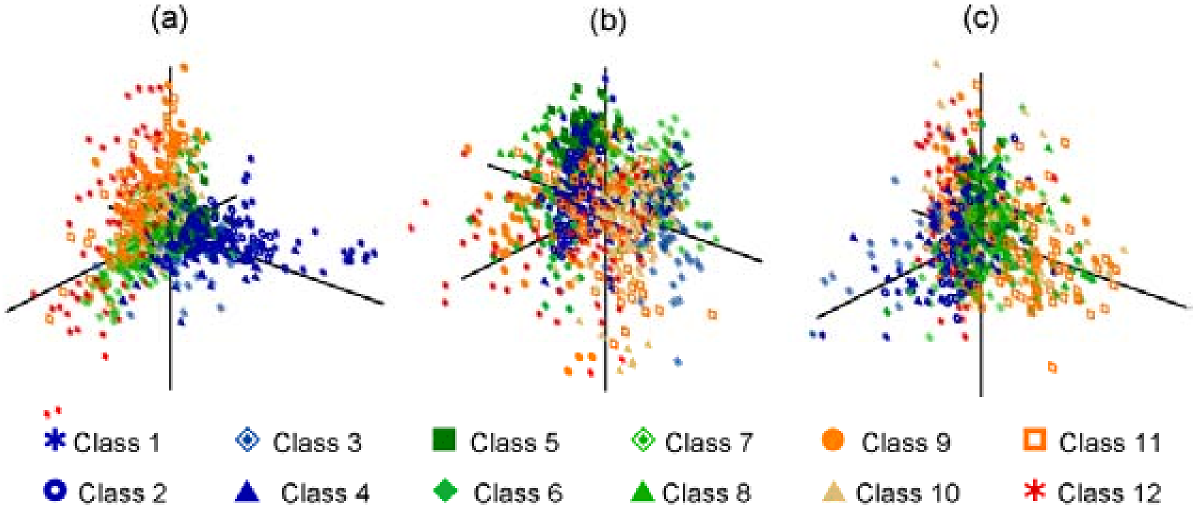

Figure 5.7. Variation in hydrology among stream gauges classes as defined by a principal components analysis of 120 hydrologic metrics. Shown are locations of all 830 stream gauges on (a) PCA1, PCA 2 and PCA3, (b) PCA4, PCA5 and PCA6, and (c) PCA7, PCA8 and PCA9, colour-coded by flow regime class (C1) membership (see Section 5.3.2).

Specifying variable uncertainty using the 30-year sMSE values resulted in the most likely classification (C2, n = 830 gauges, 14 classes) being reasonably similar to C1 (ARI = 0.481). The most important hydrologic metrics responsible for group formation were also similar between the two classifications (Pearson's *r* = 0.88 for comparison of relative importance of hydrological metrics, Figure 5.8a). Variation between stream gauges in the length of discharge record appeared to make little difference to classification group structure, at least over the range of differences in record length examined by us. A comparison of C1 with a classification based only on the subset of stream gauges with ≥25 years of record (C3, n = 334 gauges, 11 classes) revealed similar classification structure (ARI = 0.632) and similar relative importance of hydrologic metrics (*r* = 0.85, Figure 5.8a) between solutions. Randomly re-ordering the stream gauges in the dataset *al*so made little difference to the classification results (C4 – C13, 12–14 classes) (mean ARI = 0.505, range = 0.450 – 0.551, n = 10 comparisons) or the relative importance of hydrologic metrics contributing most to group formations (*r* > 0.91 for all comparisons, Figure 5.8b). In comparison to these alternative classifications, the results of a hard clustering method (C14, 12 classes) yielded greater differences in group formation, when compared with C1 (ARI = 0.371), and the similarity in the relative importance of hydrological metrics was lower, though still strongly correlated (*r* = 0.69, Figure 5.8c).

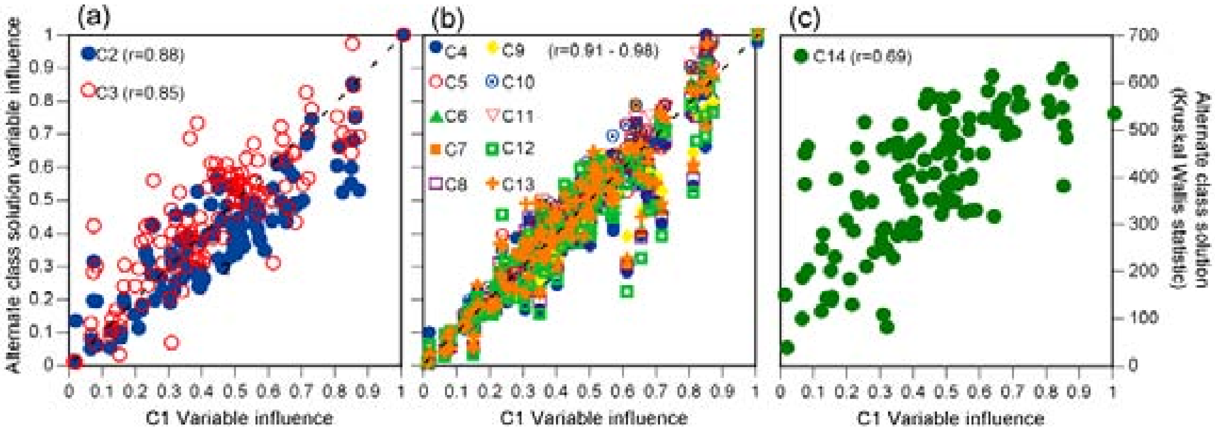

Figure 5.8. Scatter plots comparing the relative influence of hydrologic metrics on various alternative classifications (each point is an individual hydrologic metric, n= 120). (a) shows the variable influence based on C1 (x axis) *versus* C2 and C3, respectively (y axis). (b) shows the variable influence based on C1 (x axis) *versus* C4 – C13, respectively (y axis). (c) shows the variable influence based on C1 (x axis) *versus* the Kruskal Wallis statistic for C14 (y-axis). Pearson's correlation coefficients for each comparison are shown in parentheses.

5.3.3 Hydrological characteristics of flow regime classes

We used the distinguishing hydrologic metrics (as defined by Kullback-Leibler distances; Table 5.1) for the 12 flow regime classes identified by C1, together with graphical summaries of these and other key hydrologic metrics (Figure 5.9, Figure 5.10), to describe the major hydrological differences between flow regime types. We interpreted this information to summarise the 12 flow regime types as shown in Table 5.2.

The twelve flow regime classes could be first broadly grouped into perennial (classes 1 – 4) and intermittent streams (classes 5 – 12). This latter intermittent group was further divided into those streams that rarely ceased to flow (classes 5 – 8), those that regularly stopped flowing (classes 9 – 11) and those that were extremely intermittent (class 12) (Figure 5.9a, Figure 5.10). Further distinctions among classes were evident in terms of the monthly timing of discharge (Figure 5.9b), flood magnitude, frequency and duration ((Figure 5.9c, Figure 5.10), and other aspects of discharge magnitude, predictability and variability (Figure 5.10). Hydrographs for stream gauges typifying each flow regime class are also shown in Figure 5.11.

Class 1 streams (called *stable baseflow* streams), were perennial (Figure 5.9a, Figure 5.10), with comparatively high baseflow contribution (mean baseflow index = 0.35), high runoff magnitude and high constancy of monthly mean flows (Colwell's C = 0.37, Figure 5.10). This high baseflow constancy is further indicated by the generally flat slope of the flow duration curve throughout the range of percentile flow values (Figure 5.9a). These streams were highly predictable due to baseflow constancy but had a relatively weak seasonal signal (low M/P) (Figure 5.10) because discharge magnitude was relatively uniform throughout the year (Figure 5.9b). Streamflows tended to be very stable within years (i.e. low variability in daily flows) and among years, with low skewness and low rates of rise and fall (Figure 5.10, Figure 5.11). High flow events (e.g. > 1st percentile) were comparatively small, frequent and of short duration (Figure 5.10) and maximum flows generally occurred at a similar time from year to year (e.g. low variability in timing of maximum flows; Figure 5.10).

Table 5.1. Distinguishing hydrologic metrics for the 12 flow regime classes generated by the most probable classification from C1. Filled cells in the table include the top five most influential metrics for each class (based on Kullback-Leibler distances). For each metric, the figure indicates the number of class-level standard deviations separating the class-level mean from the global mean, with ‘+’ indicating that the class-level distribution is on average greater than the global distribution, while ‘-’ implies the opposite. Descriptions of each hydrologic metric are given in Appendix 5.1.

	Class (C1)											
Hydrologic metric	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Magnitude of flow events – *average flow conditions*												
Mean January flows						-4.9						
Mean February flows			+2.8			-5.7						
Mean July flows					+5.8	+7.6		+4.8		-5.3		
Mean August flows		+6.7			+5.7	+8.7				-7.6		
Mean September flows		+9.1			+6.8	+10.2		+4.8		-8.2		
Mean October flows					+4.1			+3.8		-5.7		
Mean December flows									-2.2			
CV January flows									-0.3		+3.3	
CV March flows									-0.3			
CV April flows												
CV May flows			-2.6									
CV June flows			-2.6									
CV July flows			-2.6									
CV August flows					+1.9							
Magnitude of flow events – *low flow conditions*												
Median of annual minimum flows				+3.3				-8.2	-8.5	-8.4	-8.5	
Baseflow index		+6.1		+3.5								
Low flow discharge (75th %’ile)				+3.7								
Low flow discharge (90th %’ile)				+3.7								
Low flow discharge (99th %’ile)								-5.0	-5.0		-5.0	
Magnitude of flow events – *high flow conditions*												
High flow discharge (1st %’ile)	-0.8											
High flow discharge (25th %’ile)												-6.6
High flow volume (>3xMDF)		-4.2										
Magnitude 2-year ARI	-0.8											
Frequency of flow events – *low flow conditions*												
Low flow spell count (<99th %’ile)											+3.4	
Frequency of flow events – *high flow conditions*												
High flow spell count (>25th %’ile)							+1.6					-1.9
CV high flow spell count (>25th %’ile)			+1.1				+1.3					-1.4
Duration of flow events – *low flow conditions*												
CV annual minima of 30-day means							+1.9					
Number of zero-flow days		-6.6		-6.3							+4.0	
Duration of flow events – *high flow conditions*												
Annual maxima of 7-day means	-0.9											
Annual maxima of 30-day means	-0.9											
Annual maxima of 90-day means	-0.9											
High flow spell duration (>25th %’ile)												+2.0
CV high flow spell duration (>25th %’ile)												-1.5
Timing of flow events – *average flow conditions*												
Predictability (P) of mean daily flow							-1.7					
Timing of flow events – *low flow conditions*												
Predictability (P) of minimum flow							-1.8					

Streams in class 2 (called *stable winter baseflow*) and class 3 (called *stable summer baseflow*) were also perennial with a high baseflow contribution and high runoff magnitude (Figure 5.9a, Figure 5.10) but had lower constancy and predictability of monthly mean flows compared with class 1 streams (Figure 5.10). High flow events (e.g. > 1st percentile exceedance flows) tended to be of slightly higher magnitude and longer duration, but were less frequent than in class 1 streams. A strong seasonal signal of discharge (M/P) was recorded for both classes with the majority of runoff occurring in winter in class 2 streams and summer in class 3 streams (Figure 5.9b). Streamflows in both classes tended to be very stable within and among years (low variability in daily and annual flow), with low skewness and low rates of rise and fall (Figure 5.10, Figure 5.11). High flow events (e.g. > 1st percentile) in class 3 streams were of greater magnitude, less frequent and of longer duration than in class 2 streams (Figure 5.10).

Compared with the other perennial streams, discharge in class 4 streams (called *unpredictable baseflow*) was less predictable and had a relatively weak seasonal signal (low M/P, discharge spread uniformly throughout the year; Figure 5.9b and Figure 5.10). Streamflows also tended to be less stable within and among years (higher variability in daily and annual flow), had higher skewness, and the timing of maximum flows was more variable (Figure 5.10). The relative magnitude of floods of various annual return intervals was also higher than in other perennial streams (Figure 5.9c).

Streams in classes 5, 6, 7 and 8 were intermittent and had low constancy of flows, intermediate baseflow contributions and intermediate runoff magnitudes (Figure 5.9a; Figure 5.10). Class 5 (called *unpredictable winter rarely intermittent*) and class 6 (called *predictable winter intermittent*) were dominated by winter runoff (Figure 5.9b) but differed in that class 5 streams ceased to flow less often than those in class 6 (mean of 5 days *vs* 60 days per annum, respectively) and they were less predictable (Figure 5.10). Discharge patterns in class 7 (called *unpredictable intermittent*) and class 8 (called *unpredictable winter intermittent*) streams were of very low predictability, were more variable and had relatively high skewness compared with classes 5 and 6. Streams in classes 7 and 8 differed from one another in that class 7 streams had more uniform runoff throughout the year (Figure 5.9b) and fewer zero flow days than class 8 streams (which were winter dominated and much more intermittent). Discharge in class 7 streams also tended to be less stable within and among years (higher variability in daily and annual flow), had higher skewness, and the timing of maximum flows was more variable (Figure 5.10). High flows were of a similar magnitude for both classes, but occurred more frequently and for a shorter duration in class 8 streams.

Streams in classes 9, 10 and 11 were highly intermittent (usually 100–200 zero flow days per year) which led to comparatively high flow constancy (Figure 5.10). When they did flow, class 9 streams (called *predictable winter highly intermittent*) were dominated by winter runoff and class 10 streams (called *predictable summer highly intermittent*) were dominated by summer runoff (Figure 5.9b). The strong seasonality of flows contributed to high predictability in both stream classes but they differed in that class 9 streams had much lower runoff and the timing of annual maximum flows was much less variable than in class 10 streams. Class 11 streams (called *unpredictable summer highly intermittent*) differed from other highly intermittent streams in that minimum and especially maximum monthly flows were less predictable and exhibited weaker seasonality, and although still summer dominated, the higher variability in Julian date of maximum flow suggests that high flows could occur at any time during the summer period (Figure 5.10). Class 11 streams also had much higher flow variability, skewness, rates of rise and fall and the relative magnitude of floods of various annual return intervals was also higher.

Class 12 streams (called *variable summer extremely intermittent*) were extremely intermittent (> 250 zero flow days per year) resulting in high flow constancy and hence high predictability. Although summer dominated (Figure 5.9b), the seasonality of flows was very weak (Figure 5.10). These streams were dominated by infrequent large floods which, while of similar magnitude from year to year (resulting in high predictability of maximum flows), could occur at any time of year (e.g. high variability in Julian date of maximum flows). These streams were also characterised by very high daily flow variability, skewness and rates of rise and fall (Figure 5.10, Figure 5.11).

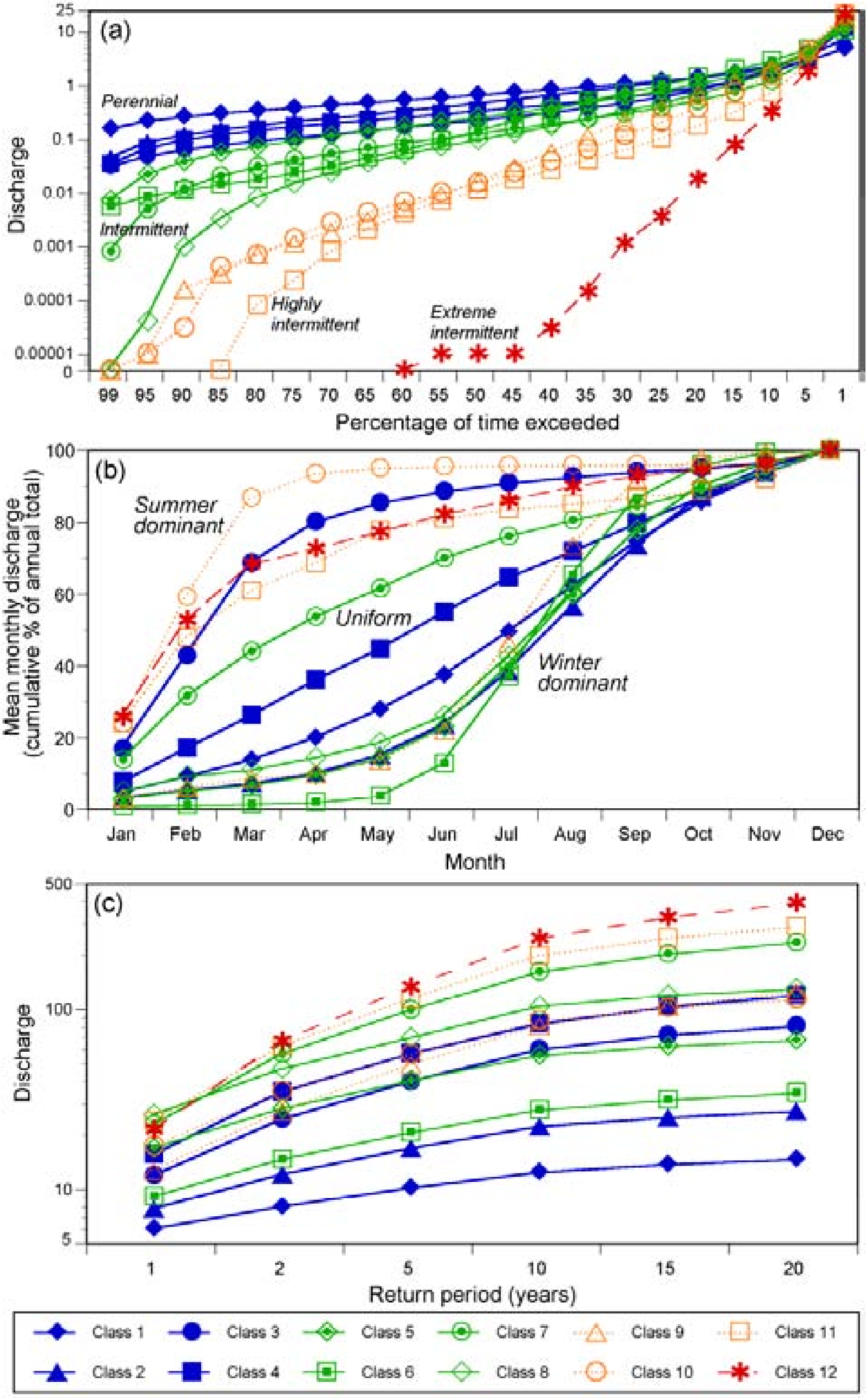

Figure 5.9. **(a) Average flow duration curves for each for each flow regime class, (b) average monthly flow for each flow regime class, and (c) average flood frequency distributions for each flow regime class.** In (a) data are the percentage of time each daily discharge was exceeded. In (b) data are expressed as a cumulative percentage of the annual total. In (c) data are the magnitude of the 1, 2, 5, 10 and 20 year Average Recurrence Interval floods, respectively. All data are standardised by long-term mean daily flow (See Appendix 5.1 for further details).

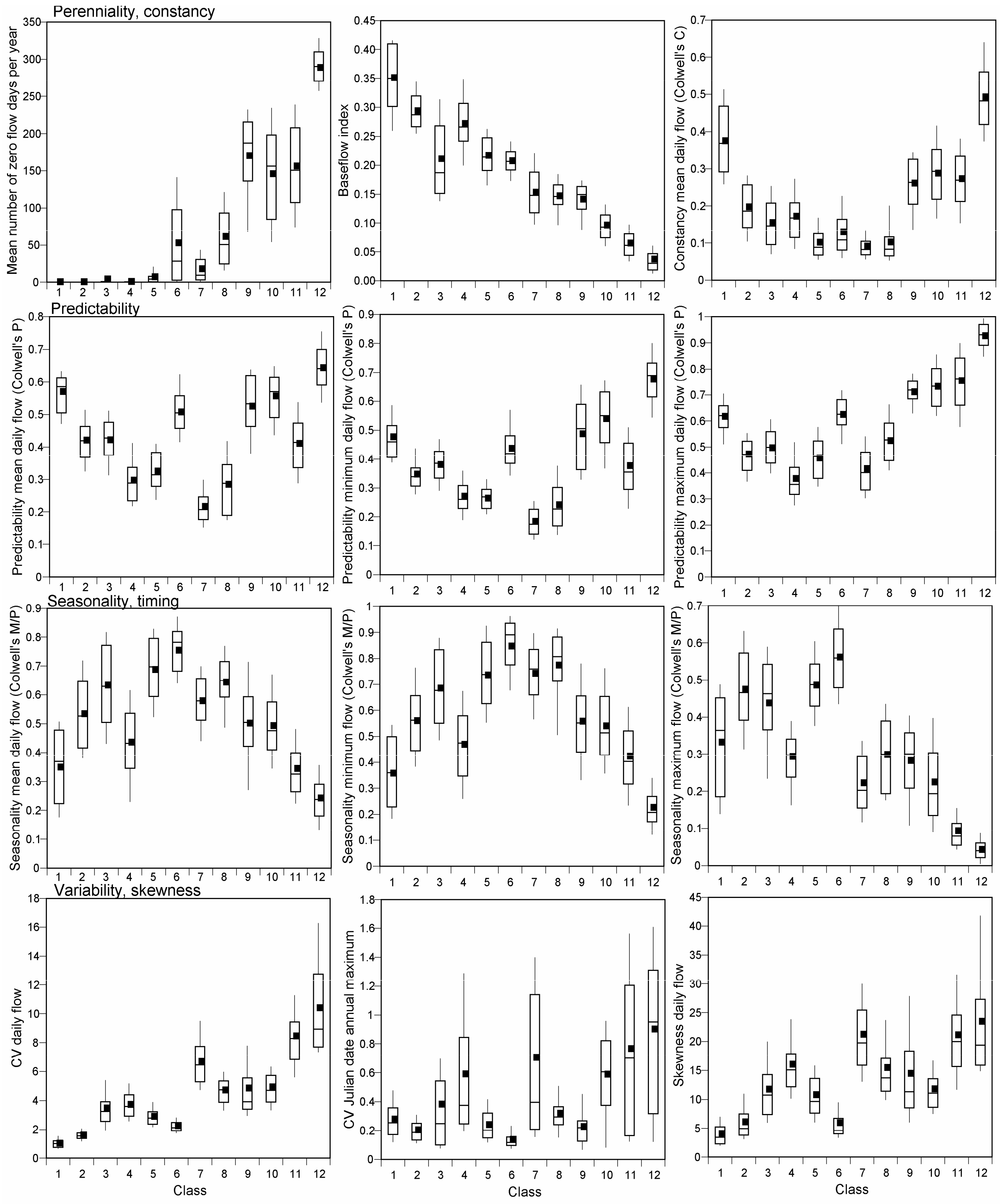

Figure 5.10. (continued overleaf). Box plots showing variation in selected hydrologic metrics between flow regime classes. Boxes define the 25th, 50th (median) and 75th percentile values and the vertical bars (whiskers) define the 10th and 90th percentile value. Mean values are defined by the symbol. Units for each metric are listed on Appendix 5.1

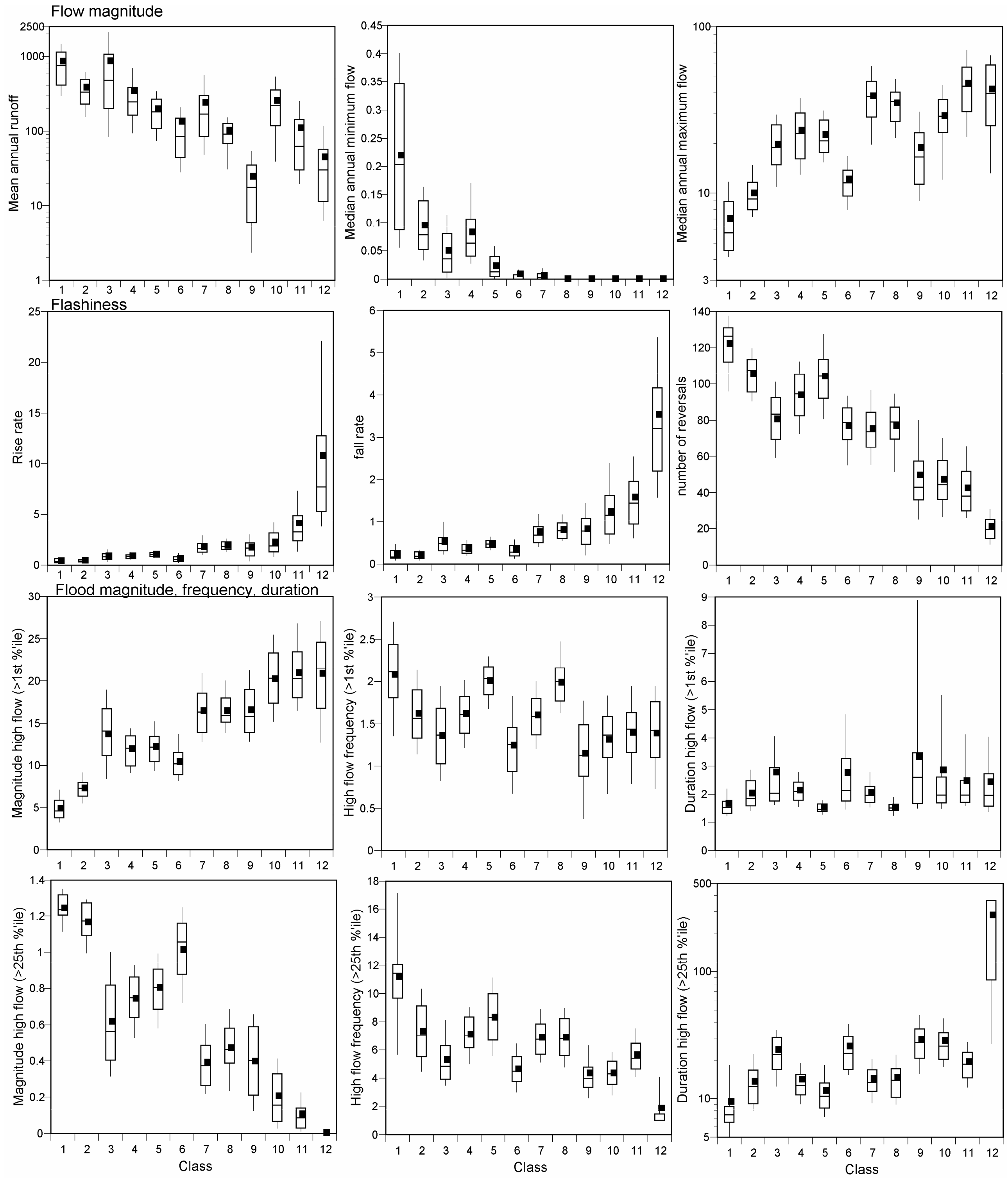

Figure 5.10. (cont'd.)

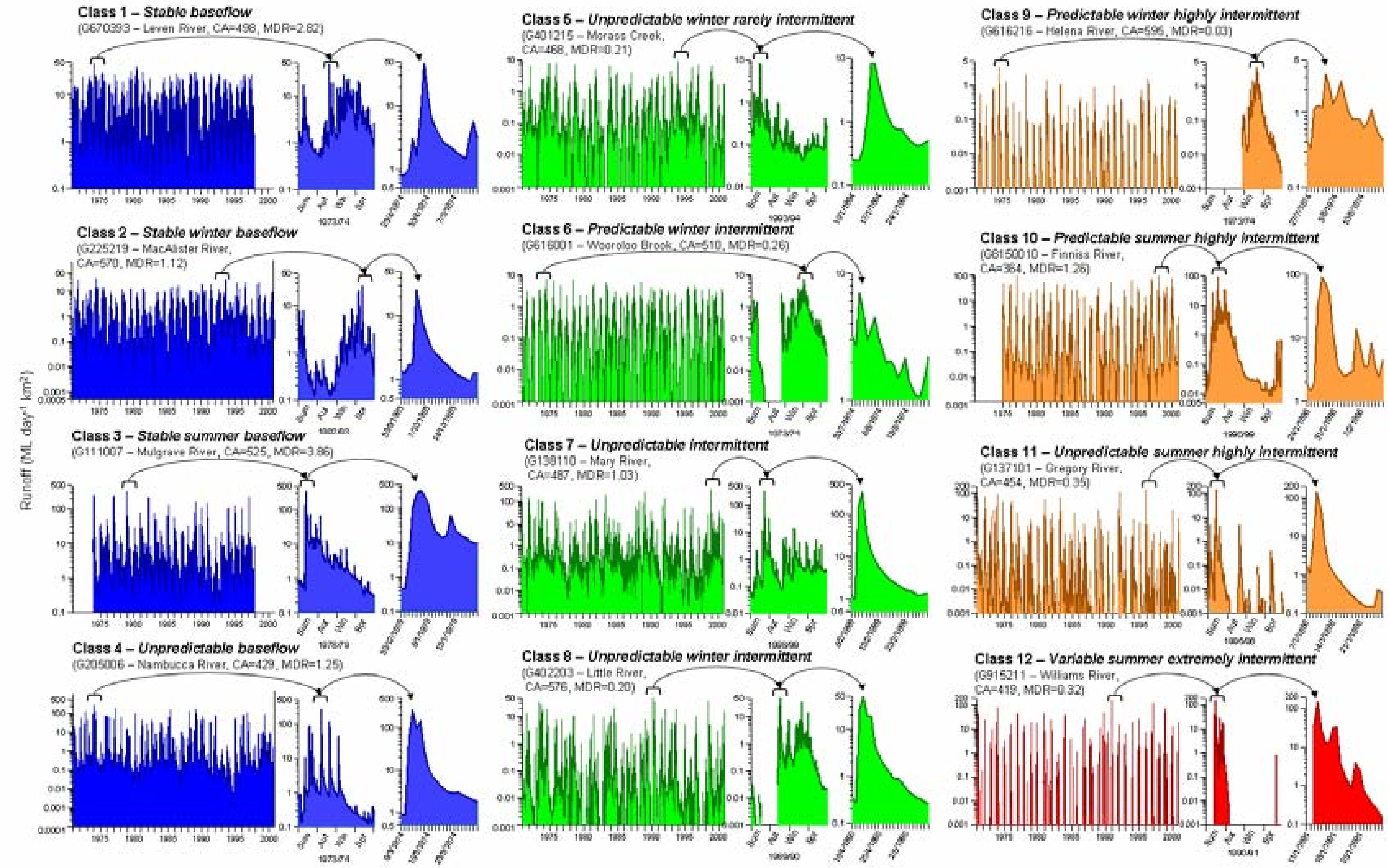

Figure 5.11. Example hydrographs of daily runoff (ML day^{-1} km^{2}) for a typical stream gauge in each flow regime class of equivalent catchment area. Variation in runoff is shown for three scales of temporal resolution including the long-term record and for the year and three week period encompassing the flow event with the highest peak magnitude. Also shown is the gauge number, upstream catchment area (km^{2}) and long-term mean daily runoff of each gauge.

Table 5.2. Summary of major hydrological characteristics of each flow regime class. Flow permanence: P = Perennial, I = Intermittent, HI = Highly intermittent, EI = Extremely intermittent. Seasonal timing: U = Uniform, W = Winter, S = Summer. Flow metrics: H = High, M = Moderate, L = Low. Note that actual values are not given (although these may be obtained from Figure 5.10) but are scaled to reflect differences across all flow regime classes.

Flow regime class	Flow permanence	Seasonal timing	Runoff magnitude	Predictability (P)	Seasonality (M/P)	Variability and skewness	1st %'ile flood			Rise and fall	25th %'ile flow			Reversals
							Mag	Freq	Dur		Mag	Freq	Dur	
1 – *Stable baseflow*	P	U	H	L	H	L	L	H	L	L	H	L	L	H
2 – *Stable winter baseflow*	P	W	H	M	M	L	L	M	M	L	H	L	M	H
3 – *Stable summer baseflow*	P	S	H	H	M	L	M	M	H	L	M	L	H	M
4 – *Unpredictable baseflow*	P	U	H	M	M	L	M	M	M	L	M	M	M	H
5 – *Unpredictable winter rarely intermittent*	I	W	M	H	M	L	M	H	L	L	M	H	L	H
6 – *Predictable winter intermittent*	I	W	M	H	H	L	M	L	H	L	H	L	H	M
7 – *Unpredictable intermittent*	I	U	M	M	L	M	M	M	M	M	L	M	M	M
8 – *Unpredictable winter intermittent*	I	W	L	H	L	M	M	H	L	M	L	M	M	M
9 – *Predictable winter highly intermittent*	HI	W	L	M	H	M	M	H	H	M	M	L	H	L
10 – *Predictable summer highly intermittent*	HI	S	M	M	H	M	H	M	H	H	L	L	H	L
11 – *Unpredictable summer highly intermittent*	HI	S	M	L	M	H	H	M	M	H	L	M	L	L
12 – *Variable summer extremely intermittent*	EI	S	L	L	H	H	H	M	M	H	L	L	H	L

5.3.4 Geographic variation in flow regime classes

The geographical distribution of flow regime classes tended to confirm the spatial patterns detected using principal components analysis (Section 5.3.1). *Stable baseflow* streams (class 1) were widely distributed geographically but occurred most frequently in the South-east Coast, Tasmanian and South-western Coast drainage divisions (Figure 5.12). Representatives of this flow regime type also occurred in the eastern Timor Sea division, northern Gulf of Carpentaria, southern North-east coast and the Murray-Darling drainage divisions. It appears that these streams are minimally influenced by the prevailing climatic signal. *Stable winter baseflow* (class 2) streams, in contrast, were restricted to the southern temperate half of the continent and occurred mainly in the South-east Coast, Tasmanian and South-west Coast drainage divisions. *Stable summer baseflow* (class 3) streams were primarily located in northern Australia occurring in the North-east Coast (particularly the Wet Tropics region), Gulf of Carpentaria and Timor Sea drainage divisions (Figure 5.12). *Unpredictable baseflow* streams (class 4) were widely distributed across southern and eastern Australia (Figure 5.12).

Unpredictable winter rarely intermittent streams (class 5) occurred mostly in south-eastern Australian coastal streams and the smaller headwater streams of the south-eastern Murray-Darling drainage division. *Predictable winter intermittent* streams (class 6) approximated the classic Mediterranean flow regime and were primarily located in south-western Australia and to a lesser extent the western portion of south-eastern Australia (Figure 5.12). *Unpredictable intermittent* (class 7) streams were widely distributed on the eastern coastal fringe of the continent, especially at the juncture of drainage Divisions I and II where the climate is transitional between temperate and subtropical. Such streams also occurred in the eastern upper headwaters of the Murray-Darling drainage division and in north-eastern Australia. *Unpredictable winter intermittent* (class 8) streams were limited to the eastern upper headwaters of the Murray-Darling drainage division and south-eastern Tasmania (Figure 5.12).

Predictable winter highly intermittent streams (class 9) were characteristic of inland areas in the South-west Coast and Murray-Darling drainage divisions. *Predictable summer highly intermittent* streams (class 10) occurred almost exclusively in the Timor Sea and Gulf of Carpentaria (Figure 5.12). *Unpredictable summer highly intermittent* streams (class 11) were almost exclusively restricted to the North-east drainage division and typically consisted of large rivers with the majority of their catchments located to the west of the Great Dividing Range but discharging east into the Coral Sea.

Variable summer extremely intermittent streams (class 12) are characteristic of arid and semi-arid regions, occurring in the Indian Ocean, Lake Eyre, Murray-Darling and southern Gulf of Carpentaria drainage divisions (Figure 5.12). An expanded discussion of spatial variation in flow regimes is included in Appendix 6.

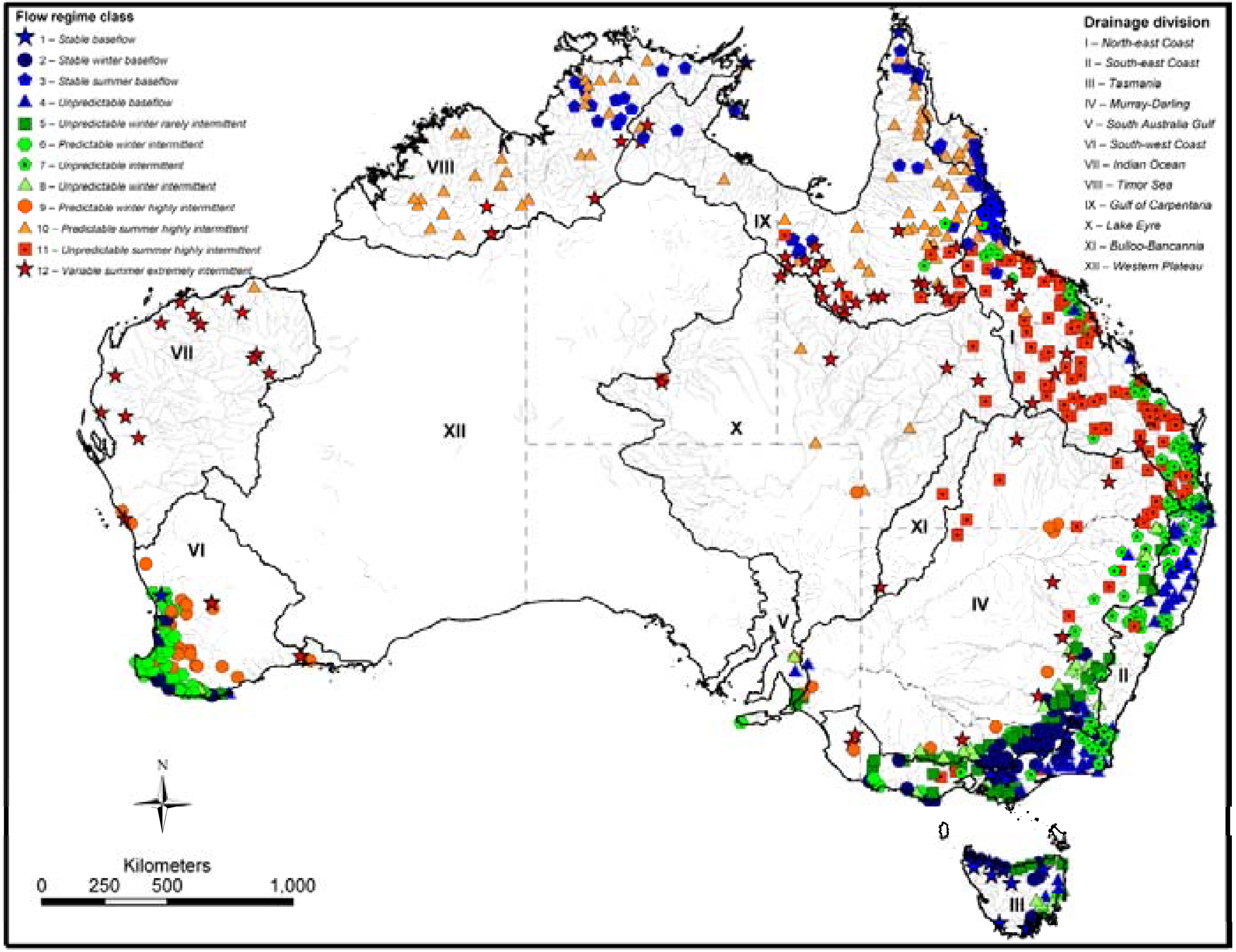

Figure 5.12. Geographical variation in flow regime class (C1) membership of 830 stream gauges in Australia.[3]

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[3] This figure incorporate Data which is © Commonwealth of Australia (Geoscience Australia) 2006. The Data has been used with the permission of the Commonwealth. The Commonwealth has not evaluated the Data as altered and incorporated within this figure, and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose.

5.3.5 Explanation and prediction of flow regime classes using external environmental data

Analysis of Similarity (ANOSIM) revealed there were significant differences between flow regime classes (from C1) in terms of the geographical location of stream gauges and their catchment topography, geology, vegetative cover and climate (Table 5.3, Figure 5.13). A strong geographic signal to flow regime types was evident when using stream gauge latitude and longitude to distinguish flow regime classes ($R_{ANOSIM} = 0.558$, $P<0.001$). Geographic variation in climate characteristics no doubt contributed to this strong discriminatory power as climate variables were similarly able to distinguish flow regime classes ($R_{ANOSIM} = 0.587$, $P<0.001$). Collectively, these two analyses indicate strong distinction between flow regimes of northern tropical Australia and southern temperate Australia. Catchment topographic variables ($R_{ANOSIM} = 0.172$, $P<0.001$) and geology, substrate and vegetative cover variables ($R_{ANOSIM} = 0.155$, $P<0.001$), although significant, showed considerably lower discriminatory power compared to other environmental variables. ANOSIM using all catchment topography, geology, vegetative cover and climate variables strongly discriminated between flow regime classes ($R_{ANOSIM} = 0.451$, $P<0.001$), as did the set of water balance variables ($R_{ANOSIM} = 0.572$, $P<0.001$).

Table 5.3. Results of analysis of similarity (ANOSIM) and classification tree (CART) analyses using various sets of geographic and environmental variables to discriminate between flow regime classes (from C1). For each set of variables, the ANOSIM Global R, classification tree predictive accuracy (overall % correct classification rate, Cohen's κ) and the variables used to construct the tree (ranked in decreasing order of importance) are given. All ANOSIM results were significant at p<0.001. Predictive accuracy of the classification tree models compares with random expectations of 9.1% (assuming all groups have equal sample size), 9.6% (if proportional to group size), and 15.1% (probability of being allocated to the group with the largest sample size). Significance values for Cohen's κ are listed in parentheses.

		CART model		
Variable set	**ANOSIM Global R**	**Accuracy (%)**	**Cohen's κ**	**Predictor variables**
1. Geographic location	0.558	47.7	0.413 (p<0.001)	(1) Latitude, (2) Longitude
2. Climate	0.587	57.8	0.534 (p<0.001)	(1) Annual mean solar radiation, (2) Mean February rainfall, (3) Mean August rainfall, (4) Mean April rainfall, (5) Mean annual rainfall, (6) Mean March rainfall, (7) Mean February actual evapotranspiration
3. Catchment topography	0.172	38.4	0.315 (p<0.01)	(1) Catchment slope, (2) Catchment relief, (3) Stream density, (4) Maximum upstream elevation, (5) Catchment relief ratio, (6) Catchment area, (7) Reach elevation
4. Geology, substrate and vegetation	0.155	37.2	0.290 (p<0.01)	(1) Old bedrock, (2) Solum plant available water holding capacity, (3) Unconsolidated material (regolith), (4) Present day tree cover
5. Catchment + Substrate + vegetation + Climate	0.451	62.1	0.579 (p<0.001)	(1) Mean rainfall in coldest quarter, (2) Mean rainfall in driest quarter, (3) Mean August rainfall, (4) Mean March areal actual evapotranspiration, (5) Mean January areal actual evapotranspiration, (6) Mean March rainfall, (7) Mean June areal actual evapotranspiration, (8) Mean November rainfall (9) Mean August rainfall, (10) Mean rainfall in warmest quarter
6. Water Balance	0.572	62.4	0.585 (p<0.001)	(1) Mean June runoff, (2) Mean May runoff, (3) CV annual runoff, (4) CV annual maximum monthly runoff, (5) 60th percentile of monthly runoff, (6) Mean November runoff, (7) Mean December runoff, (8) Skewness annual runoff (median/mean), (9) Mean February runoff, (10) Mean Spring runoff, (11) Mean October runoff, (12) Mean annual runoff

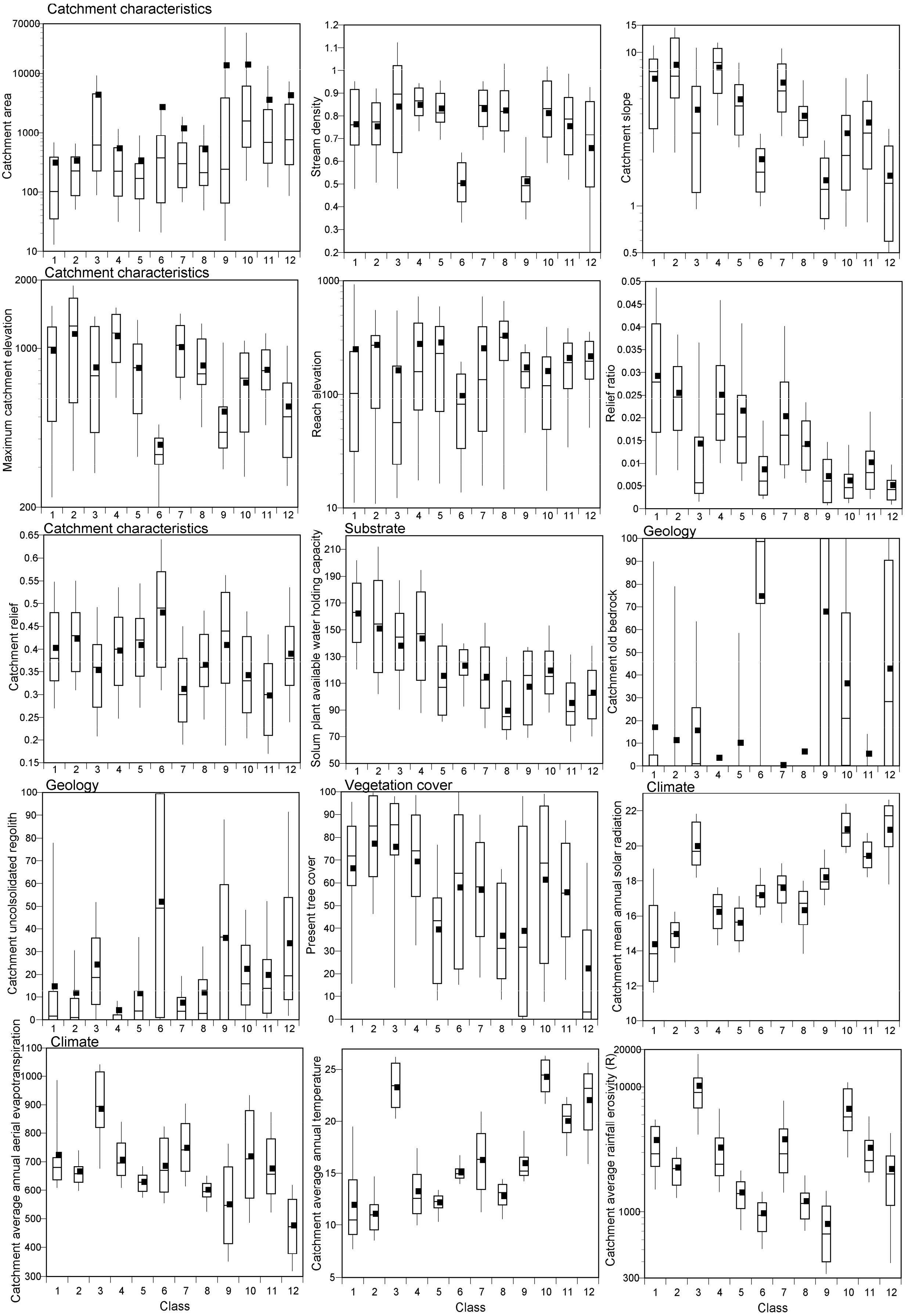

Figure 5.13. Box plots showing variation in environmental variables between flow regime classes. Only those variables selected by classification tree models are shown.

Classification tree (CART) model accuracy (percentage of gauges correctly allocated to their *a priori* flow regime class from C1) was substantially greater than would be expected by chance for each model, with classification success rates ranging from 37.2% to 62.4% (Table 5.3). The outcomes of CART modelling were similar to the results of ANOSIM analyses in that models using geographical location and climate predictor variables could more accurately discriminate flow regime classes than those using catchment topography or substrate and vegetation variables alone (Table 5.3). The model based on a combination of catchment, substrate, vegetation and climate variables, correctly classified 62.1% of stream gauges into their *a priori* flow regime class (Table 5.3, Figure 5.14). The primary and competing splitting variables mostly described temporal variation in catchment average rainfall, areal actual evapotranspiration, annual mean air temperature and rainfall erosivity (Figure 5.14). Topographic variables describing catchment slope and catchment relief were occasionally selected as competing splitting variables, but no geology or vegetation variables were selected in the final tree. The primary splitting variable in the CART model split stream gauges dominated by summer runoff (classes 12, 10 and 3) from all others on the basis of comparatively low total rainfall in the coldest quarter (Figure 5.14). Competing splitting variables indicated that these stream gauges also had high solar radiation, low rainfall in August and high annual temperatures. On the right side of the tree, two major groups of gauges were distinguished on the basis of whether their catchments experienced low or high August rainfall (competing variables described high rainfall earlier in the year). Streams in catchments receiving high rainfall in August were rarely intermittent or were perennial, whereas streams with catchments receiving little rain at this time tended to be intermittent or unpredictable. Class 3 streams (*stable summer baseflow*) were an exception. This group, limited to northern Australia, was grouped separately from other summer-dominated streams due to relatively high rainfall occurring outside the summer wet season period.

Misclassifications (i.e. compared with *a priori* defined flow regime classes) usually occurred among flow regime classes that were in close geographic proximity to one another and hence presumably shared regional climatic conditions (Figure 5.14). For example, *variable summer extremely intermittent* gauges (class 12) frequently grouped with other summer dominated flow regime classes (i.e. classes 10, 11 and 3) and *vice versa*. Stream gauges from these classes were generally situated across tropical northern Australia (Figure 5.12). The CART model had particular difficulty correctly classifying *stable summer baseflow* (class 3) streams that were not situated in the central core of the Wet Tropics region (Figure 5.12). These streams had relatively high baseflows throughout the year due to groundwater contributions from the Tindall aquifer, rather than the more constant rainfall and runoff experienced in the Wet Tropics region. Unsurprisingly, our model could not accurately predict the groundwater dominated streams, given the dominance of climatic predictor variables and the relative coarseness of the geology variables available to us for modelling (and which were not selected by the tree model).

The CART model based on water balance variables alone had a similar predictive accuracy (i.e. 62.4%) as the model based on a combination of catchment, substrate, vegetation and climate variables (Table 5.3). As observed above, this model also had difficulty correctly classifying class 3 streams that had significant groundwater contributions to baseflow.

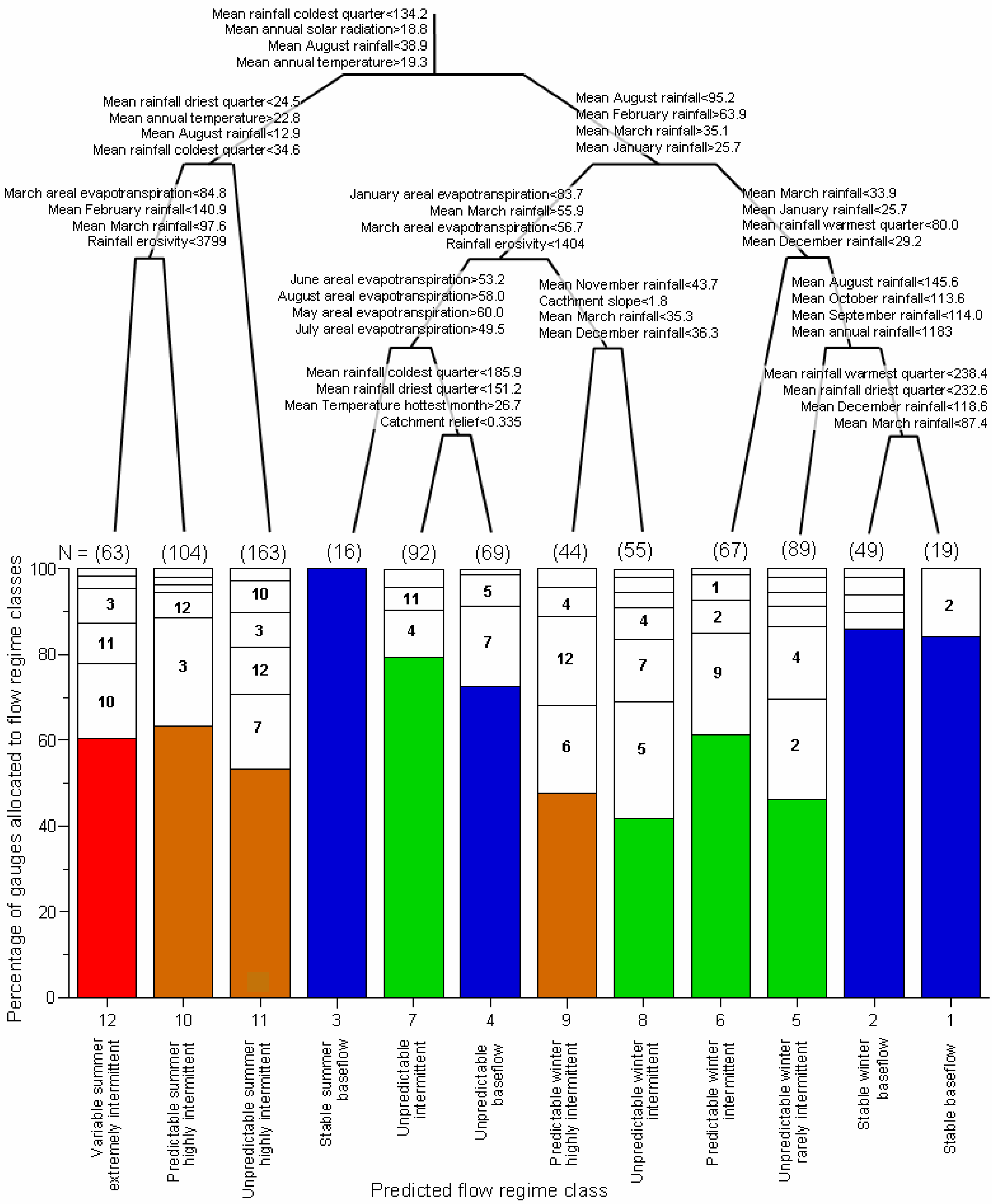

Figure 5.14. Classification tree for predicting flow regime class membership of each stream gauge using a combination of environmental variables describing catchment topography and climate. The environmental variables used in forming the tree (primary splitting variables shown first, followed by the three most important competing variables) and their critical values for determining the splits, are shown above each split. Gauges that met each splitting criteria are split off to the left branch. The number of gauges (N) within each classification tree group is given at the base of the tree. The stacked bar chart shows the percentage of gauges belonging to each tree group. The predicted flow regime class of each tree group is determined by the highest proportion of gauges belonging to a particular group (shown as closed bars), with misclassified gauges shown as open bars and numbered according to their actual flow regime class membership (for those with misclassification rates ≥5%).

5.3.6 Predicting flow regime class membership

A CART model using only 12 of the original 120 hydrologic metrics as primary splitting variables was able to correctly classify 81.2% of the 830 stream gauges into their *a priori* flow regime class ($\kappa = 0.790$, $P < 0.0001$; Figure 5.15). The 12 hydrologic metrics described low flow magnitude and duration, daily flow variability, the magnitude and variability of flows in particular months, and high flow magnitude and frequency. To determine the most likely flow regime class for a new stream gauge (i.e. one not used in the present analyses), the CART decision tree (Figure 5.15) can be used to assign the gauge to an individual flow regime class provided that data for the 12 hydrologic metrics (or for the competing splitting variables) are available.

5.3.7 Comparison with other continental environmental and biophysical classification schemes

The flow regime classification of stream gauges (C1) did not correspond well to stream gauge membership of other Australian environmental and biophysical classifications schemes (Table 5.4). Adjusted Rand index values ranged between 0. 172–0.250 for comparisons of C1 to the modified Köppen climate classification, the agro-climatic classification, the classification of river flow regime seasonality, Australian drainage division designations, a terrestrial bioregional classification, and a freshwater ecoregionalisation. This can be confirmed by a visual inspection of the geographical distribution of flow regime classes (Figure 5.12) in comparison to the distribution of groups from environmental and biophysical classification schemes (e.g. Figure 5.16). Interestingly, the extent of concordance among different classification schemes was not particularly high (median ARI value = 0.264, range = 0.135–0.603).

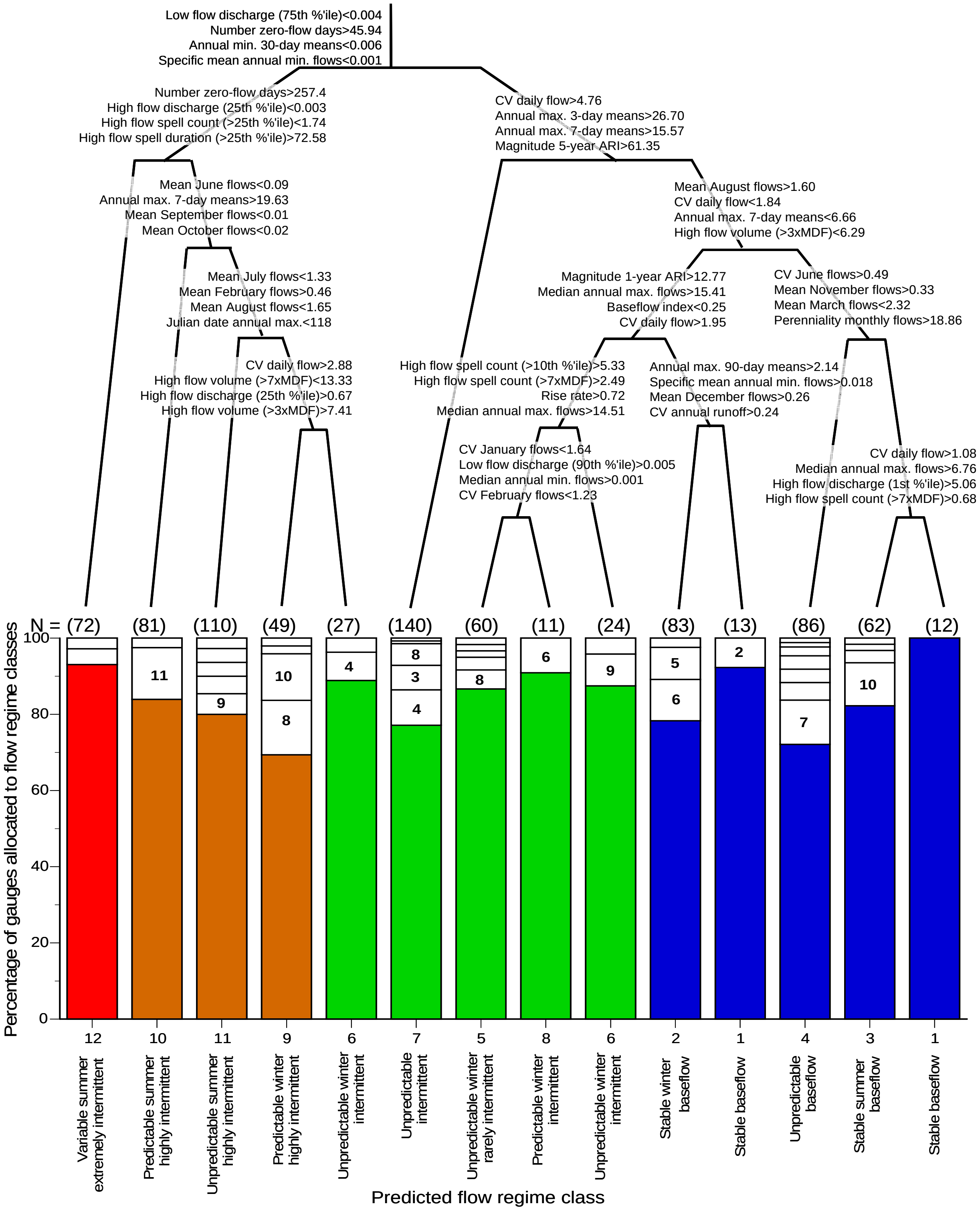

Figure 5.15. Classification tree for assigning new stream gauges to a flow regime class (C1) using hydrologic metrics. The subset of hydrologic metrics used in forming the tree (primary splitting variables shown first, followed by the three most important competing variables) and their critical values for determining the splits, are shown above each split. Gauges that met each splitting criteria are split off to the left branch. The number of gauges (N) within each classification tree group is given at the base of the tree. The stacked bar chart shows the percentage of gauges belonging to each tree group. The predicted flow regime class of each tree group is determined by the highest proportion of gauges belonging to a particular group (shown as closed bars), with misclassified gauges shown as open bars and numbered according to their actual flow regime class membership (for those with misclassification rates ≥5%).

Table 5.4. Results of adjusted Rand index comparisons between flow regime classification of stream gauges (from C1) and their membership of alternative environmental and biophysical classifications.

Other classifications	Flow regime class (C1)	Köppen climate	Agro-climate	Flow seasonality	Drainage division	Aquatic ecoregion
Köppen	0.184					
Agro-climate	0.204	0.457				
Flow seasonality	0.188	0.216	0.318			
Drainage division	0.213	0.333	0.343	0.184		
Terrestrial bioregion	0.172	0.278	0.333	0.135	0.262	
Aquatic ecoregion	0.250	0.264	0.251	0.262	0.603	0.206

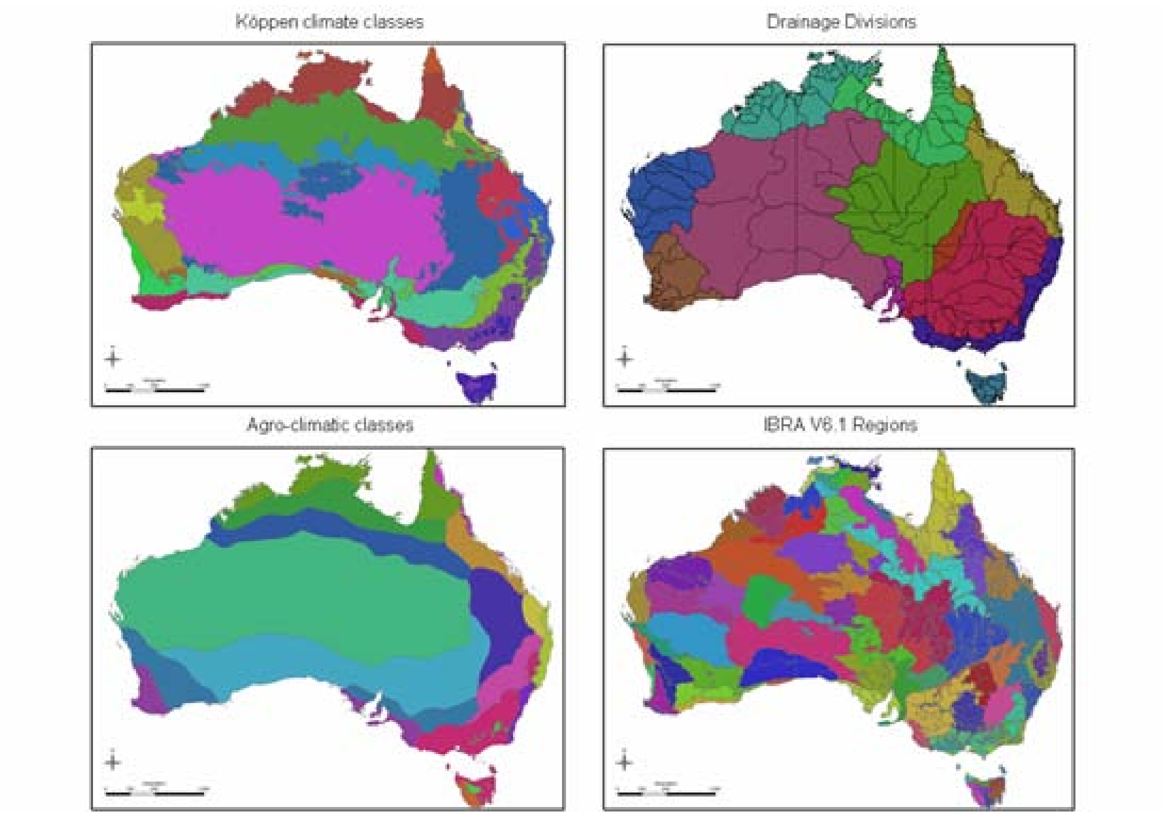

Figure 5.16. Examples of other Australian environmental and biophysical classification systems for Australia.[4]

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[4] Köppen Climate classification provided by National Climate Centre, Bureau of Meteorology (2007) and IBRA V6.1 provided by the Australian Government Department of the Environment, Water, Heritage and the Arts.

5.4 Discussion

The ecohydrological classification presented here represents the first continental-scale classification of the major ecologically relevant components of the natural flow regime for Australia. Hydrological classifications have previously been attempted in Australia at various scales, using a variety of methods, and usually describing only a subset of ecologically relevant flow regime components. Finlayson and McMahon (1988) applied the Haines *et al.* (1988) classification of streamflow seasonality at a continental scale and hydrologic classifications have been derived for particular regions (Hughes 1987; Hughes and James 1989) and individual catchments (Pusey and Arthington 1996; Thoms and Parsons 2003). The Bayesian clustering approach used here is an improvement on previous examples of hydrologic classifications for Australia and elsewhere in that the method is fully probabilistic and uncertainty is explicitly reported in terms of data specification, class specification and the final classification chosen.

We identified 12 distinctive flow regime classes that broadly differed in the degree of flow predictability and variability, the seasonal discharge pattern, flow permanence (i.e. perennial versus varying degrees of intermittency) and variations in the magnitude and frequency of extreme events (i.e. floods and low flow spells). The hydrologic metrics underlying the classification represent ecologically relevant facets of the hydrologic regime, as described by the Natural Flows Paradigm (Poff *et al.* 1997). Consequently, streams and rivers that cluster together presumably share certain ecological features (Resh *et al.* 1988; Poff and Ward 1989; Poff 1996). Several studies relating spatial patterns in assemblage composition, species' ecological traits and community function to regional variation in hydrology exist globally (e.g. Poff and Allan 1995; Monk *et al.* 2006; Konrad *et al.* 2008) but relatively few examples are available for Australia. This remains to be fully tested and is beyond the scope of the present study. However, Pusey *et al.* (2004a) showed that regional variation in fish species richness in north-eastern Australian rivers was strongly related to variations in aspects of discharge magnitude and perenniality. Pusey *et al.* (2000) attributed differences in species richness, fish abundances and relationships with habitat structure observed between rivers of north-eastern and south-eastern Queensland to differences in discharge predictability and constancy between these regions. Finally, Kennard *et al.* (2007) reported that hydro-ecological predictive models of fish assemblage composition, abundance and biomass developed for a south-eastern Queensland river varied in their ability to predict spatial and temporal variation in these assemblage properties in a nearby river that differed hydrologically (particularly with respect to flow predictability, runoff magnitude and variability and the frequency of extreme low flows). These studies collectively support the view that relationships between hydrology and ecological responses differ within and between particular regions and that this may be driven largely by variation in flow regime characteristics, however they are limited to a relatively small portion of Australia.

Knowledge of patterns in hydrological character should make it possible to infer spatial patterns in assemblage composition, species' ecological traits and community functioning (Jowett and Duncan 1990; Poff and Allan 1995; Snelder *et al.* 2005). Furthermore, predictions about how riverine ecology might respond to flow regime change can be made by comparing ecological attributes across hydrological gradients, aiding assessments of present-day environmental water requirements and assessment of changes to Australia's aquatic resources under differing scenarios of global climate change and dam construction. The improved understanding of geographic patterns in natural flow regime characteristics in Australia provided by our study provides a framework for designing field research aimed at investigating flow-ecology relationships in more detail. This knowledge is particularly required for large areas of tropical northern Australia where riverine flow regimes are still relatively undisturbed but where human impacts on riverine landscapes are predicted to increase.

It is important to note several cautionary points from a management and scientific perspective. Environmental flow assessments usually aim to identify and restore flow components that will move a river in the direction of its natural condition, or the best representation of this that can be identified (Arthington and Pusey 2003; Acreman and Dunbar 2004). The need to recognise hydrologic variation at multiple spatial scales is an important first step to setting regional-scale environmental flow management strategies (e.g.

Arthington *et al.* 2006; Poff *et al.* in press). We expect that the ecohydrological classification produced here can underpin the development of a greater understanding of flow-ecology relationships, and management efforts aimed at prescribing environmental flows for riverine restoration and protection.

Our results showed that 12 distinctive flow regime types exist for the Australian continent, at least for the stream gauges included in our analyses. This implies that attempts to manage rivers in an environmental flow context should proceed from the perspective that ecological responses to natural flow regime characteristics are likely to vary among these flow regime types. Thus, flow management strategies aimed at maintaining or restoring ecologically important components of the flow regime may not be applicable or transferable from one region (or river type) to another. A global approach (e.g. across an entire water resource management jurisdiction at the state or national level) may not be able to account for spatial heterogeneity in hydro-ecological relationships (Monk *et al.* 2006).

It is also important to note that the hydrologic descriptors used in our analysis described the long-term statistical pattern of the hydrologic regime, not the short-term history of hydrological events. Thus scientific studies aimed at explaining spatial and temporal variation in ecological attributes and their relationships with hydrology should account for site-specific hydrological history (Poff 1996), particularly if concerned with explaining ecological variables that fluctuate directly in response to short-term hydrologic events (e.g. recruitment-driven variations in abundance; Kennard *et al.* 2007) rather than ecological variables that represent long-term adjustments to hydrological regimes (e.g. species pools and ecological traits; Poff and Allan 1995; Tedesco *et al.* 2008).

Our analyses revealed that geographic, climatic and some topographic factors were generally strong discriminators of flow regime classes (e.g. Table 5.3, Figure 5.14) supporting the view that spatial variation in hydrology is determined by interactions between climate, geology, topography and vegetation at multiple spatial and temporal scales (Snelder and Biggs 2002; Snelder *et al.* 2005; Poff *et al.* 2006; Sanborn and Bledsoe 2006). Thus, the classification described here when combined with information on local climatic responses to global climate change, provides a means to determine whether changes in hydrology are likely to re-class the river in question from one regime type to another and presumably incur some environmental degradation or change. Similarly, the development of the decision tree allowing the designation of a river to a classification class based on a small number of flow metrics would assist in assessing the likely outcomes of dam construction, and water resource harvesting as well as the likely benefits of mitigating environmental flow scenarios.

Interestingly, we found a generally low degree of concordance between the flow regime classification of stream gauges and their membership of other Australian environmental and biophysical classifications schemes (note that we also observed low concordance among these other classification schemes). This lack of concordance among classifications may be due to a range of factors including the forced imposition of grouping structures on environmental data that often vary in a continuous rather than dichotomous fashion (see Pusey *et al.* (2000) and Olden *et al.* (2006) for a discussion of this point), the possible sensitivity of the statistical comparison method employed (the adjusted Rand index) to unequal group sizes (Steinly 2004), and/or the choice of input variables for individual classifications which may be important determinants of grouping structures but may not necessarily be expected to relate (either mechanistically or correlatively) to one another (e.g. Leathwick *et al.* 2003).

An important result of our study was that the geographical distribution of flow regime classes showed varying degrees of spatial cohesion (Figure 5.12), with stream gauges from certain flow regime classes often being non-contiguously distributed across the continent. This was particularly pronounced for flow regime classes described as *stable baseflow* (class 1), *predictable winter highly intermittent* (class 9) and *variable summer highly intermittent* (class 12). As a consequence, caution should be used if extrapolating flow regime characteristics from individual gauges to ungauged areas, even those within relatively close proximity. As suggested by Poff *et al.* (2006), this represents a serious constraint in terms of mapping hydrologic landscapes simply from available gauges used in an empirical classification analysis. In this context, deductively-based classification of key environmental attributes assumed to broadly shape patterns of flow regimes at large spatial and temporal scales (hydrologic landscapes, *sensu* Winter 2001) may be preferable for Australia as it is not reliant on an extensive spatial coverage of measured flow data to characterise river flow regimes (e.g. Wolock *et al.* 2004; Snelder *et al.* 2005). Note that deductive classifications are presented in Appendix 8.

Some aspects of the hydrograph could not be explained using independent environmental and hydrologic datasets. For example, the CART model had particular difficulty correctly classifying *stable summer baseflow* (class 3) streams that were not situated in the central core of the Wet Tropics region (Figure 5.12). Many of these misclassified streams had relatively high baseflows throughout the year due to groundwater contributions from the widespread Tindall aquifer, rather than the more constant rainfall and runoff experienced in the Wet Tropics region. This difficulty in correctly predicting flow regime is not surprising for these streams given the dominance of climatic variables as predictors and the relative coarseness of the geology variables available to us for modelling (and which were not selected by the CART model). Improvements in our ability to explain and predict hydrologic characteristics using independent environmental descriptors may be achieved by undertaking these analyses at finer spatial scales of resolution (i.e. to explain within-class hydrological variation), as has been shown by Sanborn and Bledsoe (2006).

Our study has broad-scale ecological implications that are directly applicable to conservation of aquatic and riparian ecosystems in Australia. With an increasingly large and thirsty human population and projected future climate change, there is growing need for preservation of remaining intact systems and deliberate and strategic design of resilient ecosystems (Palmer *et al.* 2004). By identifying streams and rivers that exhibit distinct flow regimes that are currently not altered by human activities, our results can aid in the selection of those river systems that may contribute to dynamic conservation reserves (Higgins *et al.* 2005; Nel *et al.* 2007; Snelder *et al.* 2007). A catchment containing a high diversity of flow regime types, or alternatively a low diversity or unique flow regime in comparison to other nearby catchments may be considered as a high priority for conservation. In light of the increasing degradation of Australia's freshwater ecosystems, recent efforts have emphasised the need for conservation protection in the form of comprehensive, adequate and representative freshwater reserves (Dunn 2003; Fitzsimons and Robertson 2005). Only about 2% of the 1400 named rivers in Australia are under protection by virtue of them flowing through a few large terrestrial protected areas (Nevill 2007). Although conservation of entire river basins offers the best chance of protecting aquatic biodiversity (Kingsford *et al.* 2005), unfortunately many of these protected waters are small streams that are intermittent or ephemeral, or are major river reaches without protection upstream or downstream (Nevill 2007). These areas are therefore likely to support only a small fraction of the native freshwater fish diversity in Australia. We believe that the selection of freshwater reserves and the success of conservation planning will benefit from a detailed understanding of spatial patterns of natural flow variability provided by our study.

5.5 Conclusion

Aquatic habitats and biota are threatened by many processes, especially hydrologic changes due to human land use, water extraction and from projected climate change (Bunn and Arthington 2002). Environmental water allocation, scenario testing and risk analysis of various management options, and planning for the impacts of global climate change all need to be based on predicted changes in the hydrologic regime (Poff *et al.* 2003; Stewardson and Gippel 2003; Richter *et al.* 2006). The ability to do so is constrained unless we know how much flow regimes vary between rivers and regions and the extent to which such variation results in natural changes to riverine ecology. Classification schemes are an important step in developing generalisations describing how natural systems or landscapes respond to changing global phenomena or natural resource management options (Higgins *et al.* 2005). The ecohydrological classification presented here provides scientists and managers with knowledge that can support ecologically sustainable management and restoration of freshwater ecosystems in Australia.

5.6 References

Acreman, M. and Dunbar, M.J. (2004). Defining environmental river flow requirements – a review. *Hydrology and Earth System Sciences* 8: 861–876.

Allen, G.R., Midgley, S.H. and Allen, M. (2003). *Field Guide to the Freshwater Fishes of Australia*, 2nd edition. Western Australian Museum, Perth. 394pp.

ANCOLD. (2002). *Register of large dams in Australia (ICOLD Dam Register.xls).* Australian National Committee on Large Dams. http://www.ancold.org.au

Arthington, A.H. and Pusey, B.J. (2003). Flow restoration and protection in Australian rivers. *River Research and Applications* 19: 1–19.

Arthington, A.H., Bunn, S.E., Poff, N.L. and Naiman, R.J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16: 1311–1318.

Australian Water Resources Council (AWRC) (1976). *Review of Australia's water resources 1975.* Australian Government Publishing Service, Canberra. 170 pp.

Bates, B.C. (1994). *Regionalisation of hydrological data: a review.* Report as part of Project D2: regionalisation and scaling of hydrologic data. Cooperative Research Centre for Catchment Hydrology, Monash University, Melbourne. 61 pp.

Biggs, B.J.F., Nikora, V.I. and Snelder, T.H. (2005). Linking scales of variability to lotic ecosystem structure and function. *River Research and Applications* 21: 283–298.

Bower, D., Hannah, D.M. and McGregor G.R. (2004). Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrological Processes* 18: 2515–2543.

Breiman, L., Friedman, J.H., Olshen R.A., and Stone, C.J. (1984). *Classification and Regression Trees.* Wadsworth International Group, California.

Bridgewater P.B. (1987). The present Australian environment – terrestrial and freshwater. Pp. 69–100. In Gyne, G.R. and Walton, D.W. (eds), *Fauna of Australia Volume 1A General Articles*. Australian Government Printing Service, Canberra.

Bunn, S.E. and Arthington, A.H. (2002). Basic principles and consequences of altered hydrological regimes for aquatic biodiversity. *Environmental Management* 30: 492–507.

Cambray, J.A. and Bianco, P.G. (1998). Freshwater fish in crisis, a Blue Planet perspective. *Italian Journal of Zoology* 65 (Suppl.): 345–356.

Cheeseman, P. and Stutz, J. (1996). Bayesian classification (Autoclass): theory and results. Pp. 153–180. In Fayyad, U. *et al.* (eds), *Advances in knowledge discovery and data mining*. AAAI Press and MIT Press.

Clarke, K.R. and Gorley, R.N. (2001). *Primer v5: User Manual/Tutorial.* Primer-E Ltd., Plymouth.

Colwell, R.K. (1974). Predictability, constancy and contingency of periodic phenomena. *Ecology* 55: 1148–1153.

De'ath, G. and Fabricus, K.E. (2000). Classification and regression trees: a powerful yet simple technique for ecological data analysis. *Ecology* 81: 3178–3192.

Dunn, H. (2003). Can conservation assessment criteria developed for terrestrial systems be applied to riverine systems? *Aquatic Ecosystem Health & Management* 6: 81–95.

Fausch, K.D., Torgersen, C.E., Baxter, C.V. and Li, H.W. (2002). Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. *BioScience* 52: 483–498.

Fielding, A.H. and Bell, J.F. (1997). A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* 24: 38–49.

Finlayson, B.L. and McMahon, T.A. (1988). Australia vs. the World: a comparative analysis of streamflow characteristics. Pp 17–40. In Robin F. Werner (ed), *Fluvial Geomorphology of Australia*. Academic Press, Sydney.

Fitzsimons, J.A. and Robertson, H.A. (2005). Freshwater reserves in Australia: directions and challenges for the development of a comprehensive, adequate and representative system of protected areas. *Hydrobiologia* 552: 87–97.

Fraley, C. and Raftery, A. (2006). *MCLUST Version 3 for R: Normal Mixture Modeling and Model-Based Clustering.* Technical Report no. 504, Department of Statistics, University of Washington, September 2006.

GeoSciences Australia (2006). *GEODATA TOPO 250K Series 3. Shape files format.* Commonwealth of Australia (GeoSciences Australia).

Gelman, A., Carlin, J.B., Stern, H.S. and Rubin, D.B. (2004). *Bayesian Data Analysis*, 2nd edition. Chapman and Hall/CRC Press, Boca Raton, Florida.

Grayson, R.B., Argent, R.M., Nathan, R.J., McMahon, T.A. and Mein, R. (1996). *Hydrological Recipes: Estimation Techniques in Australian Hydrology*. Cooperative Research Centre for Catchment Hydrology, Australia.

Grossman, G.D. and Ratajczak, R.E. (1998). Long-term patterns of microhabitat use by fish in a southern Appalachian stream from 1983 to 1992: effects of hydrologic period, season and fish length. *Ecology of Freshwater Fish* 7: 108–131.

Growns, J. and Marsh, N. (2002). *Characterisation of Flow in Regulated and Unregulated Streams in Eastern Australia*. Cooperative Research Centre for Freshwater Ecology, Canberra. 70 pp.

Harris, N.M., Gurnell, A.M., Hannah, D.M. and Petts, G.E. (2000). Classification of river regimes: a context for hydroecology. *Hydrological Processes* 14: 2831–2848.

Haines, A.T., Findlayson, B.L. and McMahon, T.A. (1988). A global classification of river regimes. *Applied Geography* 8: 255–272.

Hanson, R., Stutz, J. and Cheeseman, P. (1991). *Bayesian classification theory*. Artificial Intelligence Research Branch, NASA Ames Research Center, CA.

Higgins, J.V., Bryer, M.T., Khoury, M.L. and Fitzhugh, T.W. (2005). A freshwater classification approach for biodiversity conservation planning. *Conservation Biology* 19: 1–14.

Horwitz, R.J. (1978) Temporal variability patterns and the distributional patterns of stream fishes. *Ecological Monographs* 48: 307–321.

Hubert, L. and Arabie, P. (1985). Comparing partitions. *Journal of Classification* 2: 193–218.

Hughes, J.M.R. (1987). Hydrological characteristics and classification of Tasmanian rivers. *Australian Geographical Studies* 25: 61–82.

Hughes, J.M.R. and James, B. (1989). A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. *Australian Journal of Marine and Freshwater Resources* 40: 303–326.

Hutchinson, M.F., Nix, H.A and McTaggart, C. (2004). *GROWEST Version 2.0.* Centre for Resource and Environmental Studies, Australian National University, Canberra. http://cres.anu.edu.au/outputs/growest.html

Hutchinson, M.F., McIntyre, S., Hobbs, R.J., Stein, J.L., Garnett, S. and Kinloch, J. (2005). Integrating a global agro-climatic classification with bioregional boundaries in Australia. *Global Ecology and Biogeography* 14: 197–212.

Jowett, I.G. and Duncan, M.J. (1990). Flow variability in New Zealand rivers and its relationship to in-stream habitat and biota. *New Zealand Journal of Marine and Freshwater Research* 24: 305–317.

Kennard M.J., Olden J.D., Arthington A.H., Pusey B.J. and Poff N.L. (2007). Multi-scale effects of flow regime, habitat, and their interaction on fish assemblage structure in eastern Australia. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 1346–1359.

Kingsford, R.T., Dunn, H., Love, D., Nevill, J., Stein, J. and Tait J. (2005). *Protecting Australia's rivers, wetlands and estuaries of high conservation value: a blueprint*. Department of the Environment and Heritage (Australia), Canberra. http://www.environment.gov.au/water/publications/environmental/protecting-rivers.html.

Knighton, D. (1998). *Fluvial forms and processes: a new perspective*. Arnold, London.

Konrad C.P., Brasher A.M.D. and May J.T. (2008). Assessing streamflow characteristics as limiting factors on benthic invertebrate assemblages in streams across the western United States. *Freshwater Biology* doi10.1111/j.1365-2427.2008.02024.x.

Kushlan, G.A. (1976). Environmental stability and fish community diversity. *Ecology* 57: 821–825.

Lake, P.S. (2000). Disturbance, patchiness, and diversity in streams. *Journal of the North American Benthological Society* 19: 573–592.

Lake, P.S. (2003). Ecological effects of perturbation by drought in flowing waters. *Freshwater Biology* 48: 1161–1172.

Leathwick, J.R., Overton, J.McC. and McLeod, M. (2003). An environmental domain classification of New Zealand and its use as a tool for biodiversity management. *Conservation Biology* 17: 1612–1623.

Lytle, D.A, and Poff, N.L. (2004). Adaptation to natural flow regimes. *Trends in Ecology and Evolution* 19: 94–100.

McAllister, D.E., Hamilton, A.L. and Harvey, B. (1997). Global freshwater biodiversity: striving for the integrity of freshwater systems. *Sea Wind* 11: 1–140.

Magoulick, D.D. and Kobza, R.M. (2003). The role of refugia for fishes during drought: a review and synthesis. *Freshwater Biology* 48: 1186–1198.

McMahon, T.A., Vogel, R.M., Peel, M.C. and Pegram, G.G.S. (2007). Global streamflows – Part 1: Characteristics of annual streamflows. *Journal of Hydrology* 347: 243–259.

Marsh, N.A., Stewardson, M.J. and Kennard, M.J. (2003). *River Analysis Package*. Cooperative Research Centre for Catchment Hydrology, Monash University Melbourne. http://www.toolkit.net.au.

Matthews, W.J. and Marsh-Matthews, E. (2003). Effects of drought on fish across axes of space, time and ecological complexity. *Freshwater Biology* 48: 1232–1253.

Mittelbach, G.G. (1986). Predator-mediated habitat use: some consequences for species interactions. *Environmental Biology of Fishes* 16: 159–169.

Moliere, D., Lowry, J., Staben, G. and Humphrey, C. (2006). Flow characteristics of streams in the tropical rivers region. In *Proceedings of the 30th Hydrology and Water Resources Symposium*, 4–7 December 2006, Launceston, Tasmania.

Monk, W.A., Wood, P.J., Hannah, D.M., Wilson, D.A., Extence, C.A. and Chadd, R.P. (2006). Flow variability and macroinvertebrate community response within riverine systems. *River Research and Applications.* 22: 595–615.

Monk, W.A., Wood, P.J., Hannah, D.M., and Wilson, D.A. (2007). Selection of river flow indices for the assessment of hydroecological change. *River Research and Applications*. 23: 113–122.

Mosley, M.P. (1981). Delimitation of New Zealand hydrologic regions. *Journal of Hydrology* 49: 179–192.

Nathan, R.J. and McMahon, T.A. (1990). Idenification of homogeneous regions for the purposes of regionalisation. *Journal of Hydrology* 121: 217–238.

Nature Conservancy. (1997). *IHA Software and Users Manual*. Smythe Scientific Software, Boulder, Colorado.

Nel, J.L., Roux, D.J., Maree, G., Kleynhans, C.J., Moolman, J., Reyers, B., Rouget, M. and Cowling, R.M. (2007). Rivers in peril inside and outside protected areas: a systematic approach to conservation assessment of river ecosystems. *Diversity and Distributions* 13: 341–352.

Nevill, J. (2007). Counting Australia's protected rivers. From http://www.ids.org.au/~cnevill/freshwater.htm. Accessed 20/03/2007.

Nix, H.A. (1981). Simplified simulation models based on specified minimum data sets: the CROPEVAL concept. Pp 151–169. In Berg, A. (ed), *Application of Remote Sensing to Agricultural Production Forecasting*. Commission of the European Communities, Rotterdam.

Oberdorff, T., Guegan, J.F. and Hugueny, B. (1995). Global scale patterns of fish species richness in rivers. *Ecography* 18: 345–352.

Olden, J.D., and Poff, N.L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19: 101–121.

Olden, J.D., Joy, M.K. and R.G. Death. (2006). Rediscovering the species in community-wide modeling. *Ecological Applications* 16: 1449–1460.

Palmer M.A., Bernhardt E., Chornesky E., Collins S., Dobson A., Duke C., Gold B., Jacobson R., Kingsland S., Kranz R., Mappin M., Martinez M.L., Micheli F., Morse J., Pace M., Pascual M., Palumbi S., Reichman O. J., Simons A., Townsend A. & Turner M. (2004) Ecology for a crowded planet. *Science*, 304, 1251-1252

Pearsons, T.N., Li, H.W. and Lamberti, G.A. (1992). Influence of habitat complexity on resistance to flooding and resilience of stream fish assemblages. *Transactions of the American Fisheries Society* 121: 427–436.

Peel, M.C., Finlayson, B.L. and McMahon, T.A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* 11: 1633–1644.

Poff, N.L. (1996). A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology* 36: 71–91.

Poff, N.L. and Ward, J.V. (1989). Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* 46: 1805–1818.

Poff, N.L. and Ward, J.V. (1990). The physical habitat template of lotic systems: recovery in the context of historical pattern of spatio-temporal heterogeneity. *Environmental Management* 14: 629–645.

Poff, N.L. and Allan, J.D. (1995). Functional organization of stream fish assemblages in relation to hydrologic variability. *Ecology* 76: 606–627

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997). The natural flow regime: a paradigm for river conservation and restoration. *BioScience* 47: 769–84.

Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B., Arthington, A.H., Rogers, K.H., Meyer, J.L., and J.A. Stanford. (2003). River flows and water wars: emerging science for environmental decision-making. *Frontiers in Ecology and the Environment* 1: 298–306.

Poff, N.L., Olden, J.D., Pepin, D.M and Bledsoe, B.P. (2006). Placing global streamflow variability in geographic and geomorphic contexts. *River Research and Applications* 22: 149–166.

Poff, N.L., Richter, B., Arthington, A.H., Bunn, S.E., Naiman, R.J., Apse, C., Kendy, E., Warner, A.T., Jacobson, R.B., Rogers, K., Tharme, R., Freeman, M., Bledsoe, B.P., Merritt, D., Acreman, M., O'Keefe, J., Henriksen, J., Olden, J. and Kennen, J. (in press). The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology*.

Postel, S. and Richter, B. (2003). *Rivers for life: Managing water for people and nature*. Island Press, Washington, DC.

Puckridge, J.T., Sheldon, F., Walker, K.F. and Boulton, A.J. (1998). Flow variability and the ecology of large rivers. *Marine and Freshw Research* 49: 55-72.

Puckridge, J.T., Sheldon, F., Walker, K.F. and Boulton, A.J. (2001). Flow variability and the ecology of large rivers. *Marine and Freshwater Research* 49: 55–72.

Pusey, B.J. and Arthington, A.H. (1996). Streamflow variability within the Burdekin River. Pp. 213–220. In *Proceedings of the 23rd Hydrology and Water Resources Symposium.* Australian Institute of Engineers, Barton.

Pusey, B.J. and Bradshaw, S.D. (1996). Diet and dietary overlap in fishes of temporary waters of southwestern Australia. *Ecology of Freshwater Fish* 5: 183–194.

Pusey, B.J., Kennard, M.J. and Arthington, A.H. (2000). Discharge variability and the development of predictive models relating stream fish assemblage structure to habitat in north-eastern Australia. *Ecology of Freshwater Fish* 9: 30–50.

Pusey, B.J., Arthington, A.H. and Kennard, M.J. (2004a). Hydrologic regime and its influence on broad-scale patterns of fish biodiversity in north-eastern Australian rivers. In: *Proceedings of the 5th International Symposium on Ecohydraulics*, Madrid, Spain, 12–17 September 2004.

Pusey, B.J., Kennard, M.J. and Arthington, A.H. (2004b). *Freshwater Fishes of North-Eastern Australia*. CSIRO Publishing, Collingwood, VIC. 684 pp.

Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.E., Sheldon, A.L., Wallace, J.B. and Wittmar, R.C. (1988). The role of disturbance in stream ecology. *Journal of the North American Benthological Society* 7: 433–455.

Richter, B.D., Warner, A.T., Meyer, J.L. and Lutz, K. (2006). A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications* 22: 297–318.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10: 1163–1174.

Sala, O.E., Chapin, F.S.I., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.R., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M. and Wall, D.H. (2000). Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.

Sanborn, S.C. and Bledsoe, B.P. (2006). Predicting streamflow regime metrics for ungauged streams in Colorado, Washington, and Oregon. *Journal of Hydrology* 325: 241–261.

Schlosser, I.J. (1987). A conceptual framework for fish communities in small warmwater streams. Pp. 17–24. In Matthews, W.J. and Heins, D.C. (eds), *Community and Evolutionary Ecology of North American Stream Fishes*. University of Oklahoma Press, Norman.

Schlosser, I.J. and Angermeier, P.L. (1995). Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. *American Fisheries Society Symposium* 17: 392–401

Snelder, T.H. and Biggs, B.J.F. (2002). Multi-scale river environment classification for water resources management. *Journal of the American Water Resources Association* 38: 1225–1240.

Snelder, T.H. and Dey, K. (2007). A procedure for making optimal selection of input variables for multivariate environmental classifications. *Conservation Biology* 21: 365–375.

Snelder, T.H., Biggs, B.J.F. and Woods, R.A. (2005). Improved eco-hydrological classification of rivers. *River Research and Applications* 21: 609–628.

Sokal, R.R. and Rohlf, F.J. (1995). *Biometry: the principles and practice of statistics in biological research*, 3rd edition. W. H. Freeman and Co., New York

Statistical Sciences. (1999). S-PLUS, version 2000 for Windows. Mathsoft Inc., Seattle, WA.

Stein, J.L., Stein, J.A. and Nix, H.A. (2002) Spatial analysis of anthropogenic river disturbance at regional and continental scales: identifying the wild rivers of Australia. *Landscape and Urban Planning* 60: 1–25.

Steinley, D. 2004. Properties of the Hubert-Arabie adjusted rand index. *Psychol. Methods* 9: 386–96.

Stern, H., de Hoedt, G. and Ernst J. (2008). Objective classification of Australian climates. http://www.bom.gov.au/climate/environ/other/koppen_explain.shtml.

Stewardson, M.J. and Gippel, C.J. (2003). Incorporating flow variability into environmental flow regimes using the Flow Events Method. *River Research and Applications* 19: 459–472.

Tedesco, P.A., Hugueny, B., Oberdorff, T., Dürr, H.H., Mèrigoux, S. and de Mèrona, B. (2008). River hydrological seasonality influences life history strategies of tropical riverine fishes. *Oecologia* 156: 691–702.

Thoms, M.C. and Parsons, M. (2003). Identifying spatial and temporal patterns in the hydrological character of the Conadmine-Balonne river, Australia, using multivariate statistics. *River Research and Applications* 19: 443–457.

Unmack, P.J. (2001). Biogeography of Australian freshwater fishes. *Journal of Biogeography* 28: 1053–1089.

Venables, W.N. and Ripley, B.D. (1999). *Modern Applied Statistics with S-PLUS*, 3rd edition. Springer-Verlag, New York.

Vörösmarty, C.J., Green, P. Salisbury, J. and Lammers, R.B. (2000). Global water resources: vulnerability from climate changes and population growth. *Science* 289: 284–288.

Vörösmarty, C.J., Lettenmaier, D., Leveque, C., Meybeck, M., Pahl-Wostl, C., Alcamo, J., Cosgrove, H., Grassl, H., Hoff, H., Kabat, P., Lansigan, P., Lawford, R. and Naiman, R. (2004). Humans transforming the global water system. *EOS* 85: 509–514.

Webb, J.A., Bond, N.R., Wealands, S.R., Mac Nally, R., Quinn, G.P., Vesk, P.A. and Grace, M.R. (2007). Bayesian clustering with AutoClass explicitly recognises uncertainties in landscape classification. *Ecography* 30: 526–536.

Winter, T.C. (2001). The concept of hydrologic landscapes. *Journal of the American Water Resources Association* 37: 335–349.

Wolock, D.M., Winter, T.C. and McMahon, G. (2004). Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. *Environmental Management* 34 (Suppl 1): S71–S88.

World Wildlife Fund (WWF) (2008). *Freshwater ecoregions of the world.* http://www.worldwildlife.org/science/ecoregions.cfm

Zalewski, M., Janauer, G.A. and Jolankai, G. (1997). *Ecohydrology. A new paradigm for the sustainable use of aquatic resources.* UNESCO IHP Technical Document in Hydrology 7. IHP – V Projects 2.3/2.4, UNESCO Paris. 58 pp.

Zaret, T. and Rand, A.S. (1971). Competition in tropical stream fishes: support for the competitive exclusion principle. *Ecology* 52: 336–342.

Appendix 5.1. Description of the 120 hydrologic metrics used in the analyses and their interrelationships (as defined by principal components analysis). Abbreviations used are: MDF, mean daily flow; MADF, mean annual daily flow; CV, coefficient of variation; ARI, Average Recurrence Interval.

Hydrologic metric	PC[1]	PCA loading [2]	U [3]	T[4]	Hydrologic metric definition
Magnitude of flow events – *average flow conditions*					
Mean daily runoff	7	0.94	2	D	Mean daily flow divided by catchment area[5]
Median daily runoff	7	0.84	2	D	Median daily flow divided by catchment area
CV daily flow	1	0.90	7	D	Coefficient of variation in daily flows
Skewness in daily flow	1	0.77	7	D	Skewness in daily flows (g_1 - Sokal and Rohlf 1995)
Mean January flows	5	0.70	1	M	Mean daily flow for each month averaged across years
Mean February flows	5	0.83			
Mean March flows	5	0.82			
Mean April flows	12	0.65			
Mean May flows	12	0.63			
Mean June flows	5	-0.60			
Mean July flows	5	-0.83			
Mean August flows	5	-0.83			
Mean September flows	5	-0.85			
Mean October flows	5	-0.74			
Mean November flows	5	-0.46			
Mean December flows	13	0.51			
CV January flows	3	0.62	7	M	Coefficient of variation in mean daily flows per month
CV February flows	3	0.57			
CV March flows	3	0.64			
CV April flows	3	0.69			
CV May flows	3	0.69			
CV June flows	3	0.59			
CV July flows	3	0.54			
CV August flows	3	0.51			
CV September flows	3	0.59			
CV October flows	3	0.61			
CV November flows	3	0.62			
CV December flows	3	0.60			
Mean annual runoff	7	0.94	3	A	Mean annual flow divided by catchment area
CV annual runoff	1	0.64	7	A	Coefficient of variation in annual flows
Skewness in annual runoff	1	0.42	7	A	Skewness in annual flows (g_1 - Sokal and Rohlf 1995)
Median annual runoff	7	0.91	3	A	Median annual flow divided by catchment area
Magnitude of flow events – *low flow conditions*					
Median of annual minimum flows	2	0.94	7	A	Median of the lowest annual daily flow divided by the MADF averaged across all years
Baseflow index	2	0.60	7	A	Ratio of base flow to total flow, averaged across all years, where baseflow is calculated using 3-way digital filter (Grayson *et al.* 1996)
CV Baseflow Index	1	0.73	7	A	Coefficient of variation in Baseflow index
Low flow discharge (75th %’ile)	2	0.88	1	A	75th, 90th and 99th percentiles, respectively, from the flow duration curve
Low flow discharge (90th %’ile)	2	0.92			
Low flow discharge (99th %’ile)	2	0.89			
Specific mean annual minimum flows	7	0.72	2	A	Mean annual minimum flow divided by catchment area
Magnitude of flow events – *high flow conditions*					
Median of annual maximum flows	1	0.63	7	A	Median of the highest annual daily flow divided by MADF averaged across all years
High flow discharge (1st %’ile)	2	-0.46	1	A	1st, 10th and 25th percentiles, respectively, from the flow duration curve
High flow discharge (10th %’ile)	1	-0.81			
High flow discharge (25th %’ile)	1	-0.61			
Specific mean annual maximum runoff	7	0.78	2	A	Mean annual maximum flow divided by catchment area
High flow volume (>1xMDF)	1	0.77	4	A	Mean of the high flow volume (calculated as the area between the hydrograph and the upper threshold defined as 1, 3 and 7 times MDF, respectively) divided by MDF
High flow volume (>3xMDF)	1	0.87			
High flow volume (>7xMDF)	1	0.91			
Magnitude 1-year ARI	6	0.55	1	A	Magnitude of flood events with Average Recurrence Intervals of 1, 2 and 5 years, respectively (partial series). Flood independence criteria = 7 days.
Magnitude 2-year ARI	1	0.81			
Magnitude 5-year ARI	1	0.92			
Magnitude 10-year ARI	1	0.94	1	A	Magnitude of flood events with Average Recurrence Intervals of 10, 15 and 20 years, respectively (annual series). Flood independence criteria = 7 days between peaks.
Magnitude 15-year ARI	1	0.93			
Magnitude 20-year ARI	1	0.91			
Skewness in maximum annual flows	9	0.78	7	D	Skewness in maximum annual flows (g_1 - Sokal and Rohlf 1995)

Hydrologic metric	PC[1]	PCA loading[2]	U[3]	T[4]	Hydrologic metric definition
Frequency of flow events – *low flow conditions*[6]					
Low flow spell count (<75th %'ile)	4	-0.51	5	A	Mean number of annual occurrences during which the magnitude of flow remains below a lower threshold defined by the 75th, 90th and 99th percentiles, respectively (from the flow duration curve).
Low flow spell count (<90th %'ile)	3	0.76			
Low flow spell count (<99th %'ile)	3	0.77			
CV low flow spell count (<75th %'ile)	10	0.38	7	A	Coefficient of variation in number of annual occurrences during which the magnitude of flow remains below a lower threshold (75th, 90th and 99th percentiles, respectively)
CV low flow spell count (<90th %'ile)	3	-0.51			
CV low flow spell count (<99th %'ile)	3	-0.47			
Frequency of flow events – *high flow conditions*[6]					
High flow spell count (>25th %'ile)	4	-0.52	5	A	Mean number of annual occurrences during which the magnitude of flow remains above a higher threshold defined by the 25th, 10th and 1st percentiles, respectively (from the flow duration curve)
High flow spell count (>10th %'ile)	6	0.69			
High flow spell count (>1st %ile)	6	0.88			
CV high flow spell count (>25th %'ile)	10	0.79	7	A	Coefficient of variation in number of annual occurrences during which the magnitude of flow remains above a higher threshold (25th, 10th and 1st percentiles, respectively)
CV high flow spell count (>10th %'ile)	14	-0.47			
CV high flow spell count (>1st %'ile)	6	-0.75			
High flow spell count (>3xMDF)	6	0.72	5	A	Mean number of annual occurrences during which the magnitude of flow remains above a higher threshold defined as 3 and 7 times MDF, respectively
High flow spell count (>7xMDF)	6	0.73			
Duration of flow events – *low flow conditions*[6]					
Annual minima of 1-day means	2	0.94	1	D, M, S	Magnitude of minimum annual flows of various duration, ranging from daily to seasonal (i.e. 1, 3, 7, 30 and 90 days, respectively)
Annual minima of 3-day means	2	0.94			
Annual minima of 7-day means	2	0.94			
Annual minima of 30-day means	2	0.93			
Annual minima of 90-day means	2	0.87			
CV annual minima of 1-day means	8	0.89	7	D, M, S	Coefficient of variation in magnitude of minimum annual flow of various duration, ranging from daily to seasonal (i.e. 1, 3, 7, 30 and 90 days, respectively)
CV annual minima of 3-day means	8	0.91			
CV annual minima of 7-day means	8	0.91			
CV annual minima of 30-day means	8	0.72			
CV annual minima of 90-day means	3	0.37			
Low flow spell duration (<75th %'ile)	4	0.82	4	A	Mean duration of flows which remain below a lower threshold defined by the 75th, 90th and 99th percentiles, respectively (from the flow duration curve)
Low flow spell duration (<90th %'ile)	4	0.81			
Low flow spell duration (<99th %'ile)	4	0.80			
CV low flow spell duration (<75th %'ile)	11	0.80	7	A	Coefficient of variation in duration of annual occurrences during which the magnitude of flow remains below a lower threshold (75th, 90th and 99th percentiles, respectively)
CV low flow spell duration (<90th %'ile)	11	0.82			
CV low flow spell duration (<99th %'ile)	11	0.72			
Number of zero-flow days	4	0.64	5	A	Mean annual number of days having zero flow
CV number of zero-flow days	4	-0.42	7	A	Coefficient of variation in annual number of days having zero flow
Duration of flow events – *high flow conditions*[6]					
Annual maxima of 1-day means	1	0.92	1	D, M, S	Magnitude of maximum annual flows of various duration, ranging from daily to seasonal (i.e. 1, 3, 7, 30 and 90 days, respectively)
Annual maxima of 3-day means	1	0.90			
Annual maxima of 7-day means	1	0.83			
Annual maxima of 30-day means	1	0.64			
Annual maxima of 90-day means	2	-0.56			
CV annual maxima of 1-day means	9	0.64	7	D, M, S	Coefficient of variation in magnitude of maximum annual flows of various duration, ranging from daily to seasonal (i.e. 1, 3, 7, 30 and 90 days, respectively)
CV annual maxima of 3-day means	1	0.66			
CV annual maxima of 7-day means	1	0.68			
CV annual maxima of 30-day means	1	0.67			
CV annual maxima of 90-day means	1	0.64			
High flow spell duration (>25th %'ile)	10	-0.57	4	A	Mean duration of flows which remain above a higher threshold. Defined by the 25th, 10th and 1st percentiles, respectively (from the flow duration curve)
High flow spell duration (>10th %'ile)	14	0.77			
High flow spell duration (>1st %'ile)	6	-0.80			
CV high flow spell duration (>25th %'ile)	10	0.79	7	A	Coefficient of variation in duration of annual occurrences during which the magnitude of flow remains above a higher threshold (25th, 10th and 1st percentiles, respectively)
CV high flow spell duration (>10th %'ile)	15	0.60			
CV high flow spell duration (>1st %'ile)	6	-0.57			
Timing of flow events – *average flow conditions*[7]					
Predictability (P) of mean daily flow	4	0.76	7	D	Colwell's (1974) predictability (P) of mean daily flow
Constancy (C) of mean daily flow	4	0.70	7	D	Colwell's (1974) constancy (C) of mean daily flow
Seasonality (M/P) of mean daily flow	1	-0.49	7	D	Colwell's (1974) seasonality (M/P) of mean daily flow
Perenniality of monthly flows	2	0.54	7	A	Percentage contribution to mean annual discharge by mean monthly flow in the six driest months of the year
Timing of flow events – *low flow conditions*[7]					
Julian date of annual minimum	5	0.54	7	D	The mean Julian date of the 1-day annual minimum flow over all years
CV Julian date of annual minimum	16	0.75	7	D	Coefficient of variation in Julian date of the 1-day annual minimum flow over all years

Hydrologic metric	PC[1]	PCA loading[2]	U[3]	T[4]	Hydrologic metric definition
Predictability (P) of minimum daily flow	4	0.79	7	D	Colwell's (1974) predictability (P) of minimum daily flow
Seasonality (M/P) of minimum daily flow	4	-0.51	7	D	Colwell's (1974) seasonality (M/P) of minimum daily flow
Timing of flow events – *high flow conditions*[7]					
Julian date of annual maximum	5	-0.81	7	D	The mean Julian date of the 1-day annual maximum flow over all years
CV Julian date of annual maximum flow	16	0.59	7	D	Coefficient of variation in the Julian date of the 1-day annual maximum flow
Predictability (P) of maximum daily flow	4	0.63	7	D	Colwell's (1974) predictability (P) of maximum daily flow
Seasonality (M/P) of maximum daily flow	1	-0.64	7	D	Colwell's (1974) seasonality (M/P) of maximum daily flow
Rate of change in flow events – *average flow conditions*					
Rise rate	1	0.62	6	D	Mean rate of positive changes in flow from one day to the next
CV rise rate	1	0.65	7	D	Coefficient of variation in rate of positive changes
Fall rate	1	0.55	6	D	Mean rate of negative changes in flow from one day to the next
CV fall rate	1	0.72	7	D	Coefficient of variation in rate of negative changes
Number of reversals	4	-0.51	5	D	Number of negative and positive changes in flow from one day to the next
CV reversals	1	0.60	7	D	Coefficient of variation in number of negative and positive changes

[1] PC refers to the individual principal component with highest absolute loading for each hydrologic metric. The percentage of total variance explained by each of the first 16 PC's was 34.3, 9.1, 8.5, 7.2, 6.0, 3.0, 2.7, 2.6, 1.7, 1.6, 1.3, 1.2, 1.2, 1.1, 1.0 and 0.9, respectively.

[2] PCA loading refers to the actual loading score of each metric on the principal component.

[3] U refers to the units of the metric: 1, ML day^{-1}; 2, ML day^{-1} Km^{2}; 3, ML year^{-1} Km^{2}; 4, days; 5, year^{-1}; 6, ML day^{-1} day^{-1}; 7, dimensionless. Note that all magnitude metrics expressed in ML day^{-1} were standardised by dividing by mean daily flow prior to analyses.

[4] T refers to the temporal aspect of the hydrograph that the hydrologic metric represents: daily (D), monthly, (M), seasonal (S), or annual (A).

[5] Catchment area refers to the total area of the catchment (Km^{2}) upstream of each gauge.

[6] Independence criteria for low and high spell frequency and duration = 7 days between spells.

[7] Colwell's (1974) predictability (P) of flow is composed of two independent, additive components: constancy (C – a measure of temporal invariance) and contingency (M – a measure of periodicity). Colwell's measures were calculated using mean, minimum and maximum daily flows, respectively, in each month. We used 11 flow classes (log$_{2}$ class size) with a central class of 20xMDF.

Appendix 6

Spatial variation in the ecohydrological classification

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Summary

The aim of this report appendix is to examine the spatial distribution of flow regime types defined within the classification presented in Appendix 5. We assess:

- the extent to which different regions (defined in a number of ways) differ in the types and diversity of flow regimes present
- the effect of catchment area on flow regime richness and diversity
- the concordance between regional classifications of flow diversity and that described in the continental-scale classification
- whether the latter is capable of describing flow regime variation at smaller spatial scales.

The continental-scale classification developed in this project clearly defined differences in flow regime across Australia. These differences were most clearly evident between northern tropical/subtropical Australia and southern temperate Australia. Arid zone streams were more similar to tropical streams reflecting the influence of northern weather patterns on these streams. Temperate Australia contained more flow regime types than did tropical Australia, reflecting the generally greater complexity of weather patterns responsible for generating rainfall and hence stream runoff and greater topographic diversity in southern Australia Division II in temperate Australia and Division I in tropical Australia contained the greatest diversity of flow regime types. Some divisions were characterised by the preponderance of particular flow regions (i.e. Mediterranean signal in Division VI or extreme intermittency in Division VII). However, most flow regime types were recorded from a range of divisions within the broad climatic division discussed above. Care must be exercised when comparing different regions or divisions because of the non-random distribution of gauges across the landscape.

Catchment size had a significant effect on streamflow diversity. Small streams contained a diverse range of streamflow types. In comparison slightly higher diversity was observed in moderate to large streams. Very large streams contained a reduced array of flow regime classes. This effect was not due to issues associated with catchment size-related variation in the number of gauges (although this effect was nonetheless important) but probably more related to the fact that very large streams are, by virtue of their large size, restricted to areas of Australia receiving a low diversity of weather patterns and that certain flow regime signals characteristic of smaller streams are ameliorated progressively downstream as additional runoff is contributed by tributaries.

Small streams were notable for the high number of flow regime classes typified by high predictability or stable flows, contrary to what may be expected under the assumption that the combined flows of many small tributaries results in increased predictability and decreased variability. Again however, care must be exercised when comparing across streams of differing catchment size because the placement of gauges across the landscape is not random and primarily addresses the needs of hydrographers and hydrologists rather than ecologists interested in defining ecohydrological variation.

Comparison of the results of the present classification and previously published regional classifications revealed a range of levels of concordance. For example, the classification developed for Tasmania (Hughes 1987) was broadly concordant with the present classification (although we recognised a greater diversity of regime types) probably because spatial variation in rainfall and its influence on streamflow is sufficiently substantial to be identified by both schemes. The classification developed by Hughes and James (1989) for Victoria was, in contrast, poorly supported by the present classification. Greater diversity was described and more spatially significant classing of streams was observed in the present study. The general lack of concordance between the present classification and previous regional classifications may be a result of the scale of investigation but is probably related more to issues associated with the number and nature of metrics used to characterise the flow regime and greater rigour in addressing the methodological requirements of such exercises outlined in Appendix 2.

Examination of flow regime diversity at smaller spatial scales revealed that whilst the present classification performed well at large scales, it was perhaps unable to fully characterise flow diversity present at the scale of individual river basins or small well-defined regions such as south-eastern Queensland or the Wet Tropics region. This is perhaps not surprising given the differences in spatial scale involved. The present classification was concerned with characterising flow diversity at a very large scale and accordingly when applied at smaller scales, all variation present must be assessed against the range of variation detected at the largest scale. It is here suggested that when and if examination of spatial variation at these smaller scales is desired, then a three-step process is required. First, spatial variation is assessed using the flow regime classes derived from the continental classification, thus allowing spatial variation flow regime to be placed in a larger context. Second, the full set of metrics, which will eventually become available online but is currently available on application from the senior author, is reclassified using only those locations restricted to the area of concern to produce a classification relevant to the area of concern. Third, the resultant outputs should then be combined.

6.1 Introduction, aims and scope

Appendix 5 described data preparation, initial exploratory analyses, classification method and the outcomes of the classification and its relationship to landscape and climatic variables. The various classification class were described and a summary description of the geographic spread of the derived flow classes across the Australian landscape was presented. The overarching aim of this appendix is to explore in more detail, the spatial arrangement of flow classes across the landscape at a variety of spatial scales. First, we describe the spatial arrangement of the derived flow classes at the continental-scale by reference to the existing drainage divisions. Second, we explore the influence of catchment size on flow regime diversity to assess how much flow regime varies between streams of differing size and to determine whether variation due to differences in catchment size is sufficiently large to obfuscate any variation that might exist at larger scales. Third, we examine how closely the classification derived in the present study conforms to, extends or improves upon existing flow classification schemes developed in Australia (see Appendix 2 for full description of these schemes). Finally, we examine flow regimes within selected regions (e.g. drainage divisions and discrete geographical areas such as the Wet Tropics region) or rivers to assess the extent of diversity that may be found at this scale and to assess whether the classification scheme developed here for continental Australia is able to fully describe spatial variation in flow regime at this finer scale.

6.2 Distribution of gauging stations across Australia and influence on spatial variation in diversity of flow regimes

The distribution of streamflow gauging stations across the Australian continent is non-uniform and there is consequently great spatial variation in the number and density of gauges (Figure 6.1). For example, the great majority of gauging stations used in the present study (i.e. conforming to our criteria for inclusion with respect to record length, absence of significant human modifications to flow regimes, and data quality) are located in the eastern portion of the continent (Divisions I and II). Some areas such as central coastal Western Australia (Division VII and the northern portion of Division VI) are very sparsely gauged. Similarly, the western portion of the Gulf of Carpentaria (Division IX), the Lake Eyre basin (Division X) and the Bulloo-Bancannia basin (Division XI) are almost without a gauge network or have poor quality streamflow records (e.g. short records or containing large numbers of missing data). Gauge density (# of gauges km^2) consequently varies greatly between drainage divisions. Highest density is found in Divisions II, III and I (in decreasing order) and least in divisions VII, XI and X (in decreasing order). It is worth noting that although many stream gauges within Division IV (Murray-Darling Basin) did not comply with our criteria for inclusion within the classification analysis (i.e. because of extensive flow modification), this division contained a significant number of gauges, albeit of a distribution limited mostly to the eastern tributary systems of this drainage.

The consequences of this non-uniform distribution of gauges relate primarily to the issue of describing and quantifying flow regime diversity between divisions. In essence, this is analogous to the well-known sampling phenomena in ecological studies wherein species richness is related to study area, or the number of samples or individuals examined. As a result, the diversity of flow regime classes within a region may be more related to the size of a region or number of gauges examined within a region than it is to any intrinsic flow regime diversity within that region. We examined this possibility by correlation analysis to determine whether flow regime diversity (number of low classes per division and Shannon Weaver H') varied according to number of gauges, drainage division area or gauge density (Figure 6.2).

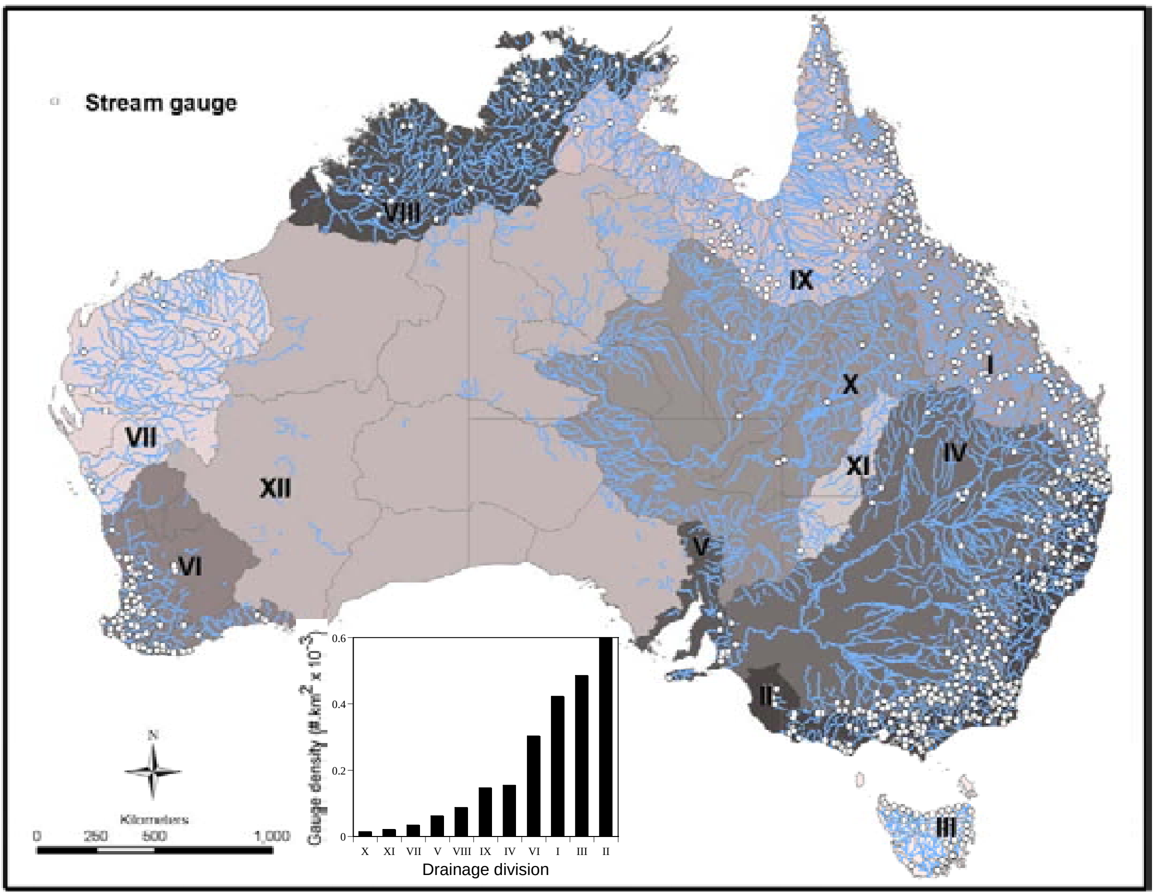

Figure 6.1. Number of gauges (both high and medium quality) within each drainage division and the gauge density within each division (inset).

The number of flow classes within a division was significantly correlated with both the number and density of gauges in each division (Figure 6.2a and d). The number of flow classes present within a drainage division was not significantly correlated with the division area (Figure 6.2c). Similarly, flow diversity (proportional contribution by different classes) increased significantly with increasing gauge number in a linear fashion but also appeared to plateau at about 100 gauges per division (Figure 6.2b). This suggests that between-division differences in flow diversity (both number and H') may be a function of intensity of investigation (i.e. regions with many gauges have a high diversity of flow conditions irrespective of size) and raises the possibility that at least five of the 11 drainage divisions were under-sampled (i.e. too few gauges were available to adequately quantify the number of flow classes present). This finding also suggests, among other things, that future investment in the nation's streamflow network infrastructure might profitably be allocated to increasing gauge density in some divisions more than others. However, it is likely that more, yet undetected, flow classes would be represented by only a few stations given the asymptotic increase in diversity evident in Figure 6.2b.

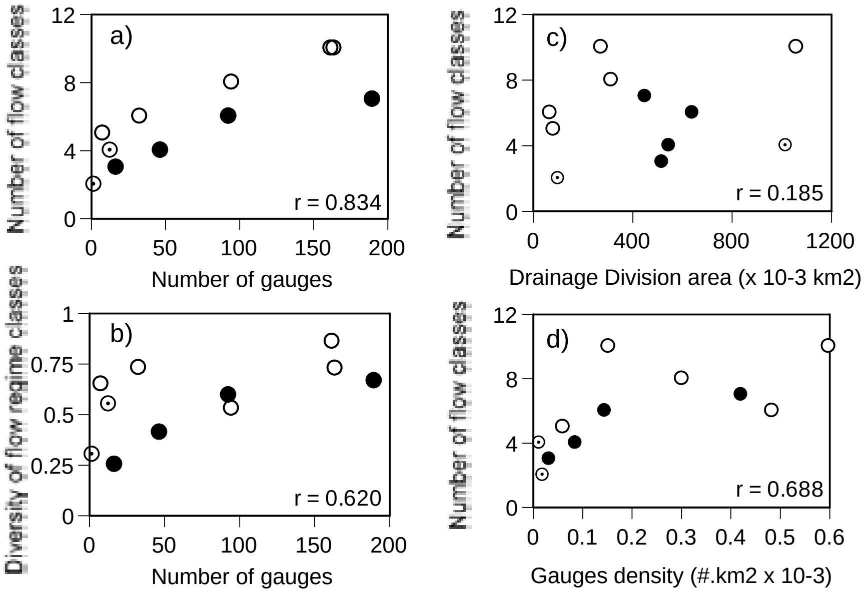

Figure 6.2. The influence of gauge number, drainage division area and gauge area on flow regime richness and diversity (H'). ○= temperate Australian drainage divisions (II, III, IV, V & VI); ⦿ = arid zone divisions (X & XI); and ● = tropical drainage divisions (I, VII, VIII and IX).

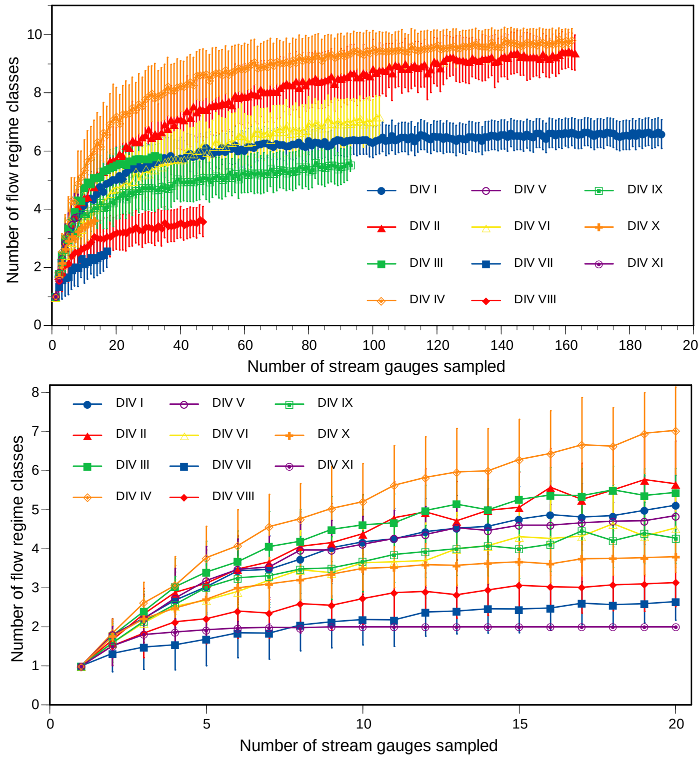

Figure 6.3. The influence of sample number (gauges per division) on estimation of flow regime diversity (a). Shown are the mean (SE) of the number of flow classes detected for increasing sample intensity. Increasing diversity with increasing sample intensity up to 20 samples is also shown (b)

We further investigated the influence of sample number (gauge number) on the estimation of flow regime diversity within drainages by a randomised sampling procedure (sequentially adding more gauges). Clearly, sample number does influence the ability to quantify flow regime diversity within drainage divisions (Figure 6.3a) as diversity (number) increases with increasing number of gauges. In some divisions (e.g. II, IV and VI) an asymptotic value is not reached until after 100 gauges. Note that these divisions are all located in the southern temperate part of the continent. It should also be noted that the number of gauges examined for these divisions exceeds this number, so although there may have been a slight increase in flow diversity if more gauges had been examined, this increase would have been minor. When the randomisation was limited to a mean number of 20 (much less than available for all but the most arid drainage divisions) (Figure 6.3b), it is evident that spatial variation (between division) in flow regime diversity exists but importantly, the rank order of variation is consistent with the rank order of diversity observed without consideration of sample intensity (Figure 6.4). In addition, it is likely that the concentration of gauges in some divisions is by design, reflecting the necessity of placing more gauges across a landscape that is, in itself, topographically, climatically and geologically diverse. If this were the case, as is most likely, and given that the number of gauges examined was proved adequate by the randomisation analysis, then drainage divisions may be confidently compared.

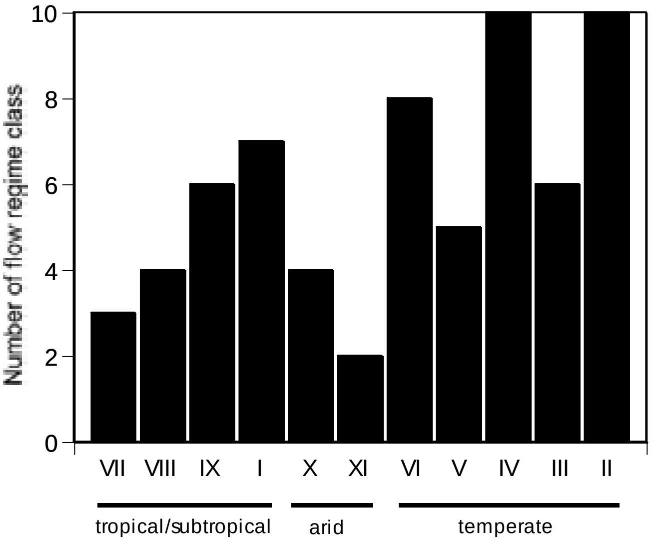

Figure 6.4. Number of flow regime classes within each drainage division classed according to prevailing climate (tropical/subtropical, arid and temperate).

Comparison of flow regime diversity within drainage divisions classed according to prevailing climate (Figure 6.4) does not initially suggest great differences between climatic regions although differences between drainage divisions are apparent. However, when comparisons also include reference to the number of gauges or their density within each division (Figure 6.2a and d, Figure 6.3), it is clear that temperate drainage divisions contain more flow regime classes than do tropical divisions. Two, not mutually exclusive, causes may be postulated. First, northern regions are widely influenced by large scale weather systems such as the southern wet-season migration of the equatorial monsoon and the persistent (throughout summer) development and presence of a heat lows over the Pilbara and Kimberley regions in the west and the southern Gulf region in the east. Southern regions, in contrast, experience wet season weather resulting from the complex and temporally variable interaction of westerly winds, subtropical anticyclones and depressions formed over the Southern Ocean (Sturman and Tapper 2001). Second, southern Australia, especially south-eastern Australia, is much more topographically diverse than northern Australia and the

Great Dividing Range reaches its maximum height in the south also (Twidale and Cambell 1993). Interaction between landscape diversity and complex wet-season weather patterns may produce the greater diversity of flow regimes observed in southern Australia. It is noteworthy that the most topographically and climatically diverse of the tropical regions (Division I) contains the most flow regime classes. Note also that this division spans approximately 15° of latitude and may potentially be influenced by both temperate and tropical weather systems.

6.3 Broad-scale distribution of flow regime classes – within and between drainage divisions

5.3.1 Division I (North-east Coast)

Division I (North-east Coast) contained a total of seven flow regime classes (Figure 6.5) and was dominated by flow classes 11 (*unpredictable summer highly intermittent*), 7 (*unpredictable intermittent*) and 3 (*stable summer high baseflow*). Representatives of flow regime classes 5 (*predictable summer highly intermittent*), 4 (*unpredictable high baseflow*), 12 (*extreme harsh summer intermittent*) and 1 (*stable high baseflow*) also occurred in small numbers in this division. Flow classes 11 and 7 were typically restricted to south of 19°S whereas flow class 3 occurred north of this point (Figure 6.6). Further discussion of finer scale variation in this division is presented below.

5.3.2 Division II (South-east Coast)

Division II (South-east Coast) contained 10 different flow classes and was dominated by flow classes 7 (*unpredictable intermittent*) and 4 (*unpredictable high baseflow*), with fair representation by classes 2 (*stable winter high baseflow*) and 5 (*unpredictable winter rarely intermittent*) and minor representation by flow classes 11, 12, 6 (*predictable winter intermittent*), 8 (*unpredictable winter intermittent*), 9 (*predictable winter highly intermittent*) and 1 (Figure 6.5). Class 7 streams exhibited a non-continuous clumped distribution with one class centred in northern coastal New South Wales (essentially continuous with the distribution of this flow type in south-eastern Queensland and further illustrating the artificiality of the borders of the North-east Coast and South-east Coast drainage divisions), another class centred around the Hunter Valley region and a southern set on the NSW/Victoria border (i.e. the Bega region). Class 4 streams were located in coastal NSW and eastern coastal Victoria (Figure 6.6). Extensive river regulation in that part of Division II bounded by Newcastle in the north and Bega in the south (and accordingly subsequent exclusion from the classification analysis of streams in this area) resulted in few classifiable streams within this area. In all likelihood, this uncharacterised area would have contained streams predominantly within classes 4 and 7. The Victorian and south-eastern South Australian section of drainage division II contained a high diversity of flow regime classes (2, 4, 5, 6, 8, 9 and 11). Further discussion of the spatial arrangement of flow regime classes in Victoria is included below (section 6.7.2).

5.3.3 Division III (Tasmania)

Six flow regime classes (1, 2, 4, 5, 7 and 8) occurred in Tasmania with class 1 being the most frequently observed regime. This regime type occurred in all but three of the drainage divisions but nowhere was it as important as in Tasmania. An expanded discussion of the spatial distribution of flow regime types is given below.

5.3.4 Division IV (Murray-Darling)

No gauges on the main stem of the major branches of the Murray-Darling River system (i.e. Murray, Darling, Murrumbidgee, Macquarie rivers) were included in the classification due to pervasive flow regime modification in these catchments. Gauged streams were limited to tributary systems. Nonetheless, the average catchment size of these streams was still large (mean = 2,648 ± 672 (SE) km^2) and the range in size (26–79,037 km^2) suggests that a substantial diversity of streams were assessed. A total of 10 different flow regime classes were detected in this drainage with classes 2 and 5 being the most abundant, followed by classes 7 and 8. Class 2 streams typically drained the western flanks of the Great Dividing Range in north-eastern Victoria and south-eastern NSW. Class 5 streams were distributed throughout the eastern periphery of the drainage whereas class 7 streams were predominantly located in the eastern periphery of the northern part of the drainage. Classes 2, 9 and 11 were located in the northern and north-western portions of the basin and in the case of class 9, on the lower reaches of tributaries draining the western flanks of the GDR.

5.3.5 Division V (South Australian Gulf)

A total of five flow regime classes (4, 5, 6, 8 and 9) from only eight gauges were detected in this small area. Classes 5 and 9 were the most common but given the small number of gauges little more can be said of them.

5.3.6 Division VI (South-west Coast)

A total of eight different flow regime types were recorded from south-western Australia. No other temperate drainage division was dominated by so few flow classes as this division, with flow regime classes 6 and 9 comprising more than 80% of the total of 102 gauges. Flow regime class 6 (*predictable winter intermittent*) tended to be located in a dense coastal band, inland of which occurred class 9 streams (*predictable winter highly intermittent*), reflecting the typical wet season delivery of rainfall associated with westerly frontal systems which do not penetrate very far inland. Streams on the periphery of this division were of class 12 reflecting the rapid transition away from the coast to xeric conditions.

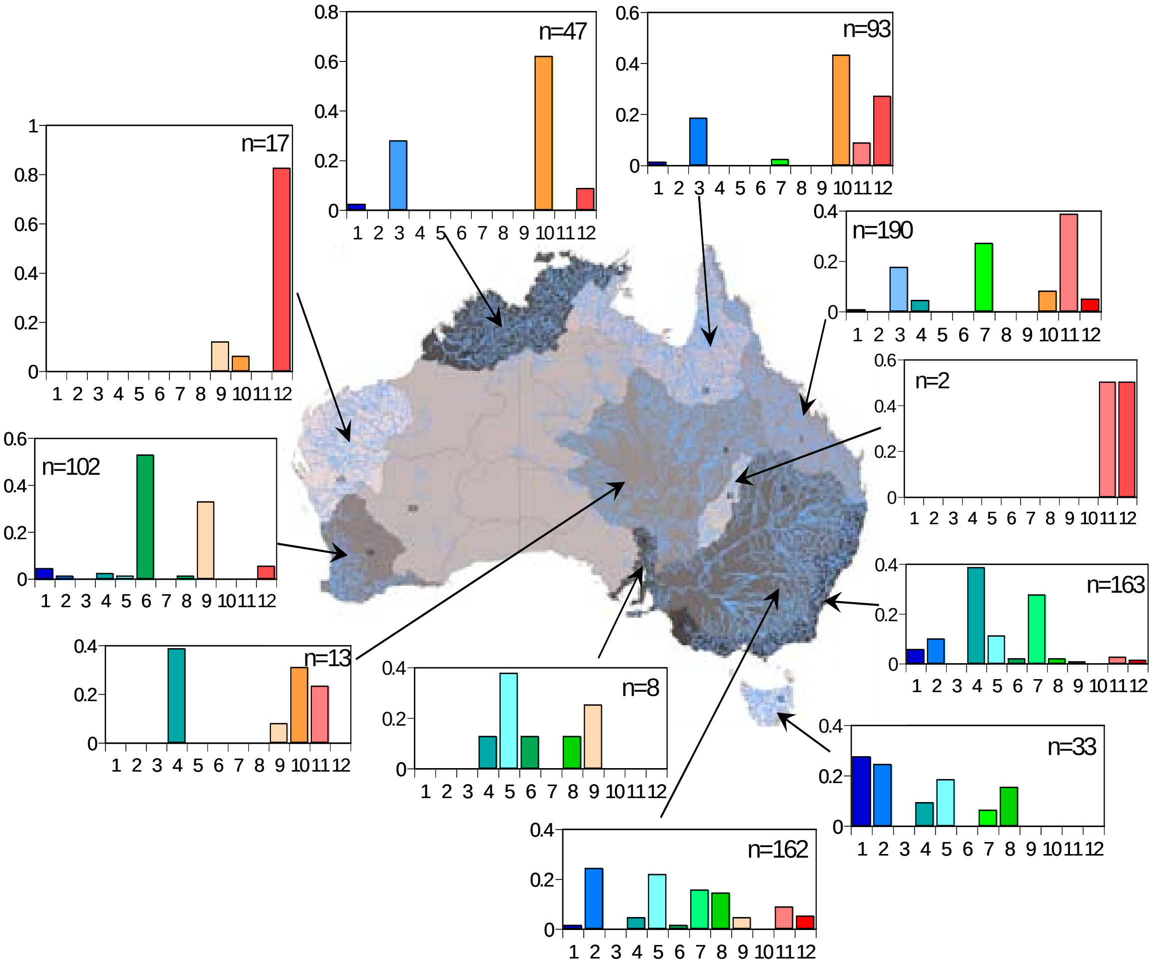

Figure 6.5. Diversity of flow regime classes (proportion of total number of gauges contributed by each flow class) within each of the Australian drainage divisions

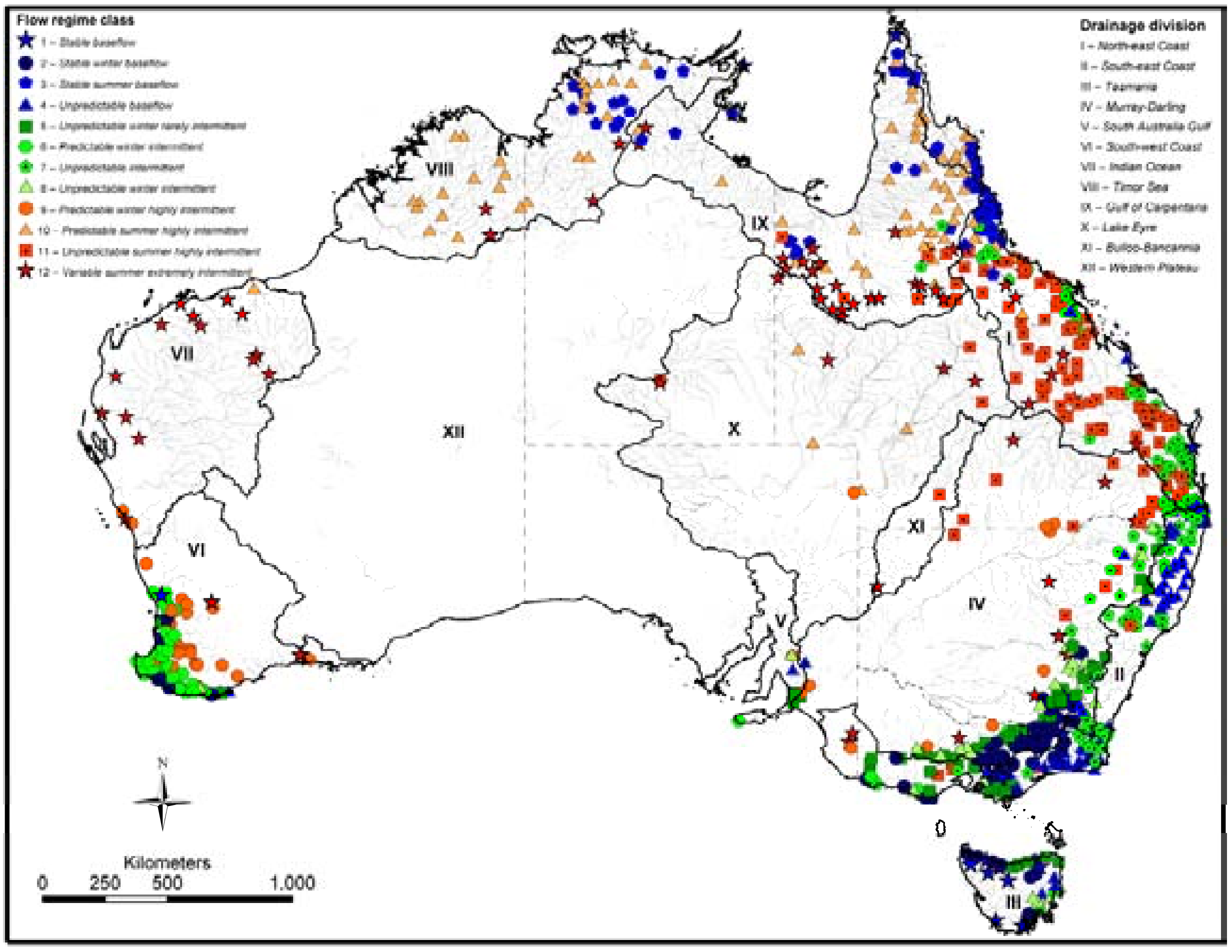

Figure 6.6 Spatial distribution of flow regime classes across the Australian continent.

6.3.7 Division VII (Indian Ocean)

Only 17 gauges were available from this division for inclusion within the classification with all but three (two class 9 and one class 10) being within class 12 (*extreme harsh summer intermittent*). This division was the most unique of all divisions examined. The two class 9 streams occurred in the southern periphery of the region (Greenough River) and the class 10 stream occurred on the northern periphery (De Grey River).

6.3.8 Division VIII (Timor Sea)

Four flow regime classes (1, 3, 10 and 12) were recorded from this large division which encompasses the Kimberley region eastward to north-eastern Arnhem Land. This low diversity may perhaps reflect the relatively small number of gauges, however it is clear from Figure 6.3 that it is unlikely that many more regime types would have been encountered had more gauges been available for inclusion (i.e. an asymptotic value was almost reached). The dominant flow class present was class 10 (*predictable summer high intermittency*). Most streams of the Kimberley are of this type. This flow regime type also extended into the Northern Territory and it is probable that ungauged streams in the eastern portion of the division are of this type also. Class 12 streams, otherwise characteristic of the Pilbara region, also occur in this division but were limited to the southern periphery. Class 3 streams (*stable summer high baseflow*) also occur in this division but are mostly limited to the Daly River. The high baseflow contribution to flow in these streams is almost entirely due to high groundwater inputs during the dry season. A single class 1 stream (Yirrkala Creek) was recorded. This small creek (catchment area =15.7 km^2) is spring fed.

6.3.9 Division IX (Gulf of Carpentaria)

Six flow regime classes (1, 3, 7, 10, 11 and 12) occurred in this large division. Flow regime class 10 was the most commonly observed regime type as it was in Division VIII and parts of Cape York Peninsula within Division I. This flow regime type appears characteristic of wet/dry tropical rivers without significant groundwater inputs. The most extreme flow regime type observed (class 12) also occurred in the most southern periphery of the Gulf region. It is noteworthy that such streams also occurred in close proximity to their hydrological antithesis (i.e. class 3 streams in which perennial flow was a significant feature). For example, the Roper River in the Northern Territory is perennial yet its upper headwater tributaries are highly intermittent (class 12). In this case, significant groundwater springs maintain high flow in the main channel year round (as is also observed in the Daly River in Division VIII). Similarly, the Gregory River, and some tributary streams, is perennial due to high groundwater inputs during the dry season, despite most tributaries being of varying degrees of intermittency (i.e. classes 10, 11 and 12). Some streams in the upper Mitchell and Wenlock Rivers were perennial also but the underlying water sources included spring-derived groundwater, significant rainfall during the dry season and the maintenance of downstream delivery from high runoff areas in headwater streams. Further discussion of the flow regimes within the Mitchell River is included below. One stream (Jardine River, 2418 km^2) was classified as a class 1 stream. Although, the northern tip of Cape York Peninsula is the wettest part of northern Australia, dry and west season differences in rainfall are pronounced (Sturman and Tapper 1996); the perenniality identified here suggests significant groundwater derived inputs in this stream also. With the additional exception of Yirrkala Creek in Division VIII and Teewah Creek (55.7 km^2) in the extreme south-eastern corner of Division I, this flow class was much more typical of southern drainage divisions.

6.3.10 Drainage divisions X and XI (Lake Eyre Basin and Bulloo-Bancannia)

These poorly-gauged xeric regions were characterised by streamflow regimes of varying degrees of intermittency (classes 9, 10, 11 and 12).

6.4 Broad scale distribution of flow classes – are flow regime classes characteristic of particular areas?

Most of the flow regime classes characterised in this study are relatively widespread (Figure 6.7). Flow classes 6 and 9 (*predictable winter intermittent* and *predictable winter highly intermittent*, respectively), although detected in eastern Australia, were predominantly found in south-western Australia. Similarly, flow regime classes 5, 7 and 11 were most frequently encountered in eastern Australian drainage basins. Note that this class of classes, in contrast to classes 6 and 9, are collectively characterised by their unpredictable flow regimes. With the exception of these 5 classes, the remainder were longitudinally widespread. In contrast, clear latitudinal distinction between flow regime classes was observed. Classes 1, 2, 4, 5, 6, 8 and 9 were predominantly located in southern temperate Australia; classes 3 and 10 were largely located in tropical northern Australia; and classes 7, 11 and 12 were predominantly restricted to a central band encompassed by 20 to 30° S, roughly equating to the arid zone in the continent's west and centre.

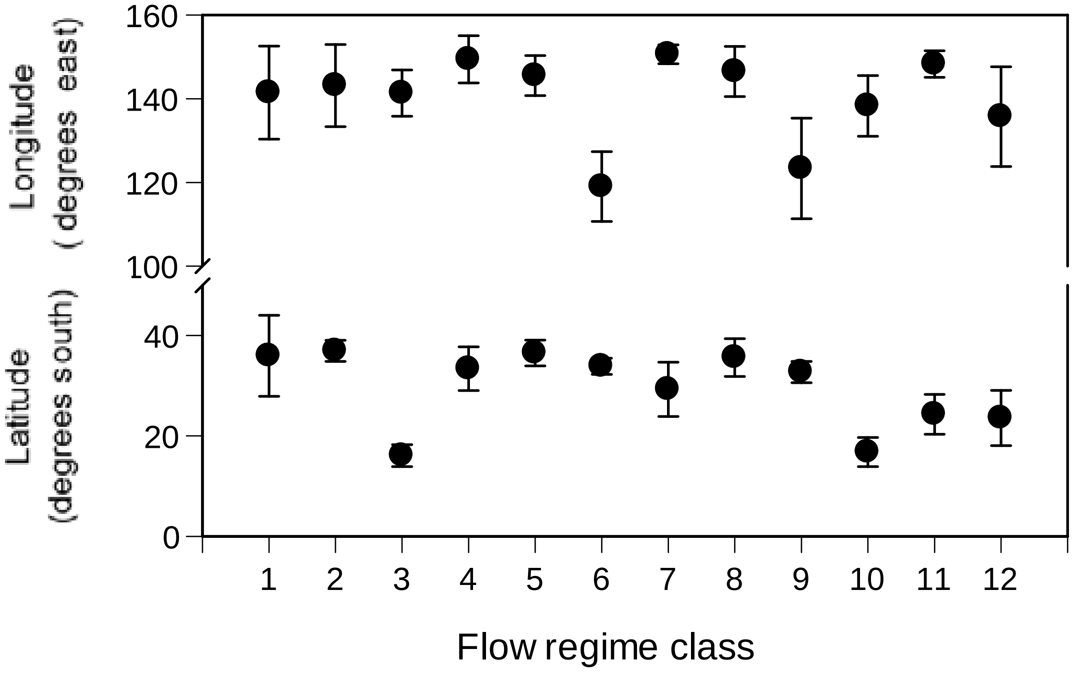

Figure 6.7. Mean (± S.E.) longitude (° E) and latitude (° S) of gauging stations within each flow regime class.

In answer to the question posed at the beginning of this section, with the exception of flow class 6 and to a lesser extent flow class 9, most flow classes were present in a number of different drainage divisions and were thus not characteristic of particular regions at the divisional scale. However, it is clear from the material above that there are large-scale regional differences that transcend drainage divisions. These differences are explored more below.

6.5 Broad scale distribution of flow regime classes – tropical/subtropical versus temperate

In addition to the general tendency for some flow regime classes to be characteristic of certain latitudes or longitudes, we investigated whether the proportional contribution of different flow regime classes within drainage divisions was sufficiently spatially structured to result in clear distinction between northern and southern Australia. Divisions were classed according to latitude and climate into the following regions: temperate (divisions II–VI); arid (divisions X and XI); and tropical/subtropical (divisions I, VII–IX). [Note – preliminary analyses investigated whether drainage division VII should be included with the arid zone divisions its inclusion as such did not alter the conclusions drawn from analyses in which it was classified as a tropical/subtropical division.] We estimated the Bray Curtis dissimilarity for sample by sample comparisons where the sample objects were drainage divisions and object attributes were the proportional contribution of each flow regime class. A dendrogram (UPGMA classing method) was constructed based on the similarity matrix and between-region comparisons undertaken using the ANOSIM routine available in Primer (5.2.2 for Windows).

Clear separation between divisions classed as subtropical/tropical or arid from those classed as temperate is evident in the classification dendrogram and from the results of the ANOSIM comparison (Figure 6.8). The ANOSIM results presented in Figure 6.7 are based on a comparison in which arid zone divisions (X and XI) were classed with tropical/subtropical divisions. Although significant Global R values (0.681 or 0.702) were detected when three class (subtropical/tropical, temperate and arid with the latter being defined as both with or without drainage division VII)) were included in the ANOSIM analysis, significance was based on differences between temperate and either tropical/tropical or arid regions but not between subtropical/tropical and arid regions indicating that most of the separation was between temperate and tropical regions and not within these regions.

These findings reinforce the previous analysis above in which flow regime classes were classed according to latitude or longitude. Strong geographical separation was observed corresponding to differences in the types of flow regimes occurring in temperate and tropical regions of the continent. Arid zone streams were included with streamflow types characteristic of subtropical/tropical divisions, suggesting that when these streams did flow it was due to inland penetration of northern monsoonal weather patterns more than inland penetration of temperate weather systems. Within the temperate drainage divisions, clear separation of the western divisions V and VI (South Australian Gulf and Southwest Coast, respectively) from the remaining eastern divisions was evident. Further discussion of the correspondence between flow regime types and climate or seasonality (e.g. application of the Haines seasonality classification by McMahon and Finlayson 2003) is presented in Appendix 5.

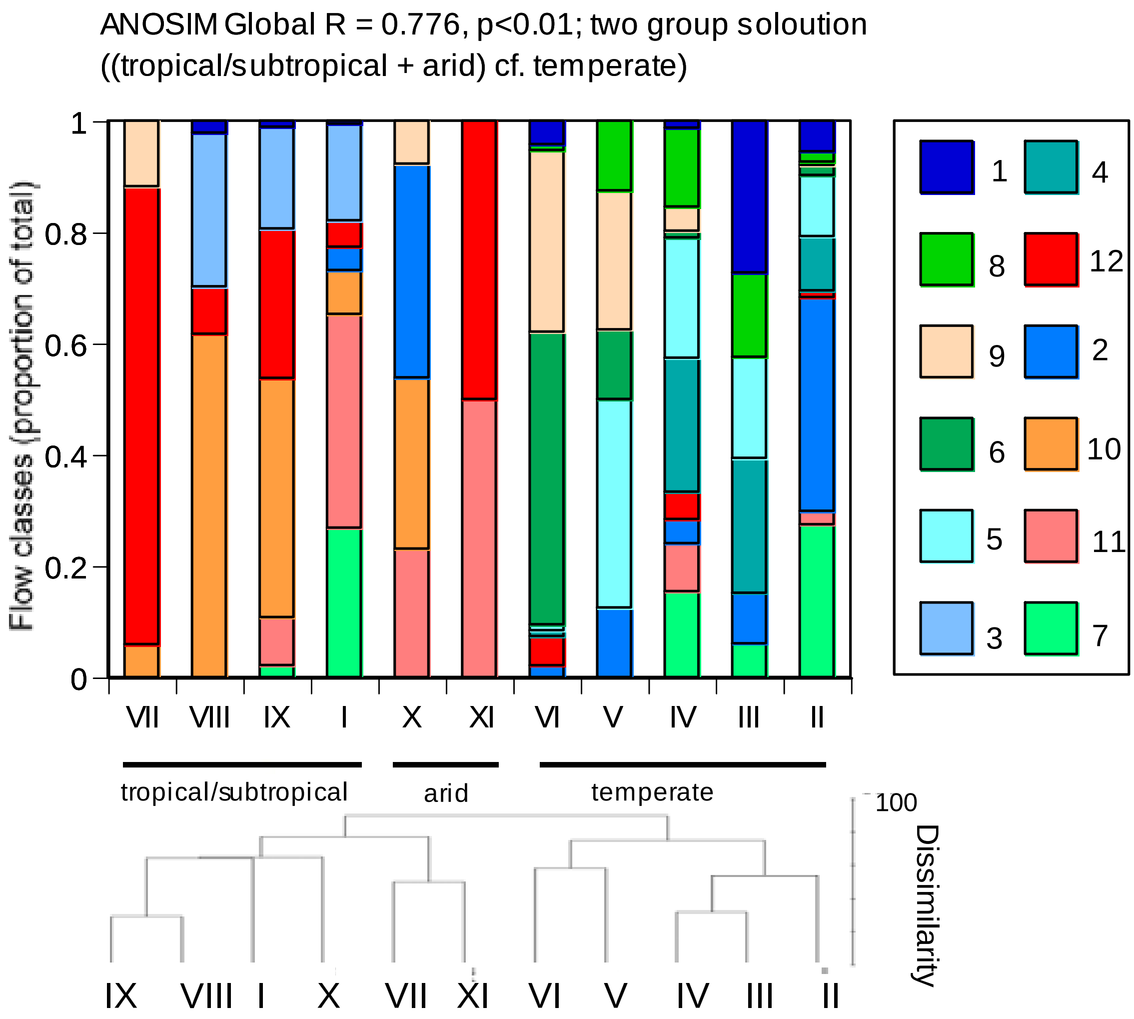

Figure 6.8. Proportional contribution of gauges defined by each flow regime class to the total number of gauges in each drainage division. Also shown are the results of UPGMA cluster analysis and ANOSIM testing for multivariate differences in flow regime diversity between temperate and tropical Australia.

6.6 Spatial variation in flow regime due to catchment size

As was noted for the distribution of gauges across the continental landscape (section 6.2), the distribution of catchment areas for the gauges used in the classification exercise was also not uniform (Figure 6.9). Almost half of the gauges examined were of medium size, between 100 and 1,000 km^2 in area. Similar numbers of gauges were examined in small (<100 km^2) or large (1,000–10,000 km^2) streams whereas few streams were examined that were in the very large (10,000–100,000 km^2) or extremely large (>100,000 km^2) categories. We compared the distributions of catchment size for each flow regime class by Chi-squared contingency test against the distribution for the entire data set to determine whether particular flow regime classes were dominated by either small or large streams or in proportions not expected from the initial sample population (i.e. total data set).

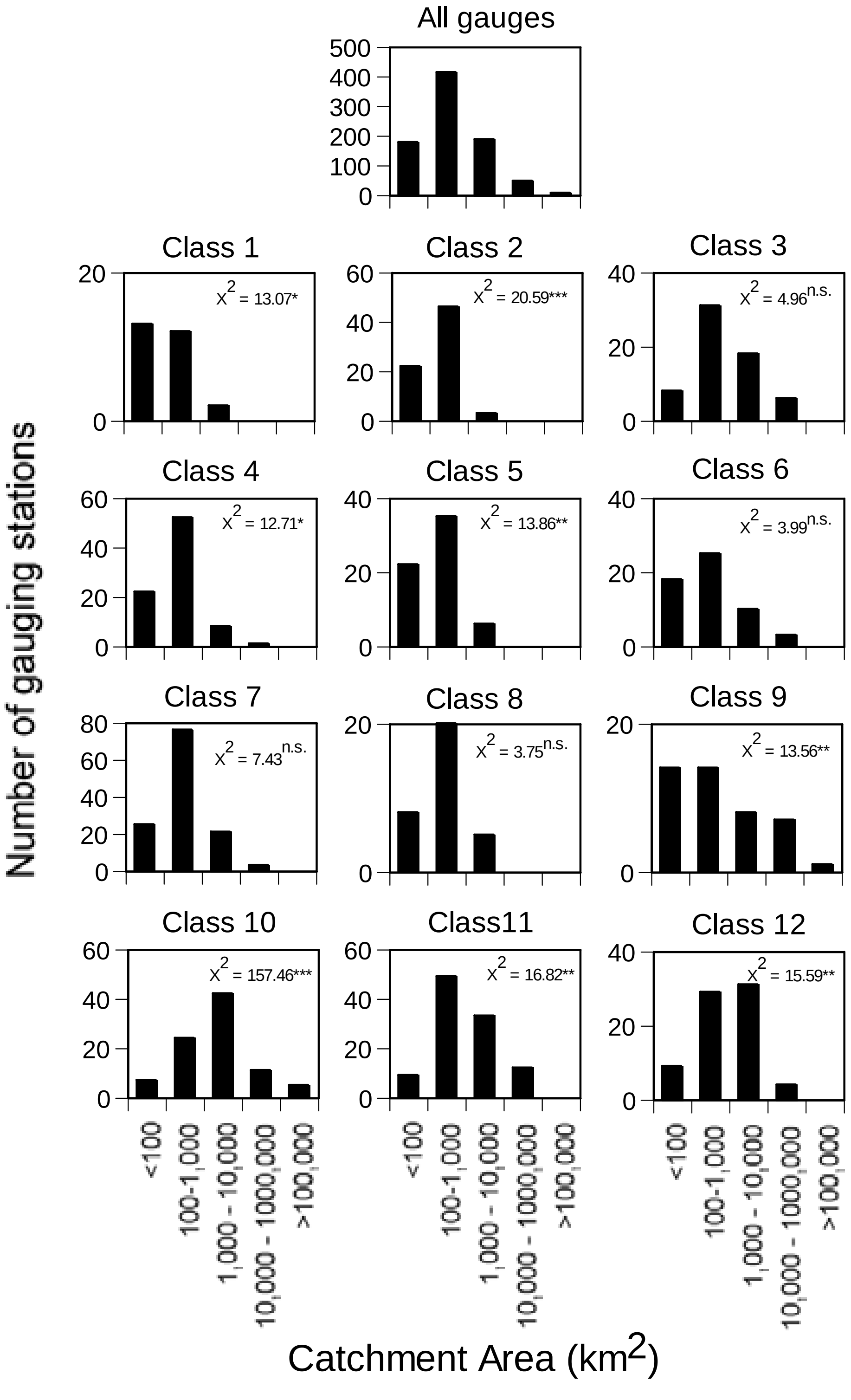

Figure 6.9. Frequency distribution of streams by catchment area for the entire data set and for each of the flow regime classes (1–12) derived from classification of flow metrics. Also shown in the value of Chi-squared comparisons of the distribution of catchment areas in each flow class with that of the total data set. n.s. = $p>0.05$, * = $p<0.05$, ** = $p<0.01$ and *** = $p<0.001$.

Streams characterised by flow regimes within classes 3, 6, 7 and 8 were of a similar size range as those of the entire data set suggesting that these flow regimes occurred across a range of streams types and in the frequency expected from random sampling of the initial range of gauges (Figure 6.9). Streams within flow regime classes 1 (*stable high baseflow*), 2 (*stable winter high baseflow*), 4 (*unpredictable high baseflow*) and 5 (*unpredictable winter rarely intermittent*) were significantly smaller than predicted, although collectively catchment area varied by three orders of magnitude (<100 to 100,000 km^2). That these classes of streams, skewed towards small size, should be collectively characterised by high baseflow or rare intermittency suggests that they are of high ecological value in the landscape, providing continued habitat throughout the year and refugia at times of low or no flow in adjacent streams. Moreover, this pattern is in contrast to the normal expectation that small headwater streams should be more prone to intermittency than downstream receiving reaches.

Streams characterised by flow regime classes 10 (*predictable summer high intermittency*) and 12 (*extreme harsh summer intermittent*) were significantly skewed towards larger catchment areas whereas streams of flow regime class 9 (*predictable winter high intermittency*) were over represented by both small and very large streams. That such large streams tend to experience prolonged and presumably widespread cessation of flow suggests that the biota within these streams must either move substantial distances to access dry season refugia or be well adapted to survive in small proximal refugia for long periods. Moreover, the existence of such refugial pools in these streams is likely to have great ecological significance.

We further examined the influence of stream size on flow regime type separately for tropical and temperate Australia (Figure 6.10). In the tropical/subtropical comparison, flow regime diversity changes little across the range of size classes available. Seven flow classes were present in the smallest streams whereas six flow regime classes were present in streams with catchment areas >100 km^2. Given that the additional flow class (1) in the smallest streams was represented by only three streams, this additional diversity was inconsequential. The proportional representation by class 10 (*predictable summer intermittent*) decreased slightly with catchment area whereas the proportional representation by flow class 12 (*unpredictable intermittent*) increased slightly. However, these flow regime classes were not uniformly distributed across the tropical region, being more common in drainage divisions VIII and I, respectively (Figure 6.8), and the relatively small size-related changes evident in Figure 6.9 are more likely due to differences in the size range of streams between divisions than any real change due to catchment size. For example, flow regime class 11 remains important in the largest stream size category in Division 1 (the only tropical division in which it was common) (Figure 6.9) yet these streams make up only 21% of the largest stream size class for the entire tropical region. Thus, effects of stream size on the diversity of flow regime types in the tropics are relatively minor. This was also observed in Division I (North-east Coast) where flow regime diversity did not change greatly with catchment size until streams exceeded 10,000 km^2 in size, where after only three flow classes were present. It must be pointed out however, that few streams of this size were available for inclusion and the lower flow diversity may simply reflect the effect of sampling intensity for streams of this size.

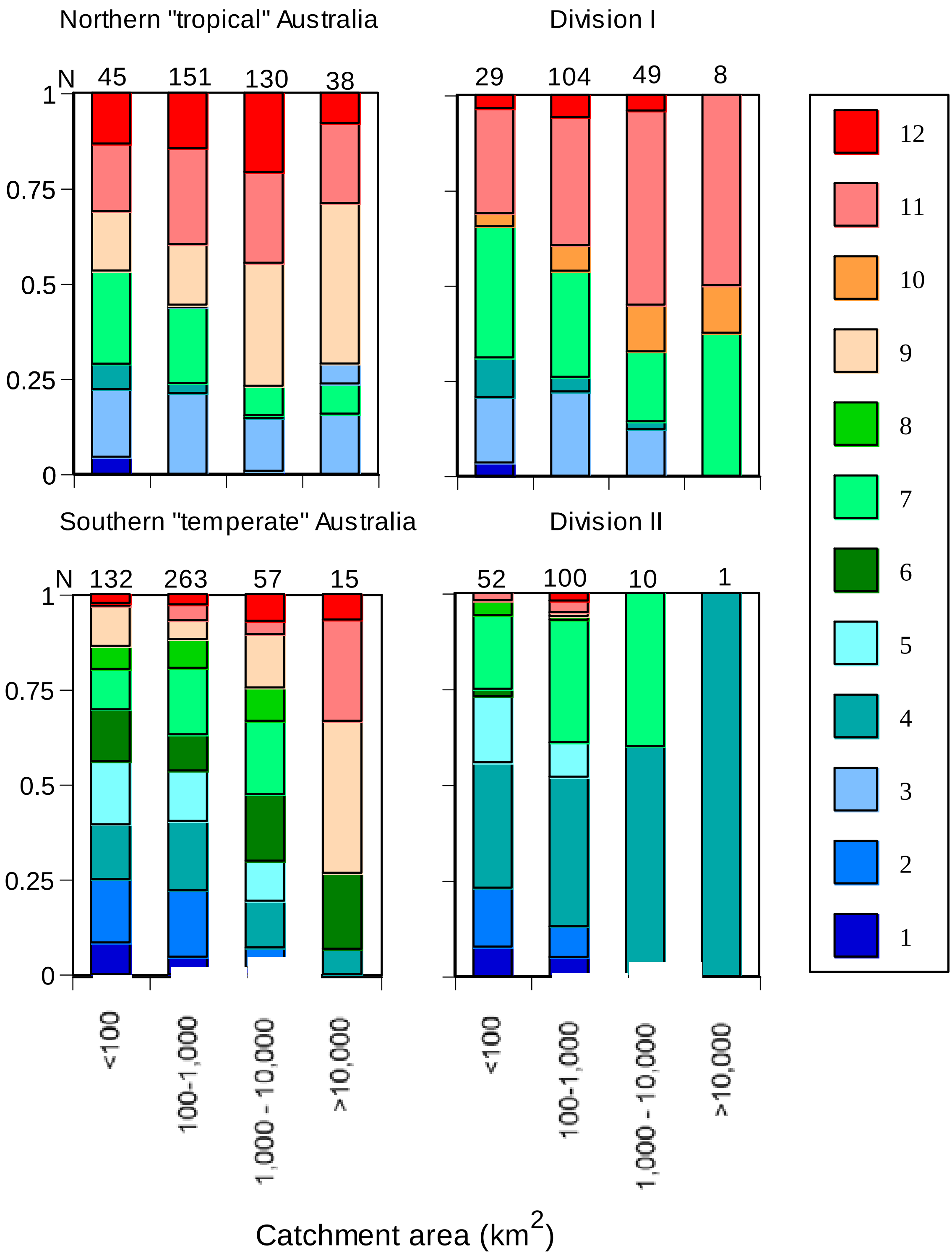

Figure 6.10. Changes in flow regime diversity and regime type with increasing stream size in northern and southern Australia and in Division I and II.

A contrasting pattern is observed in southern temperate Australia (Figure 6.10). Flow diversity is high for streams less than 10,000 km^2 in area (number of flow regime classes = 10, 10 and 10 for <100, 100–1,000 and 1,000–10,000 km^2, respectively) but then decreased sharply to only five flow regime classes in the largest sized streams (>10,000 km^2). Notably, the flow regime classes uncommon in the smaller sized streams but common in the largest (e.g. 9 and 11) are both characterised by intermittency. Common flow regime types in the smaller streams but absent in the largest (e.g. 2, 5 and 7) include unpredictable intermittent streams (0) as well as streams characterised by high dry season baseflows (5) or rare intermittency (7).

Thus, flow regime diversity in southern Australia appeared to remain invariant over a large range of stream sizes, except for the very largest of streams where a reduced diversity was observed. The low diversity in this class of streams may simply reflect the number of large streams examined. High flow diversity (nine classes) was observed for streams <1,000 km^2 in Division II in contrast with a much reduced diversity in streams larger than this (Figure 6.10). Again, this may reflect the small number of streams examined.

Data presented in Figure 6.9 suggests that, although some flow regime classes are characteristic of smaller streams whereas others are found in larger streams only, size-related differences in flow diversity across a gradient in stream size are minimal until stream size is large whereupon diversity is then reduced. Whether this truly reflects an effect of stream size or is related to other factors requires assessment. For example, the reduced diversity of flow regime types may simply reflect that few such large streams were sampled and consequently diversity was low (i.e. it is a sampling phenomenon). Alternatively, catchments in excess of 10,000 km^2 may, by virtue of large size, be constrained to drain inland areas only where climatic conditions may not be diverse. Very large rivers may have a low diversity of flow regimes because they are limited to areas of climatic and topographic uniformity (i.e. inland Australia) and as a consequence, certain flow regime signals are simply not possible.

We examined the influence of sampling intensity within streams of differing catchment size by constructing accumulation curves for each catchment area size class (Figure 6.11). Estimates of the mean number of flow regime classes for each sampling interval (cumulative number of stream gauges) were generated using 100 bootstrapped randomisations that incrementally constructed combinations of stream gauges. As intimated in Figure 6.2, the diversity (number) of flow regime classes increases with sampling intensity. The rate of increase was similar for small (<100 km^2) and intermediate-sized streams (100–1,000 km^2) streams, slightly lower for the larger-sized streams (1,000–10,000 km^2) and much lower for the very large streams (>10,000 km^2). Asymptotic values occurred at about 100 gauges for all but the very large streams. No asymptotic value could be obtained for this largest class of streams because insufficient gauges were available, although it appears that an asymptote was being approached after 50 samples. We further examined the influence of sample intensity by limiting the total number of samples for each size class to 53 (i.e. the total number available for the largest size class). [The curve for this size class is the same in both panels of Figure 6.11.] In this examination, and despite the fact that asymptotic values had not been fully reached for any size class, there is a clear difference between flow regime diversity between size classes. The very largest streams had a reduced possible number of flow regime classes. Thus, apparent differences in flow diversity evident in Figure 6.10 are not artefactual and related to sampling intensity, but more probably reflect the effect of basin size and consequent distribution across the continent.

This raises a very important issue with respect to describing the distribution of flow regime types across the landscape. Our sample points (i.e. gauging stations) are not randomly distributed. They have been placed in the landscape to primarily address issues related to water supply and not necessarily to address issues related to aquatic ecology or the description of flow diversity at large scales. For example, in this study many small streams of both tropical and temperate Australia are distinguished by high baseflow conditions or low intermittency. This initially seems contrary to what we might expect of small streams. However, it is highly likely that such streams were chosen for gauging precisely because they were unusual in comparison to many streams around them. Small streams with high baseflow components may be important in understanding patterns of dry-season streamflow in downstream receiving streams whereas intermittent small streams are not. Intermittent small streams probably numerically outweigh small streams of high baseflow in most regions.

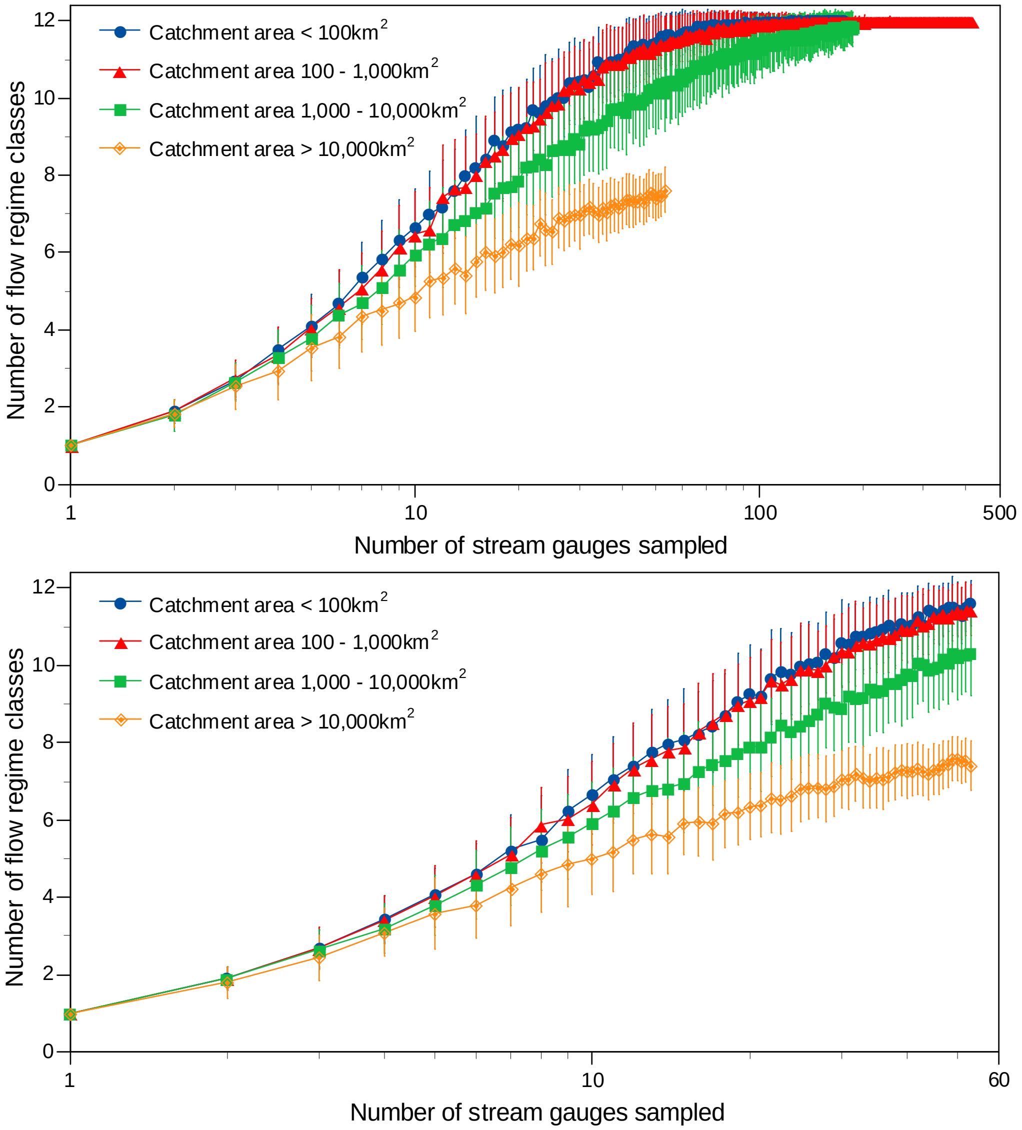

Figure 6.11. Cumulative increase in the mean (± SD) total number of flow regime classes encountered with increasing numbers of stream gauges sampled. Separate curves are shown for stream gauges within four catchment area ranges. Both northern and southern Australian gauges were included. Estimates of the mean number of flow regime classes for each sampling interval (cumulative number of stream gauges) were generated using 100 bootstrapped randomisations that incrementally constructed combinations of stream gauges. The top plot shows the results for cumulative number of gauges up to the maximum number present within each catchment area range. The bottom plot shows the results for cumulative number of gauges up to the total number present within the largest catchment area class (n = 53).

6.7 Flow regime diversity at the within-region or within-river scale

In the following sections, we address the extent of flow regime variation within regions (not drainage divisions although in some cases these coincide) or drainage basins. Our choice of regions was based on several factors. First, we assessed within-region variation if previous flow regime classifications existed for that particular region or if significant flow-related research had been undertaken in that region. (Note – this latter criterion was not an exhaustively pursued). We are here interested in assessing how well the existing and current classifications match. Second, we chose particular regions or rivers for intensive examination if they were current or planned targets of intensive flow-related ecological research. Third, we excluded regions for which spatial distribution of flow regime types was either uniform (e.g. the Pilbara region) or self-evident from Figure 6.6 (i.e. south-western Australia).

6.7.1 Flow regime diversity within Tasmania

Hughes (1987) identified four distinctive and spatially significant flow regime types across Tasmania (see Appendix 2). Six flow regime classes (1 – *stable high baseflow*; 2 – *stable winter high baseflow*; 4 – *unpredictable high baseflow*; 5 – *unpredictable winter rarely intermittent*; 7 – *unpredictable intermittent*; and 8 – *unpredictable winter intermittent*) were recognised in the current study. Hughes's (1987) class 1 streams were characterised by intermediate levels of MAR (410 mm), moderate CV of annual flow, moderate skewness, high monthly CVs, low variability in peak flows and high variability in low flows. This class were distributed predominantly across northern Tasmania. Also distributed across northern Tasmania (but typically further inland) were Hughes's (1987) class 4 streams which were typified by moderately high runoff (762 mm), low CVs of annual, monthly and monthly maximum flows but high CVs of monthly minimum flows. This class of streams include classes 1, 2 and 5 from the present study, all of which are characterised by low within year variability. The present study suggests that class 5 streams were more characteristic of the north-eastern portion of Tasmania.

Class 3 streams in the classification of Hughes (1987) were characterised by high MAR and low variability and were characteristic of the south-western portion of the island. Fifteen of the 77 streams examined by Hughes (1987) were within this class. This class equates to class 1 in the present study and of which five of the eight streams so classified occurred in the south-western portion, as described in Hughes (1987). The remainder occurred in the northern portion of the island, interspersed among class 2 and class 5 streams. Fewer streams within the south-western portion of the island were examined in the present study than in Hughes (1987) because they failed to satisfy our criteria for inclusion due to the significant river regulation present there (Figure 6.12).

The final class described by Hughes (1987) (her class 2) were characterised by low runoff (142 mm), high CV of annual flow, high skewness and high CVs of monthly total, maximum and minimum flows. This class was characteristic of south-eastern Tasmania. In contrast, four different flow regime classes (2, 5, 7 and 8) were recorded from this region in the present study.

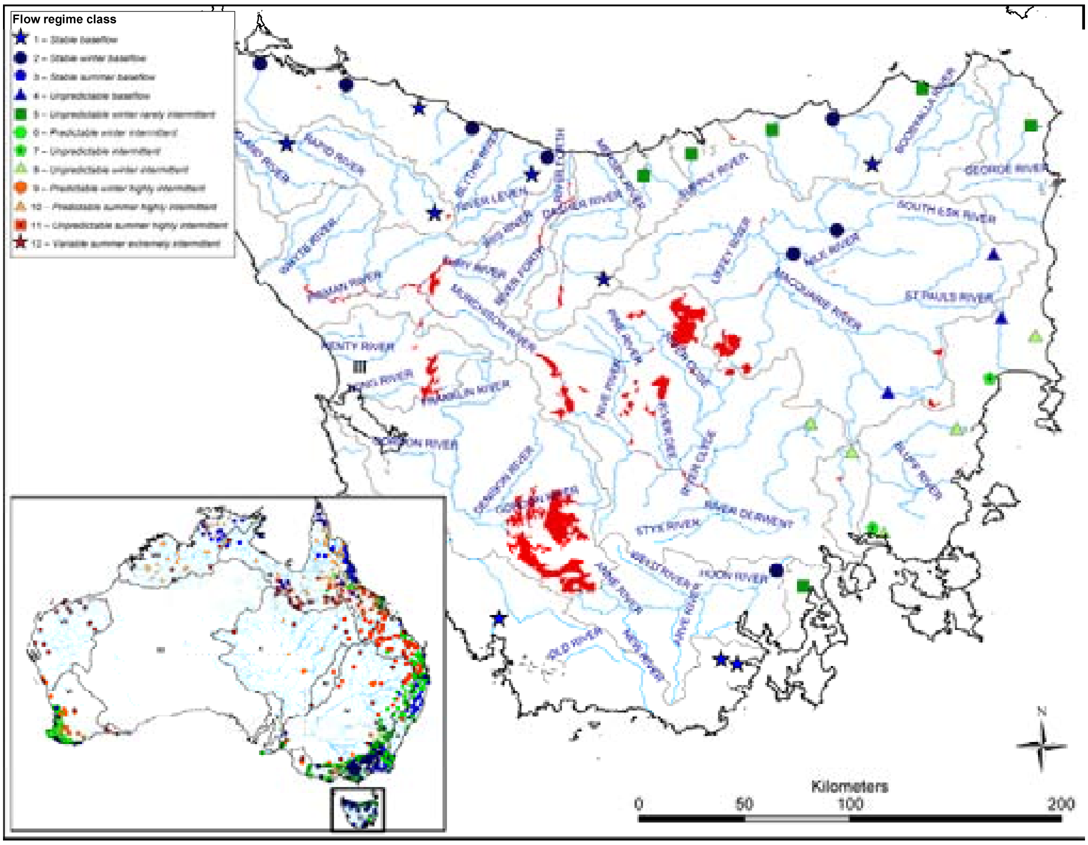

Figure 6.12. Distribution of flow regime classes across Tasmania.

The spatial component of the classification presented by Hughes (1987) is highly congruent with spatial variation in rainfall (her Figure 1), no doubt reflecting the contribution of mean annual runoff (MAR) to the final derivation of classification classes. However, class 11 streams were typically associated with very high annual rainfall (>1200 mm yr^{-1}) areas and class 5 and class 7 streams were typically associated with high rainfall (800–1200 mm yr^{-1}) areas in the present study where differences in magnitude were standardised so as not to contribute to class discrimination. A greater diversity of flow regime types was observed in areas where rainfall was less than 800 mm yr^{-1} (i.e. classes 2, 4, 5, 7, and 8). Thus, it appears that in Tasmania, spatial variation in total amount of rainfall is closely related to many facets of the flow regime.

6.7.2 Flow regime diversity within Victoria

Victoria is hydrologically diverse, containing 10 of the 12 possible continental flow regime classes (lacking classes 3 and 10) (Figure 6.13). However, 73.4% of all gauges were within only three flow classes: 4 (*unpredictable high baseflow*); 5 (*unpredictable winter rarely intermittent*); or 2 (*stable winter high baseflow*) (in increasing order) (Figure 6.14).

Flow regime classes 4 and 2 were located predominantly in the eastern half of Victoria. Rivers classified as class 4 were typically southerly flowing rivers with their headwaters on the southern flanks of the Australian Alps. High baseflows characteristic of this class are probably greatly supplemented by snowmelt as well as rainfall throughout the year. Class 2 streams also drained the southern flanks of the Australian Alps but were much more abundant in the upper headwater creeks of systems draining the northern flanks of the Alps and forming the left bank upper tributaries of the Murray River. These streams also received high baseflow derived from snowmelt but were heavily influenced by rainfall occurring within the winter months. A concentration of class 1 (*stable high baseflow*) streams occurred around the upper La Trobe River valley, an area noted for its abundant groundwater (Scheaffer *et al.* 2001).

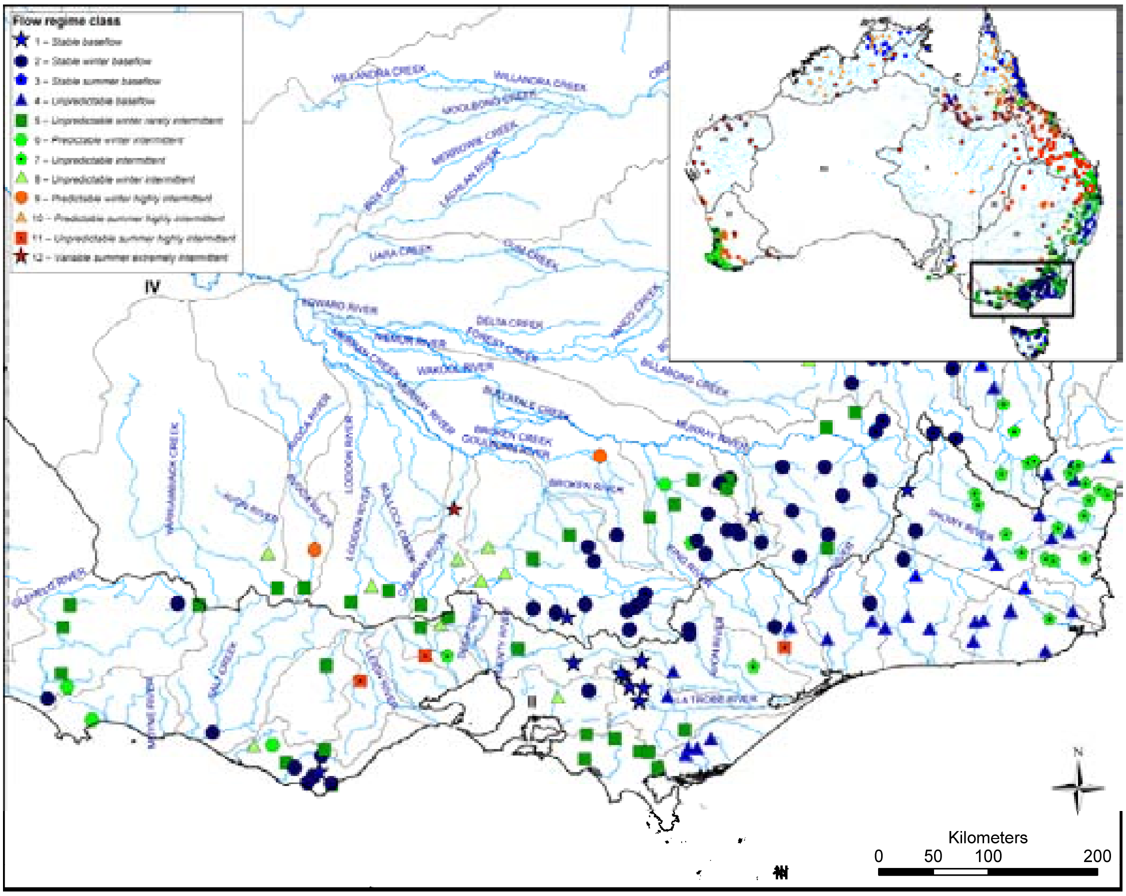

Figure 6.13. The distribution of flow regime classes throughout Victoria.

Class 5 (*unpredictable winter rarely intermittent*) streams occurred in two distinct areas. The first, and smallest, was limited to the southern coastal region (i.e. southerly draining streams) whereas the second larger class were located in the left bank tributaries of the Murray River. Within this latter class, class 5 streams occurred in the headwaters of streams not draining the northern flanks of the Australian Alps, and in the middle reaches of streams draining the Alps (i.e. downstream of class 2 streams). Further downstream these same streams were characterised by flow regime classes 8, 9 and 12 indicating a transition to greater degrees of intermittency.

The hydrological classification by Hughes and James (1989) recognised five different flow regime classes in Victoria. Hughes and James (1989) provide location, number and name details for each gauge within each flow class, enabling a direct comparison with the results of the present study. This comparison is presented in Figure 6.14.

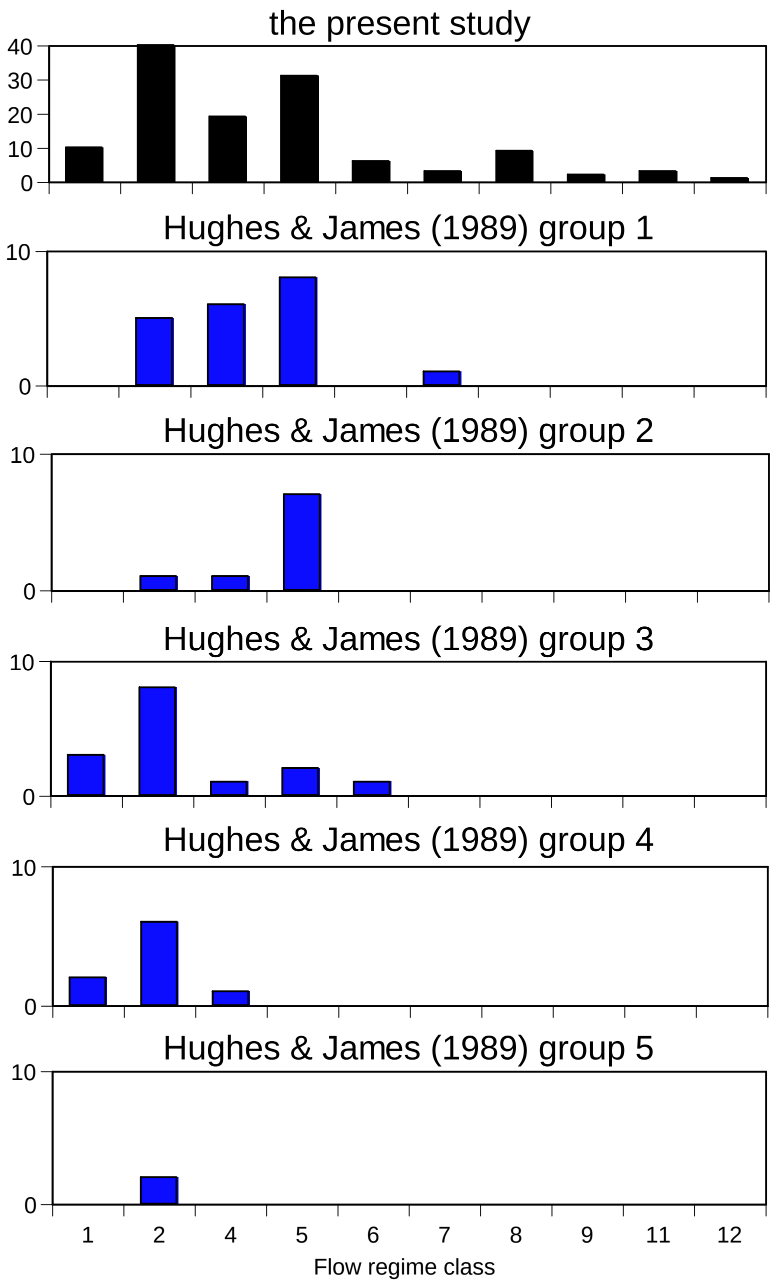

Figure 6.14. Flow regime classes present in Victoria. The number of gauges within each flow regime class is shown in the top panel. Also shown in the lower panels (blue bars) are the flow regime classes in the present study of streams within the five hydrological classes derived by Hughes and James (1989).

There was little agreement between the flow regime classes identified by Hughes and James (1989) and those identified in the present study. For example, flow class 1 of Hughes and James (1989) included streams within four different flow classes from the present study (2, 4, 5, and 7). Similarly, class 3 contained streams within five different flow classes from the present study (1, 2, 4, 5 and 6). Class 2 streams (the most abundant) occurred in all of the flow classes identified by Hughes and James (1989). Similarly, classes 4 and 5, which were also abundant, occurred in four of the five classes identified by Hughes and James (1989). The reasons for the poor match between these two classification schemes may be related to inclusion of variables not standardised for variation in magnitude and the use by Hughes and James (1989) of a relatively small number of hydrological metrics.

6.7.3 Flow regime diversity in south-east Queensland

Drainage Division I, which includes south-east Queensland, is an extremely large division which spans 15 degrees of latitude and is accordingly hydrologically diverse (seven flow classes). However, only four flow classes (4, 7, 11 and 12) were present in the south-eastern portion of this division and notably, all are typified by their unpredictable flow regimes and, with the exception of class 4, by varying degrees of intermittency (Figure 6.15).

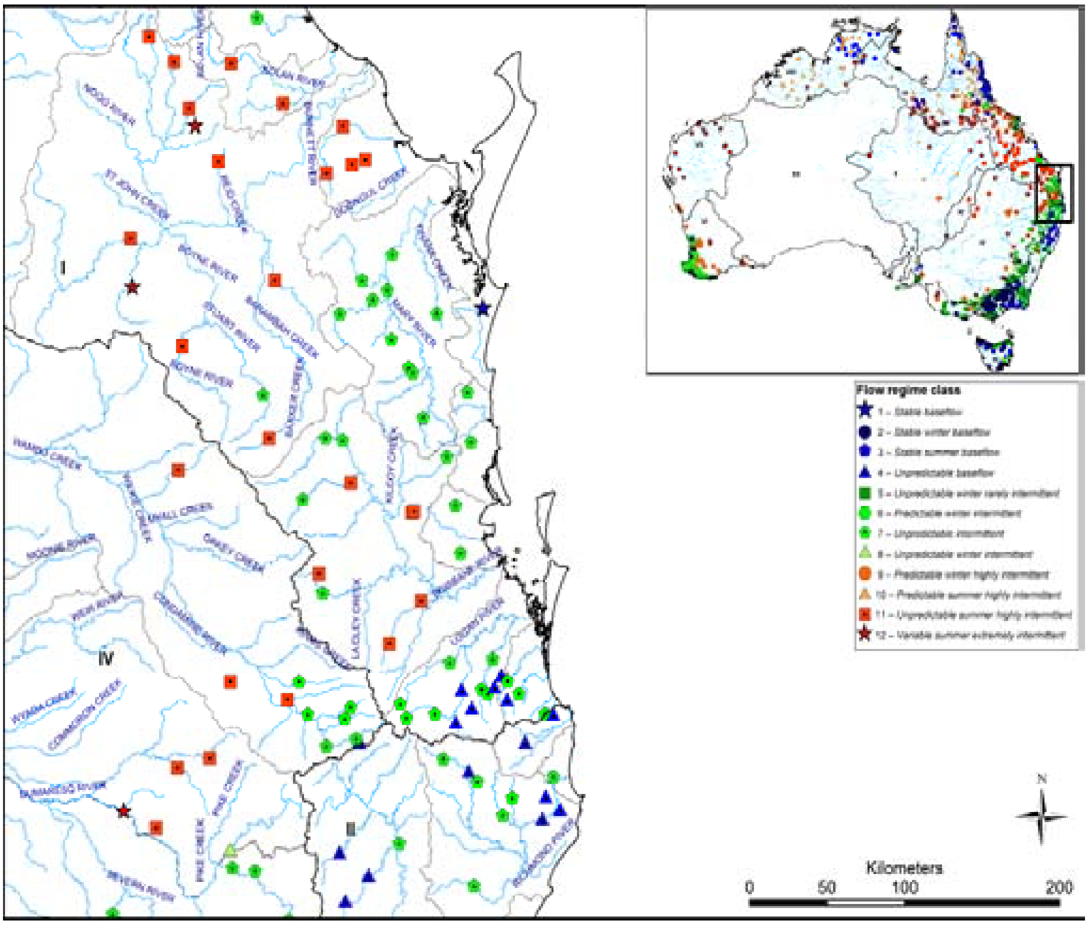

Figure 6.15. Flow regime diversity in south-eastern Queensland. The black line denotes the southern boundary of drainage division I.

Class 11 (*unpredictable summer highly intermittent*) streams were typically located in the northern section of this region (Burnett River drainage and associated coastal catchments (e.g. Kolan River) and the upper Fitzroy River drainage) but also occurred in the upper headwaters of the Brisbane River. The Great Dividing Range is low (rarely exceeding 900 m.a.s.l) and distant from the coast in the northern part of this region (approximately 350 km at the 25° S latitude, decreasing to approximately 150 km at 27° S in the upper headwaters of the Brisbane River) forming an extensive low-altitude eastern coastal plain. Significant mountain ranges (D'Aguilar and Conondale Ranges) within the Brisbane River catchment occur to the immediate west and north-west of Brisbane only. It is clear that this limited topographic diversity results in limited hydrological diversity in this part of the region also. The Mary River, in contrast, is bordered to the west by the north/south oriented Coastal Ranges and these ranges mark a clear spatial separation between flow class 7 and class 11 type streams to the north and west. All gauges within this river were classified as class 7 (*unpredictable intermittent*). Flow regimes in this river are influenced by both northern and southern weather systems and floods during June and July are not uncommon (Pusey *et al.* 1993).

The southern most rivers in Divison I are bounded to the south by the east/west oriented McPherson Range (of which Mt Warning constitutes a significant feature) and to the west by the Great Dividing Range which approaches within 100 km of the coastline at this point. Streams in this region were a mixture of classes 7 and 4 (*unpredictable high baseflow*) regimes.

Extensive flow-related research has been undertaken in this region by the authors (Pusey *et al.* 1993, 2000, 2004; Mackay *et al.* 2003; Kennard 2005, Kennard *et al.* 2006, 2007; Stewart-Koster *et al.* 2007) and the comparatively low flow diversity observed in this region is in contrast to our perceptions based on this research. It is likely that this measured low diversity is constrained in expression relative to other flow regime types evident when classification of stream gauges is undertaken at the larger, continental-scale. Given also that the classification method used in the present study is non-hierarchical, whilst methodologically fully appropriate for the large spatial scale examined, there is no provision within this classification for examining finer spatial scale variation within the each of flow classes. We recommend that further classification, based on the flow metrics generated during the course of the present study, of streams limited to this region, should occur; should the need arise (i.e. for selection of stream sites across a gradient in flow characteristics). We further illustrate the difficulty in describing diversity of flow regimes present within an individual river when constrained by a continental-wide classification by reference to the Mary River.

6.7.4 Flow regime diversity in the Mary River

As mentioned above, only one flow regime class was detected in the Mary River. However, Pusey *et al.* (1993) described subtle variation in streamflow variability and predictability related to stream size and position in the catchment. Streams located low in the network were less variable and more predictable (although predictability overall was not great). Similarly, Kennard (2005) analysed the flow regime occurring at 16 stream locations. The main channel (i.e. receiving channel) was characterised by comparatively stable flows (although not necessarily increasing in stability downstream in contrast to the pattern noted for predictability by Pusey *et al.* 1993), whereas some headwater streams and all western tributaries were highly variable and characterised by extended periods of zero flow. This fine scale variation is not apparent in Figure 6.15.

We mapped the distribution of principal component scores in the Mary River (see Appendix 5 for further description) to illustrate finer spatial scale variation in flow regime not encompassed within the continental classification (Figure 6.16). Principal Component 1 was related to flow variability and flood intensity (increasingly variable streams had comparatively high flood intensities). It can be seen from Figure 6.16a that a range of PC1 scores was obtained for the Mary River with western tributaries being highly variable (amongst the highest for the continent), headwater streams less variable and lower tributaries and main channel sites being the least variable. Baseflow contribution and dry spell length also varied throughout the catchment (Figure 6.16b and c, respectively). These subtle differences in flow regime, which may be of substantial ecological significance, are not evident in the continental-scale classification. The future online availability of original flow metric scores and PC scores would allow a finer scale classification to be performed if this was required.

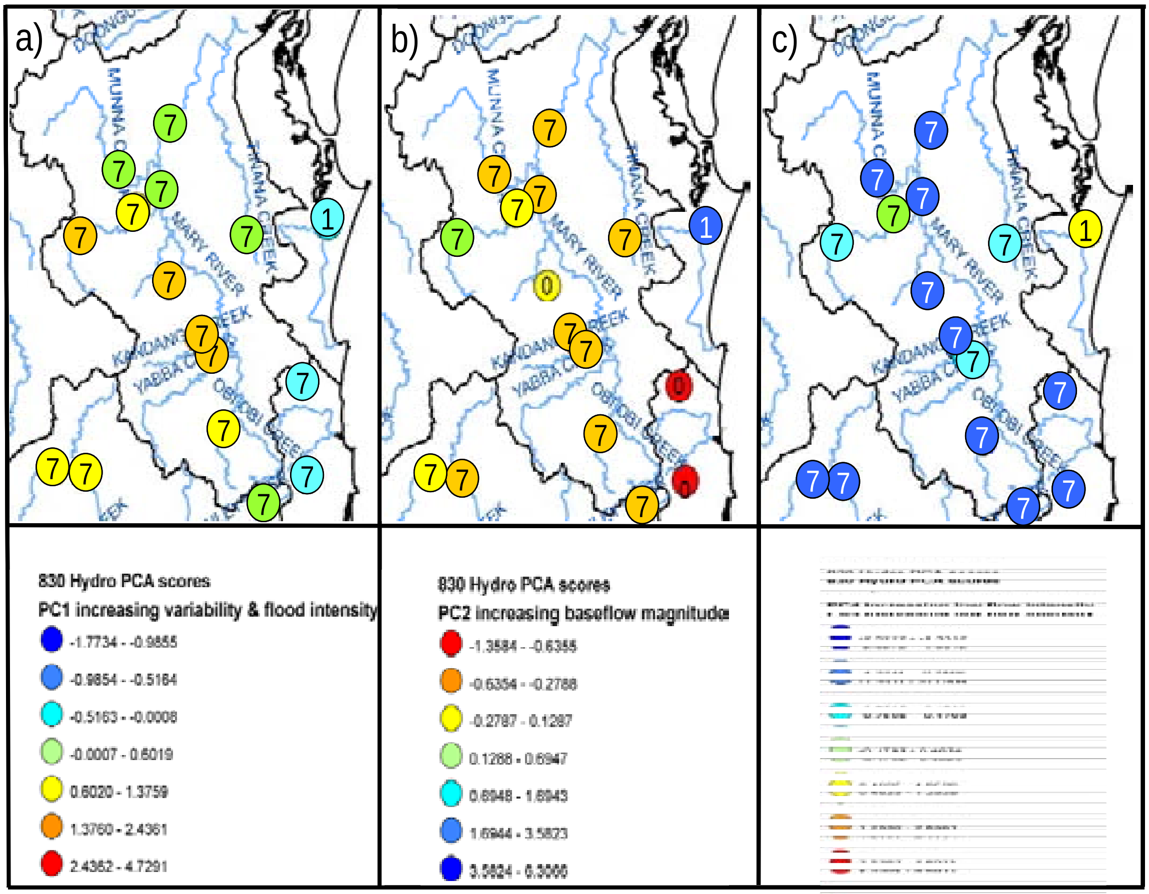

Figure 6.16. Distribution of Principal Component scores for stream gauges in the Mary River, south-eastern Queensland. Only scores for Principal Components a) 1, b) 2 and c) 4 are shown.

6.7.5 Flow regime diversity in central eastern Australia

Central eastern Australia includes two very large catchments, the Burdekin and Fitzroy Rivers, plus a number of small coastal drainages such as the Proserpine, Pioneer, Calliope, O'Connell, Don and Haughton Rivers (Figure 6.17). These small catchments were typified, in general, by flow regime class 7 (*unpredictable intermittent*). Finch Hatton Creek, a left bank tributary of the Pioneer River, drains an extensive rainforest area within the southern part of Eungella National Park on the Clark Range. Maximum elevation for the entire catchment (Mt William – 1259 m.a.s.l.) occurs in this Finch Hatton subcatchment. This creek was classified as a class 4 stream (*unpredictable high baseflow*). The Haughton River contained gauges classified as classes 11 (*unpredictable summer highly intermittent*), 4 and 12 (*extreme harsh summer intermittent*). Class 4 probably receives significant groundwater. The Fitzroy River contained only three different flow regime classes (7, 11 and 12). Of the 34 gauges present, 27 were classified as class 11, four as class 12 and three as class 7.

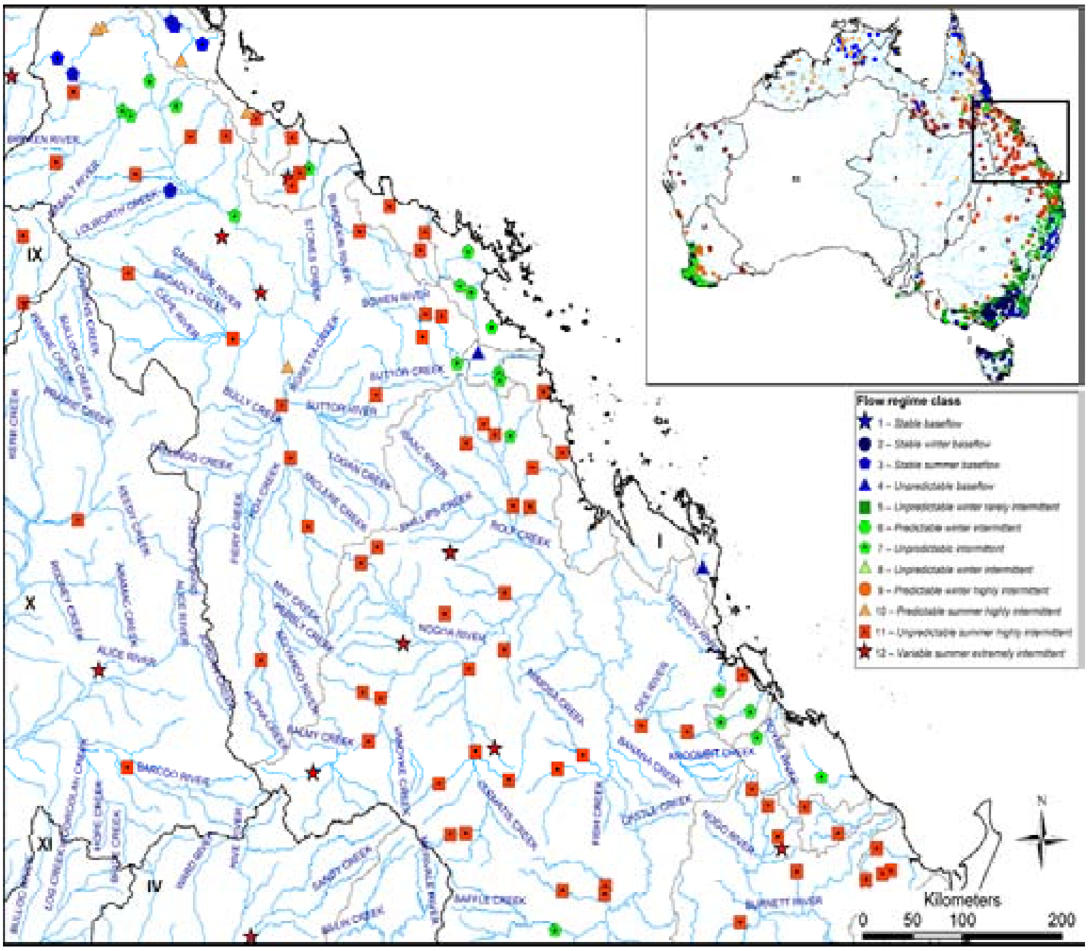

Figure 6.17. Flow regime classes present in central north-eastern Australia.

6.7.6 Flow regime diversity in the Burdekin River

The Burdekin River was, like the Fitzroy River, largely typified by streams characterised by unpredictable and intermittent flow regimes (Figure 6.17). Sixteen of 29 gauges were within regime class 11 (*unpredictable summer highly intermittent*), five within class 7 (*unpredictable intermittent*), three within class 10 (*predictable summer high intermittency*) and two within class 12 (*extreme harsh summer intermittent*). The western and southern tributary systems (Cape/Campaspe and the Suttor/Belyando, respectively) were almost exclusively of flow Class 11 and typically experienced about 150 days of zero flow per year. Left bank eastern tributaries of the upper Burdekin River were a mix of classes 7 and 11 streams. These streams and the upper reaches of the Burdekin River itself (collectively comprising < 15% of the entire catchment) contribute about 60% of the total runoff for the entire river (Pusey and Arthington 1996). Their headwaters are relatively close to the coast and drain rainforest areas at an elevation of between 800–1000m such as occurs in the Paluma Ranges. Despite this, tributary streams of this region typically experience about 120 days of zero flow per year. The presence of class 3 streams in the upper reaches of the Burdekin River is noteworthy. Both Fletcher Creek and Wyandotte Creek overlay extensive Pleistocene basalt fields and groundwater contributes greatly to the development of a *stable summer high baseflow* flow regime. Similar young basalt deposits occur upstream of the gauge located at Lucky Downs (120111). In addition, the river receives at this point inflow from Glen Lofty Creek, a significant although ungauged spring-fed system. Fletcher and Wyandotte Creeks very rarely cease to flow. Fletcher Creek stopped flowing for the first time on record only after two years of a protracted 5 year drought that occurred over the period 1991–1996 (Pusey pers. obs.).

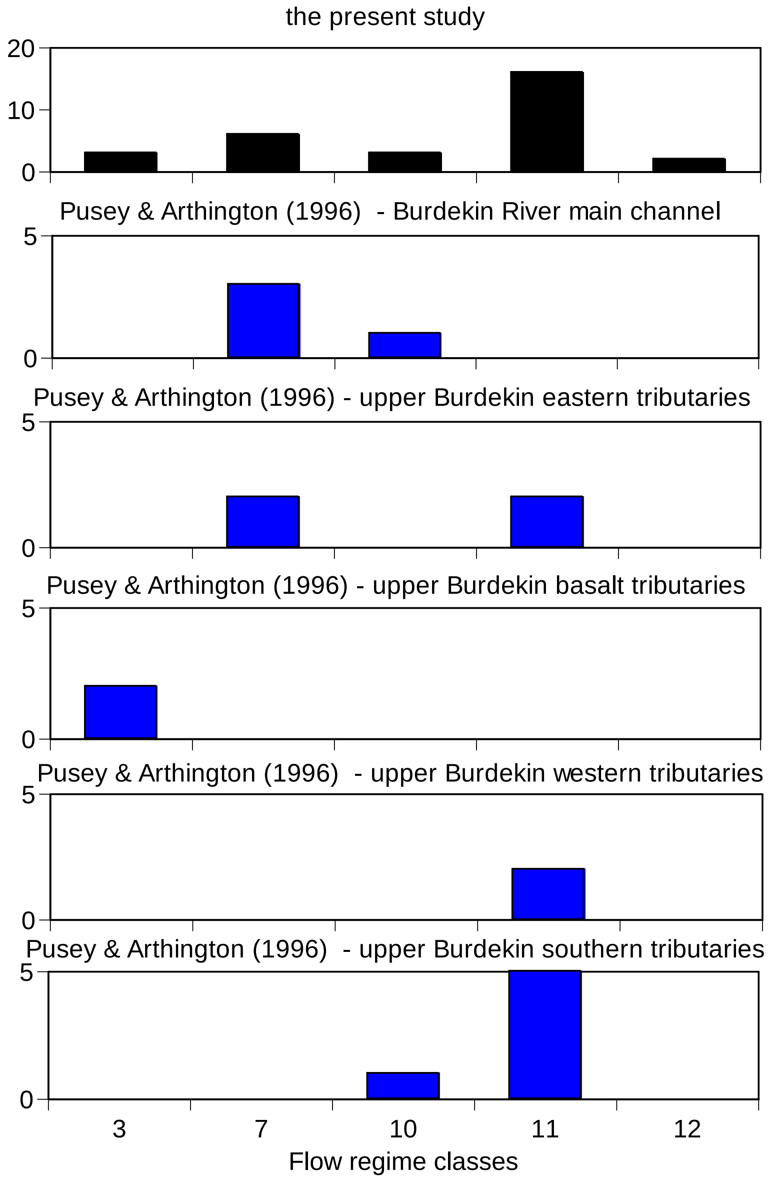

Figure 6.18. Correspondence between the *a priori* constructed flow regime classes of Pusey and Arthington (1996) for the Burdekin River and the results of the present study.

Highly significant between-class differences in flow regime metrics (mostly associated with measures of variability) were detected by Pusey and Arthington (1996) and there are moderate levels of concordance with the flow classification presented in Appendix 5 (Figure 6.18). Upper Burdekin basaltic tributary streams in Pusey and Arthington (1996) matched flow regime class 3. Western tributaries were exclusively of class 11. The remaining groups defined by Pusey and Arthington (1996) contained two flow regimes classes (either 7 and 10, 7 and 11 or 10 and 11 for the Burdekin River main channel, upper Burdekin eastern tributaries and upper Burdekin River southern tributaries, respectively).

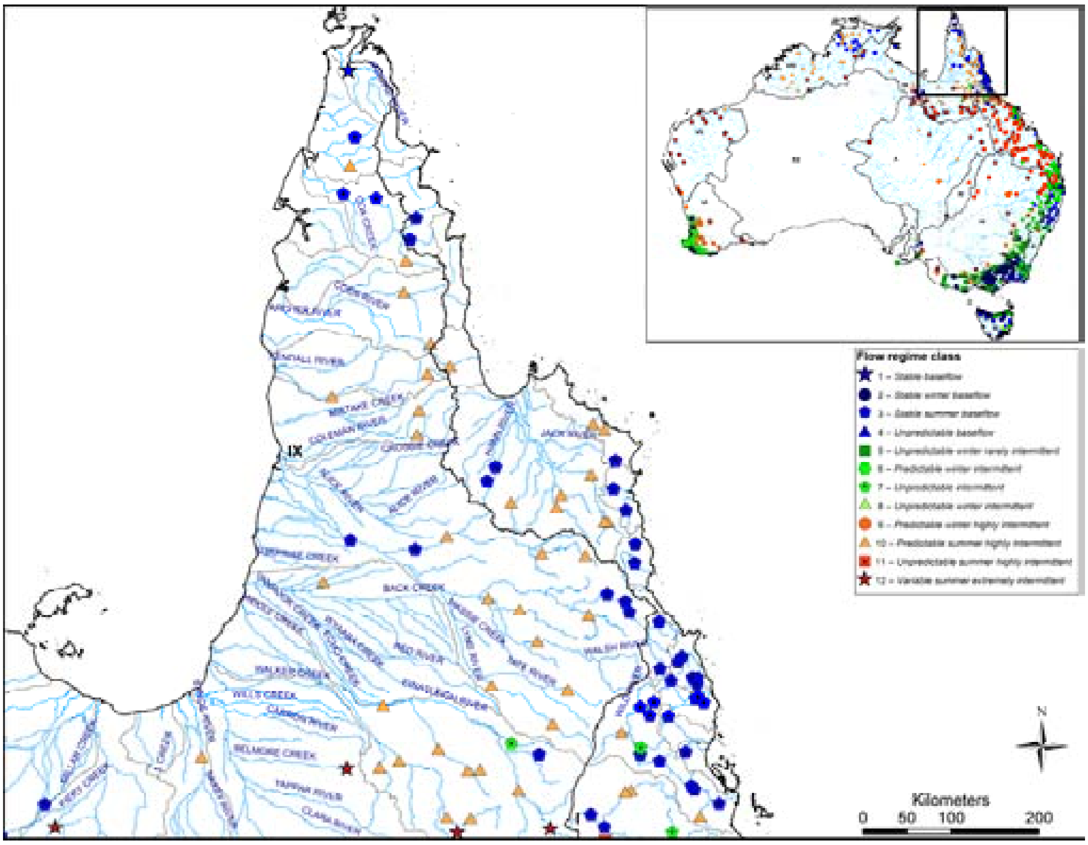

Figure 6.19. Flow regime diversity on the Cape York Peninsula region.

6.7.7 Flow regime diversity in north-eastern Australia – Cape York Peninsula

The actual extent of Cape York Peninsula (CYP) is poorly defined in a geographical sense, but is here considered to be that part of northern Queensland north of 17° 30' S on the western coast and 18° 46' S on the east coast (the southern limit of the Herbert River catchment). This definition therefore includes all CYP rivers discharging into the eastern portion of the Gulf of Carpentaria as well as rivers discharging eastward into the Coral Sea, including all major rivers of the Wet Tropics region. It does not include rivers of the southern Gulf. The region is topographically diverse with the Great Dividing Range (GDR) reaching its maximum Queensland height (1684 m.a.s.l. Mt Bartle Frere) in the Wet Tropics region. The GDR essentially abuts the east coast in this region also and dramatically decreases in height to the north. Maximum elevation does not exceed 200 m.a.s.l in a band located between 15° 15'S and 14° 57'S in the vicinity of the headwaters of the Morehead and Hann Rivers (major northern tributaries of the Normanby River) to the east and the Coleman River to the west. Elevation of the GDR then increases northward to a maximum of 671 m (Mt Carter) in the Iron Range area (an area noted for its isolated rainforest and endemic rainforest mammals and birds). It thereafter decreases in height to less than 200 m.a.s.l within approximately 50 km.

Topography is a major influence on streamflow regime in the CYP region. Streams of the Wet Tropics region were all characterised as class 3 streams (*stable summer high baseflow*) (Figure 6.19). High summer flows are due to southern migration of the monsoonal trough and cyclonic activity in the Coral Sea. In addition, these catchments also receive substantial dry-season rainfall from orographic forcing of moisture laden south-easterly winds (which predominate during this time) by the GDR and its close proximity to the coast. Cloud capture by the highest peaks may also contribute to high dry season baseflows. Further discussion of spatial variation in flow regime for this area is presented below. Streams to the west of the GDR are mostly deprived of moisture carried in the south-easterly winds (except for the upper reaches of the Mitchell River which is also more fully discussed below) and the dominant source of rainfall is the summer monsoonal low and cyclonic activity associated with deep lows formed in the Gulf of Carpentaria. Cyclones formed in the Coral Sea may also occasionally penetrate over or around the GDR. As a result, most streams of the western portion of CYP have an intermittent flow regime within class 10 (*predictable summer high intermittency*).

This same pattern (class 10) is also observed in the Normanby River catchment on the east coast (Figure 6.19). The GDR is very poorly expressed in this region. Notably, and in contrast, the Hann River in the Normanby basin is distinguished by high dry season baseflows (class 3) derived from groundwater. Class 3 streams also occur near the tip of CYP (Wenlock River to the west and the Pascoe River to the east). This region experiences very high rainfall (1200–1600 mm yr^{-1}) equivalent to that recorded in the Wet Tropics region (Sturman and Tapper 2001). Both rivers have their origins in the Iron Range area and some local orographic forcing may increase precipitation and runoff. Personal experience suggests that groundwater inputs (e.g. from creeks such as Hot Water Creek) may contribute to dry season flows also. Further to the north in the highest rainfall area of northern Australia (>greater than 1600 mm yr^{-1}), the Jardine River was classified as a class 1 stream (*stable high baseflows*). This regime type, whilst not common, was mainly restricted to southern Australia (24/27). This regime type occurred in south-eastern Queensland (Teewah Creek, 140002) and on Cape Arnhem in the NT (Yirrkala Creek 8260054). The high baseflow component in the Jardine River suggests groundwater input but the extensive swamps in this region (which may in themselves be surface expressions of groundwater) may contribute outflow during the dry season that subsequently maintains flow in the main channel.

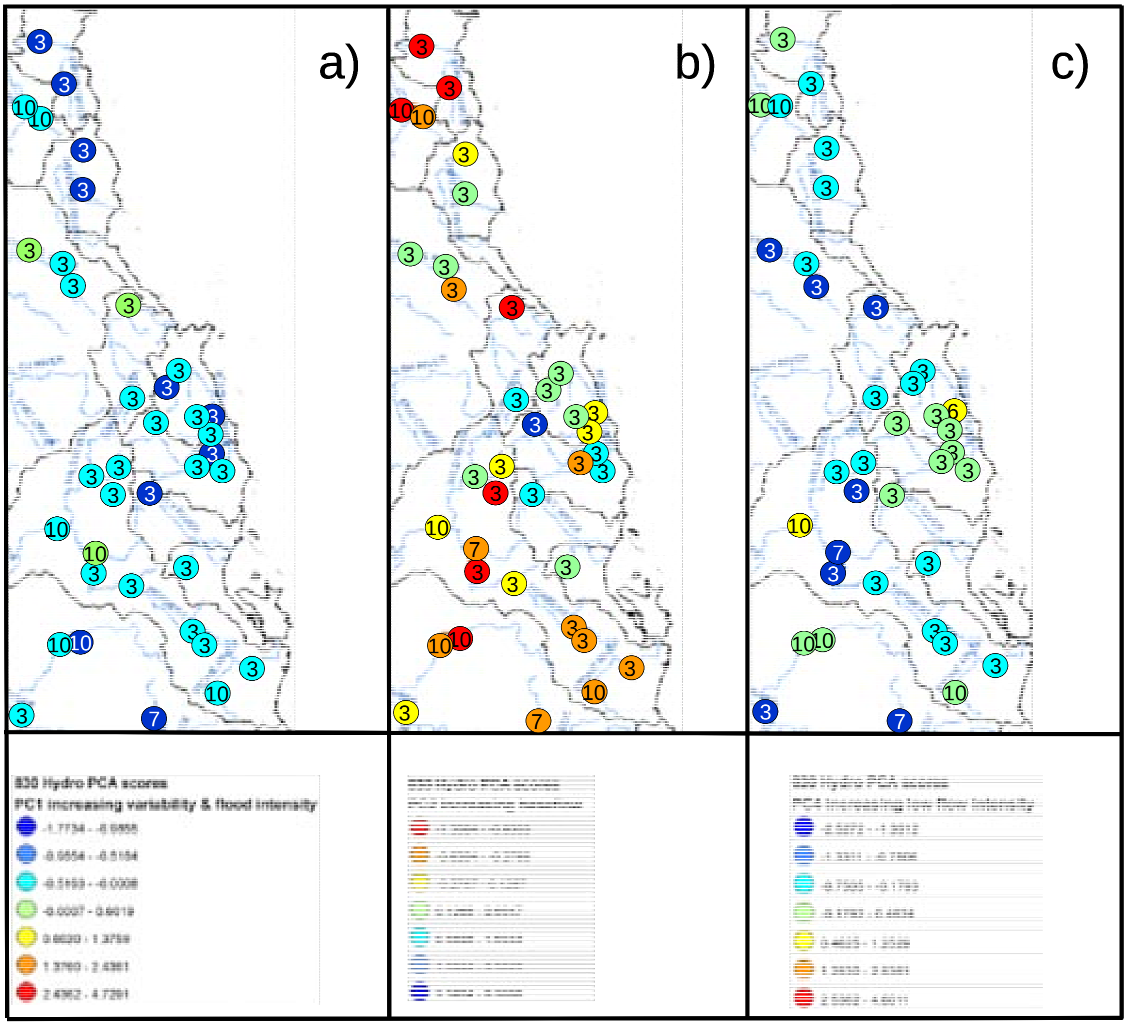

Figure 6.20. Spatial variation in flow regime for the Wet Tropics region as revealed by Principal Component 1 (a), 2 (b) and 4 (c) scores. (See Appendix 5 for derivation.)

6.7.8 Flow diversity in the Wet Tropics region

Most streams included in the present analysis within the Wet Tropics region (Annan River south to the Herbert River) were of a single flow regime class (3). Pusey *et al.* (2000) suggest that greater flow regime diversity may occur in this region and the extent of this diversity is evident in Figure 6.20. The distribution of PC1 scores suggests that the northern rivers of the Wet Tropics region (i.e. Daintree, Bloomfield, Endeavour and Annan) are distinguished by low levels of variability and flood intensity. Flaggy Creek (110011), to the immediate south, is of intermediate variability. Further south again, the lower reaches of the Mulgrave and Russell, Johnstone and Tully Rivers are of low variability whereas their tributary streams are slightly more variable, as are most streams of the Herbert River drainage. Greater spatial variation is evident in PC2 scores (perenniality, baseflows). Streams on the extremities of the region (Annan and Endeavour to the north and Herbert to the south) have low baseflows. Baseflow contribution and perenniality increase towards the centre of the region, except for in Flaggy Creek which tends towards intermittency. Similar gradients are evident for the extent of low flow intensity (spell length etc. – PC4 scores). Clearly, the classification discussed here may be incapable of describing these gradients given the large spatial scale (and hence extent of flow regime diversity involved) to which it was primarily addressed.

We suggest that if greater resolution for this region is required then an additional classification using the original suite of metrics and limited to rivers of the region be produced.

6.7.9 Flow diversity in the Mitchell River

Most (10/15) of the streams within the Mitchell River were of flow regime class 10 (*predictable summer high intermittency*), the dominant flow signature for much of northern Australia. Three locations (gauges 919005, 919013 and 919001), all of small catchment area (89–540 km^2) and in the upper headwaters of the Mitchell River, were of class 3 (Figure 6.19). These headwater perennial streams drain rainforest areas on the western border of the Wet Tropics streams and not surprisingly resemble streams of this region. Also within this class were the lower most gauges on the Palmer River (919204) and the Mitchell River (919009). Given that reaches upstream of both gauges were of flow class 2, it is highly possible that significant groundwater inputs occur in the lower Palmer River and Mitchell River.

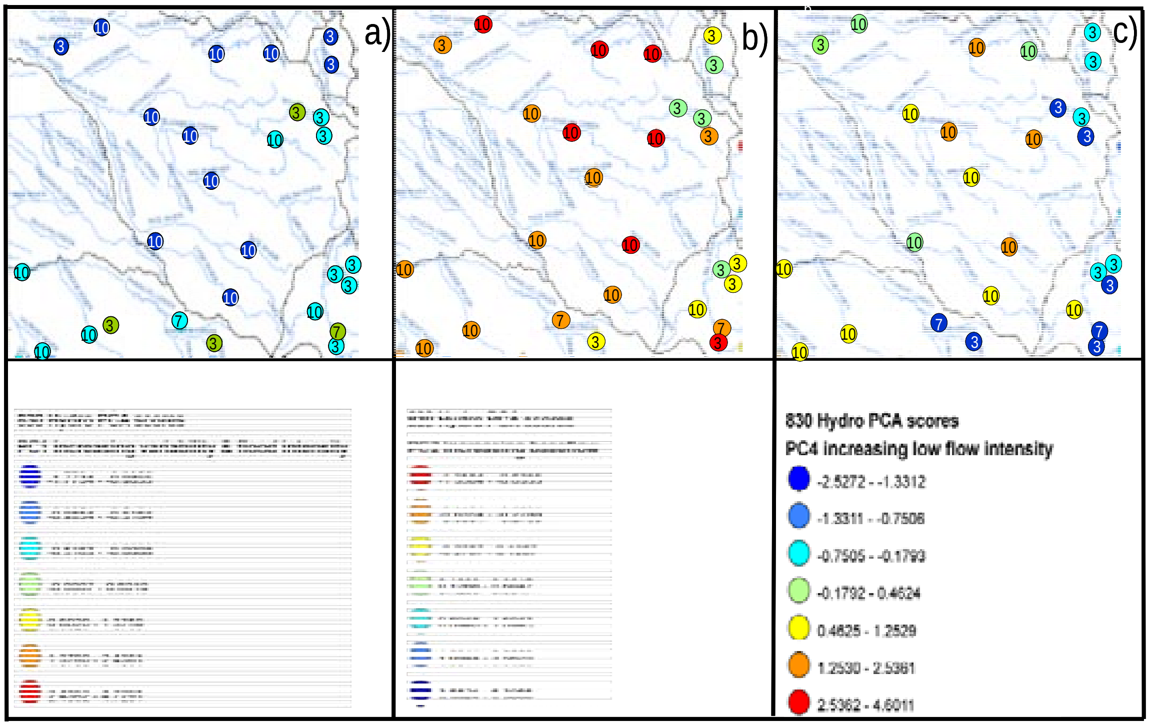

Figure 6.21. Spatial variation in flow regime for the Mitchell River as revealed by Principal Component 1 (a), 2 (b) and 4 (c) scores. (See Appendix 5 for derivation.) Flow class is given for each location also.

The spatial variation within the Mitchell River described above is only moderately well-supported when examined at finer scales (Figure 6.21). PC1 scores (gradient in flow variability and flood intensity) indicate that overall, variability and flood intensity tend towards the lower end of the spectrum defined by all gauges across the continent (Figure 6.21a). This seems initially in contrast to the patterns shown for baseflow and low flow characteristics. However, the low variability observed for most gauges results from the preponderance of very low and no flow days in the record. Notably, the most perennial streams in the catchment (i.e. in the upper Mitchell) were more variable than these intermittent streams. Baseflow was high in the upper Mitchell gauges (0.19–0.27) and these streams had a moderately high perenniality value (% contribution by six driest months) of

10.4 ± 1.8% (SE), in contrast to all other Mitchell River gauges (1.1 ± 0.2%). Notably, the Palmer River gauge (919204) and Mitchell River gauge (919009), classified as class 3 streams, were of low perenniality (1.55 and 1.87, respectively) but characterised by moderate levels of baseflow (0.142 and 0.146, respectively). Median minimum flows were zero for all gauges not classified as class 6 whereas median minimum flows for the lower Palmer River and Mitchell River gauges and the three upper Mitchell River gauges were all greater than zero. Thus, class 3 streams encompass a wide range of flows otherwise characterised by high baseflow and the absence of intermittency, the key factor being that they do not cease to flow. That such a wide range is encompassed within this flow class illustrates the pervasiveness of periods of no flow in other rivers of the tropical north.

Examination of spatial variation in occurrence of minimum and maximum daily flows in the Mitchell River further illustrates the spatial variation in flow regime not fully captured by the continental classification (Figure 6.22). On average, maximum flows occur on 16 February and there is little variation across the catchment in timing (SE of maximum flow = 1.8 days). Clearly, maximum flows are derived from the same weather event felt across the entire catchment. Minimum flows, in contrast, occur over a wide time range (7 March to 21 December). The Tate and Walsh Rivers in the catchment's south typically have a short period between the occurrence of maximum and minimum flows (mean = 136 days), whereas the Palmer River has a more prolonged period (mean = 229 days) and small tributaries in the upper Mitchell an even more extended period (mean = 288 days). The lower-most gauge on the Mitchell River (919009 at Koolatah) also has a long period (265 days) between maximum and minimum flows. It was earlier suggested that localised groundwater may contribute to dry season flows in the lower Palmer and Mitchell River. Whilst this may indeed be the case, such groundwater inputs are likely to be relatively minor (*cf* intermittency values for these gauges). It is more likely that continued downstream delivery of water from the Palmer River and from its tributaries combine to extend the period of continued flow in the lower-most gauge in this river. A similar explanation probably suffices for the stable baseflows recorded in the Mitchell River at Koolatah. It is likely that these subtle spatial differences in flow regime, not fully captured by the continental-scale classification, have significant ecological implications such as influencing the types of species present, extent of migration, growth and synchrony of life histories with flow regime.

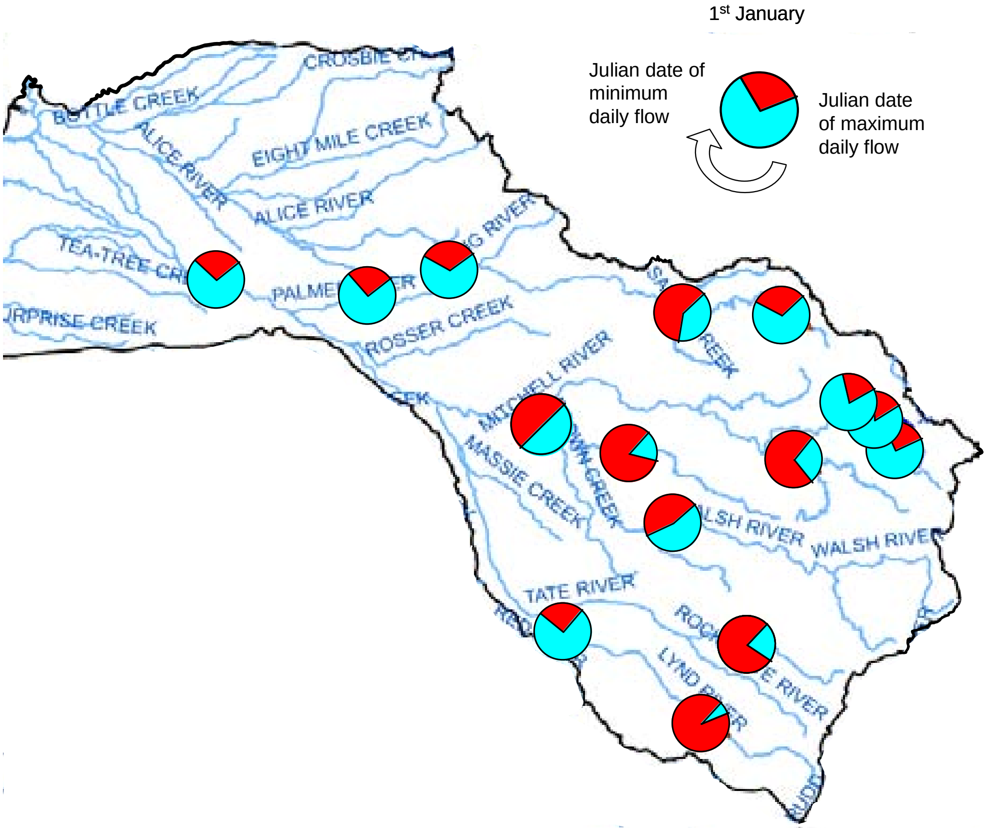

Figure 6.22. Spatial variation in the mean occurrence (Julian date) of maximum and minimum daily flows in the Mitchell River. Each pie chart represents an entire year. Maximum flows commence in the north eastern quadrant of the pie (i.e. first three months of the year) and the period between the occurrence of maximum flows and minimum flows is denoted by blue. Minimum flows occur at the commencement of the red portion of the pie. Minimum flows may or may not equal zero flow.

6.8 Summary and conclusions

The continental-scale classification developed here (see Appendix 5) clearly defined differences in flow regime across Australia. These differences were most clearly evident between northern tropical/subtropical Australia and southern temperate Australia. Arid zone streams were more similar to tropical streams reflecting the influence of northern weather patterns on these streams. Temperate Australia contained more flow regime types than did tropical Australia, reflecting the generally greater complexity of weather patterns responsible for generating rainfall and hence stream runoff and greater topographic diversity in southern Australia. Divisions II and IV in temperate Australia and Division I in tropical Australia contained the greatest diversity of flow regime types. Some divisions were characterised by a preponderance of particular flow regions (i.e. Mediterranean signal in Division VI or extreme intermittency in Division VII). However, most flow regime types were recorded from a range of divisions within the broad climatic division discussed above. Care must be exercised when comparing different regions or divisions because of the non-random distribution of gauges across the landscape.

Catchment size had a significant effect on streamflow diversity. Small streams contained a diverse range of streamflow types. Slightly higher diversity was also observed in moderate to large streams. Very large streams contained a reduced array of flow regime classes. This effect probably reflected the fact that very large streams are, by virtue of their large size, restricted to areas of Australia receiving a low diversity of weather patterns. Small streams were notable for the high number of flow regime classes typified by high predictability or stable flows, contrary to what may be expected under the assumption that the combined flows of many small tributaries results in increased predictability and decreased variability. Again however, care must be exercised when comparing across streams of differing catchment size because the placement of gauges across the landscape is not random and primarily addresses the needs of hydrographers and hydrologists rather than ecologists interested in defining ecohydrological variation.

Comparison of the results of the present classification and previously published regional classifications revealed a range of levels of concordance. For example, the classification developed for Tasmania (Hughes 1987) was broadly concordant with the present classification (although we recognised a greater diversity of regime types) probably because spatial variation in rainfall and its influence on streamflow is sufficient to be identified by both schemes. The classification developed by Hughes and James (1989) for Victoria was, in contrast, poorly supported by the present classification. Greater diversity was described and more spatially significant classing of streams was observed in the present study. The general lack of concordance between the present classification and previous regional classifications may be a result of the scale of investigation but is probably related more to issues associated with the nature and number of metrics used to characterise the flow regime and greater rigour in addressing the methodological requirements of such exercises outlined in Appendix 2.

Examination of flow regime diversity at smaller spatial scales revealed that whilst the present classification performed well at large scales, it was perhaps unable to fully characterise flow diversity present at the scale of individual river basins or small well-defined regions such as south-eastern Queensland or the Wet Tropics region. This is perhaps not surprising given the differences in spatial scale involved. The present classification was concerned with characterising flow diversity at a very large scale and accordingly when applied at smaller scales, all variation present must be assessed against the range of variation detected at the largest scale. It is suggested that when and if examination of spatial variation at these smaller scales is desired, then a three step process is required. First, spatial variation is assessed using the flow regime classes derived from the continental classification, thus allowing spatial variation flow regime to be placed in a larger context. Second, the full set of metrics, which will be available online (and currently available on request from the authors), is reclassified using only those locations restricted to the area of concern to produce a classification relevant to the area of concern. Third, the resultant outputs are then combined.

6.9 References

Hughes, J.M.R. (1987). Hydrological characteristics and classification of Tasmanian rivers. *Australian Geographical Studies* 25: 61–82.

Hughes, J. M. R., and James, B. (1989). A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. *Australian Journal of Marine and Freshwater Resources* 40: 303–326.

Kennard, M.J. (2005). *A quantitative Basis for the Use of Fish as indicators of river Health in Eastern Australia.* Ph.D. Thesis, Griffith University. 206 pp.

Kennard, M.J., Pusey, B.J., Arthington, A.H., Harch, B.D. and Mackay, S.J. (2006). Development and application of a predictive model of freshwater fish assemblage composition to evaluate river health in eastern Australia. *Hydrobiologia* 572: 33–57.

Kennard, M.J., Olden, J.D., Arthington, A.H., Pusey, B.J. and Poff, N.L. (2007). Multi-scale effects of flow regime, habitat, and their interaction on fish assemblage structure in eastern Australia. *Canadian Journal of Fisheries and Aquatic Sciences*. 64: 1346–1359.

Mackay, S.J., Arthington, A.H., Kennard, M.J. and Pusey, B.J. (2003). Spatial variation in the distribution and abundance of submersed macrophytes in an Australian subtropical river. *Aquatic Botany* 77: 169–186.

McMahon, T.A. and Finlayson, B.C. (2003). Droughts and anti-droughts: the low flow hydrology of Australian rivers. *Freshwater Biology* 48: 1147–1160.

Pusey, B.J. and Arthington, A.H. (1996). Streamflow variability within the Burdekin River. Pp. 213–220. *Proceedings of the 23rd Hydrology and Water Resources Symposium*. Australian Institute of Engineers, Barton.

Pusey, B.J., Arthington, A.H. and Read, M.G. (1993). Spatial and temporal variation in fish assemblage structure in the Mary River, south-eastern Queensland: the influence of habitat structure. *Environmental Biology of Fishes* 37: 355–380.

Pusey, B. J., Kennard, M. J. and Arthington, H. (2000). Discharge variability and the development of predictive models relating stream fish assemblage structure to habitat in northeastern Australia. *Ecology of Freshwater Fishes* 9:30–50.

Pusey, B.J., Kennard, M.J. and Arthington, A.H. (2004). *Freshwater Fishes of North-eastern Australia.* CSIRO Publishing, Melbourne. 684 pp.

Schaeffer, J., Laird, M., Kacavenda, S., Khan, S. and Yuen, S. (2001). The potential for artificial recharge of the Tertiary aquifers of the LaTrobe Valley, Victoria, Australia. Pp 1–6. In *Proceedings of Geoenvironment 2001: 2nd ANZ Conference on Environmental Geotechnics.* Newcastle.

Stewart-Koster, B., Kennard, M.J., Harch, B.D., Sheldon, F., Arthington, A.H. and Pusey, B.J. (2007). Partitioning the variation in stream fish assemblages within a spatio-temporal hierarchy. *Marine and Freshwater Research.* 58: 675-686.

Sturman, A. and Tapper, N. (1996). *The weather and climate of Australia and New Zealand.* Oxford University Press, Oxford. 476 pp.

Sturman, A. and Tapper, N. (2001). *The weather and climate of Australia and New Zealand.* Oxford University Press, Oxford. 476 pp.

Twidale, C.R. and Campbell, E.M. (1993). *Australian Landforms. Structure, process and time.* Gleaneagles Publishing, Adelaide. 560 pp.

Appendix 7

Development of a continent-wide spatial framework for the ecohydrological classification

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Summary

The development of an ecohydrological classification for all Australian streams (Appendix 8) is critically dependent on the availability of a suitable spatial framework. This framework supplies the spatial units that are the objects of the classification and the definition of surface drainage pathways that enable catchment areas to be delineated and their environmental characteristics attributed. However, existing spatial frameworks such as the AWRC drainage basins and divisions have serious shortcomings that make them unsuitable for this task including their inconsistent adherence to topographically defined hydrological boundaries and coarse scale. Accordingly, we developed a new spatial framework using novel methods of drainage analysis of a DEM (Digital Elevation Model) that are especially suited to continental-scale application.

These methods ensure a connected drainage structure and realistic patterns of drainage density while recognising the linkages between a stream and its anabranch. They were applied to a pre-release version of the national 9 second DEM upgrade (version 3) that was completed in October 2007. This upgrade involved extensive correction and supplementation of the DEM source data and utilised an enhanced version of the ANUDEM elevation gridding program.

The continent-wide stream network that was delineated accurately depicts the mapped streams at a map scale of 1:250,000. On average, the DEM derived stream network is just 61 m from the nearest mapped stream line, the expected difference due to gridding and generalisation of the vector stream lines, and almost always within the grid cell resolution of about 270 m. It identifies nearly 1.2 million stream reaches that are the objects of the classification described in Appendix 8. A sub-catchment is delineated for each stream reach according to the flow direction grid that encodes surface flow pathways. These flow pathways also define the upstream contributing area that enables the catchment of each reach to be characterised and code more than 100,000 distributary points ensuring upstream attributes may be routed to both the stream and its anabranch. The new spatial framework thus provides a suitable basis for the ecohydrological classification based on landscape and climate data. It also has applications beyond this task to a broad range of river planning and management tasks.

7.1 Introduction

The spatial framework supplies the hydrologic units that will be the objects of the climate and landscape classification (Appendix 8) and the representation of surface drainage pathways that allow us to delineate their catchments and sub-catchments and attribute their environmental characteristics.

Existing national frameworks are unsuitable. The long-standing and most widely adopted of these, the Australian Water Resources Council (AWRC) drainage basins and divisions (Australian Water Resources Council 1976; AUSLIG 1997; Geoscience Australia 2003a), has serious shortcomings. The 245 drainage basins it delineates, based on the catchments of the major river systems, do not always adhere to topographically defined hydrological boundaries and the spatial scale of these units is too coarse to enable meaningful analysis of sub-basin scale variation in stream hydrology. Although the nested sub-catchments that supported the activities of the National Land and Water Resources Audit (Hutchinson *et al.* 2000) provide a much finer sub-division of catchments, their utility is limited by their failure to recognise distributary drainage structures or the natural variation in drainage density that occurs across the continent.

Here we describe the development of a new spatial framework that overcomes the limitations of the existing frameworks. Our framework is derived using new methods of drainage analysis especially suited to continental-scale application (Stein 2005, 2007) and now largely incorporated into the ANUDEM elevation gridding program (Hutchinson 2006). Like the traditional methods (Jenson and Domingue 1988; Jenson 1991) that are found in many GIS software (e.g. ArcGIS, ESRI 2007) our analysis depends on the derivation of a grid of flow directions from a DEM (Digital Elevation Model) (O'Callaghan and Mark 1984). This grid records the direction of flow from a grid cell to its neighbours. However, our method differs from the traditional methods in three fundamental ways. Firstly, it employs a drainage enforcement algorithm (Hutchinson 2006) and comprehensive correction of DEM source data errors and inadequacies to ensure that the DEM accurately represents surface drainage characteristics. This avoids the need for DEM pre-processing steps such as sink filling or carving (Jenson and Domingue 1988; Martz and Garbrecht 1998; Jones 2002; Ryan and Boyd 2003; Soille 2004), surface reconditioning (Hellweger 1997) and stream burning (Saunders 1999) that may produce undesirable artefacts (Hellweger 1997; Gallant and Wilson 2000). Secondly, it allows flow to be directed to more than one neighbouring cell at distributary points in the drainage network so recognising the linkages between a river and its anabranch. Finally, it uses mapped streamlines to initiate the channel network rather than the usual contributing area threshold, to delineate a stream network with more realistic patterns of drainage density (recognising that the true thresholds for channel initiation are well beyond the resolution of continental-scale DEMs).

We begin this report with a description of the recently revised version of the national 9 second DEM on which this analysis is based (Section 7.2) and the derivation of a grid of flow directions that code surface flow pathways (Section 7.3). Section 7.4 then explains the method used to delineate the stream network and contributing catchment areas before we conclude with a short summary of the characteristics of the derived framework including an assessment of its accuracy (Section 7.5) and definition of terms used in Appendix 8 (Section 7.6).

7.2 The national 9 second DEM

The national 9 second DEM (Fenner School of Environment and Society ANU and Geoscience Australia 2008) is a regular grid of elevation with a grid spacing of 9 seconds of latitude and longitude equating to a distance on the ground of between 194 m and 265 m in an east-west direction (depending on latitude) and about 270 m in a north-south direction. It is the highest resolution, drainage enforced DEM with continental coverage available for Australia. Source data for the DEM include directed streamlines, elevation spot height and cliff lines (Table 7.1). The version 3 upgrade of the DEM by the Fenner School of Environment and Society at the Australian National University (Fenner School of Environment and Society ANU and Geoscience Australia 2008) was completed and made available for this project in October 2007. The upgrade particularly focussed on the improved representation of drainage divides, systematic inclusion of cliff lines and lakes and further correction of source data errors and used an enhanced version of the ANUDEM elevation gridding program (Hutchinson 2006). For instance, more than 7,000 streamline arcs were digitised and nearly 88,000 elevation spot heights added to improve the drainage accuracy of the DEM. Over 25,000 true sinks (pits or surface depressions) identified from 1:100,000 scale topographic maps were represented in the DEM. They were most often found in sand dune fields, karst areas and ephemeral lakes and clay pans in low relief areas in arid or semi-arid regions.

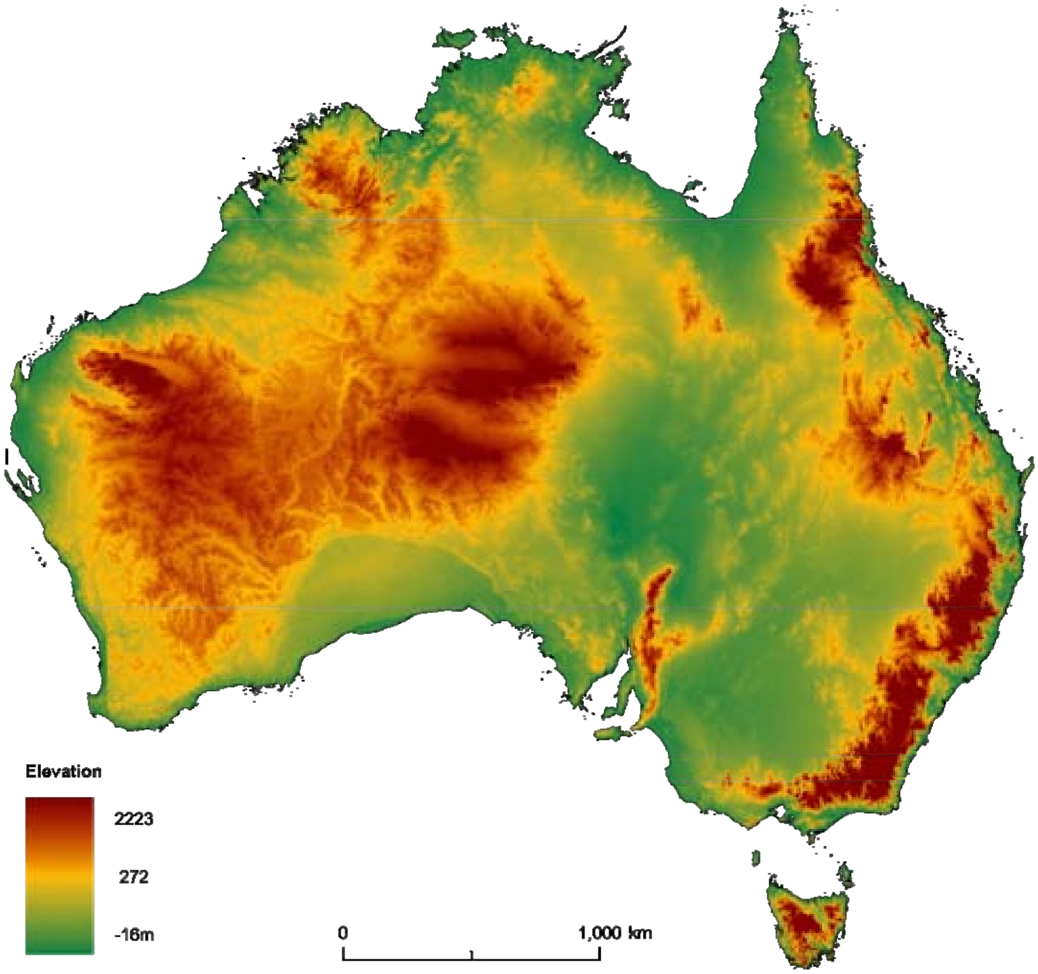

Figure 7.1. The 9 second DEM. Elevation values are mapped with a continuous colour ramp and a linear stretch of values between the mean plus or minus two standard deviations.

Table 7.1. Source data for the 9 second DEM version 3. Additional data were digitised from 1:100,000 scale topographic maps to overcome deficiencies in the original source data. See the 9 second DEM user guide for details (Fenner School of Environment and Society ANU and Geoscience Australia 2008).

Data type$_1$	**Data source**
Sink points	1:100,000 scale topographic maps
Directed streamline arcs	TOPO250K GEODATA DatabaseVersion 1 (AUSLIG 1992b)
Elevation spot heights	TOPO250K GEODATA DatabaseVersion 1 (AUSLIG 1992b), National Geodetic Data Base (NGDB) and Radar altimeter data for Lake Eyre (supplied by AUSLIG)
Lakes and reservoir polygons	TOPO250K GEODATA Version 1 (AUSLIG 1992b)
Cliff line arcs	TOPO250K GEODATA Version 2 (Geoscience Australia 2003b), 1:100,000 scale topographic maps
Coastline	GEODATA COAST-100K (AUSLIG 1992a), coastal inlets from the GEODATA TOPO–250K coastline (AUSLIG 1992b)

Like the previous upgrade (Hutchinson *et al.* 2001), the DEM was gridded in overlapping tiles corresponding with the geographic extent of Geoscience Australia's 1:1 million scale topographic map sheets, using an iterative procedure that involved extensive checking, editing and re-gridding. The individual DEM tiles were joined together with the Arc/Info Grid MOSAIC function. This function uses a proximity analysis algorithm to create a smooth transition in cell values across the overlap zone and minimise abrupt boundary changes between tiles (ESRI 2007).

The scale of the 9 second DEM is considered to be about 1:250,000 (Fenner School of Environment and Society ANU and Geoscience Australia 2008). The DEM has a standard error of 10 metres or less in the low relief areas that make up about half of the continental land area and up to about 60 metres in areas of steep and complex terrain (Fenner School of Environment and Society ANU and Geoscience Australia 2008). Suitable for applications at regional to continental scales (Fenner School of Environment and Society ANU and Geoscience Australia 2008), the 9 second DEM thus provides an appropriate basis for delineating a new national stream network for Australia.

7.3 The flow direction grid

The flow direction grid tiles that were produced by ANUDEM when fitting the DEM were merged to produce a grid with national coverage. The grid encodes a single flow direction

for all grid cells. An additional direction is coded for grid cells that contain distributary nodes in the channel system to direct flow to both arms of the bifurcating channels (
Figure 7.2). Minor shortcomings in the grid, including occasional loops, spurious sinks or crossing flow paths, were corrected using a combination of automatic procedures and manual editing. Sinks or pits in a DEM are grid cells or groups of cells with no neighbouring cells of lower elevation. The drainage direction of these grid cells is therefore undefined and they do not contribute flow to any other cells, so terminating flow paths.

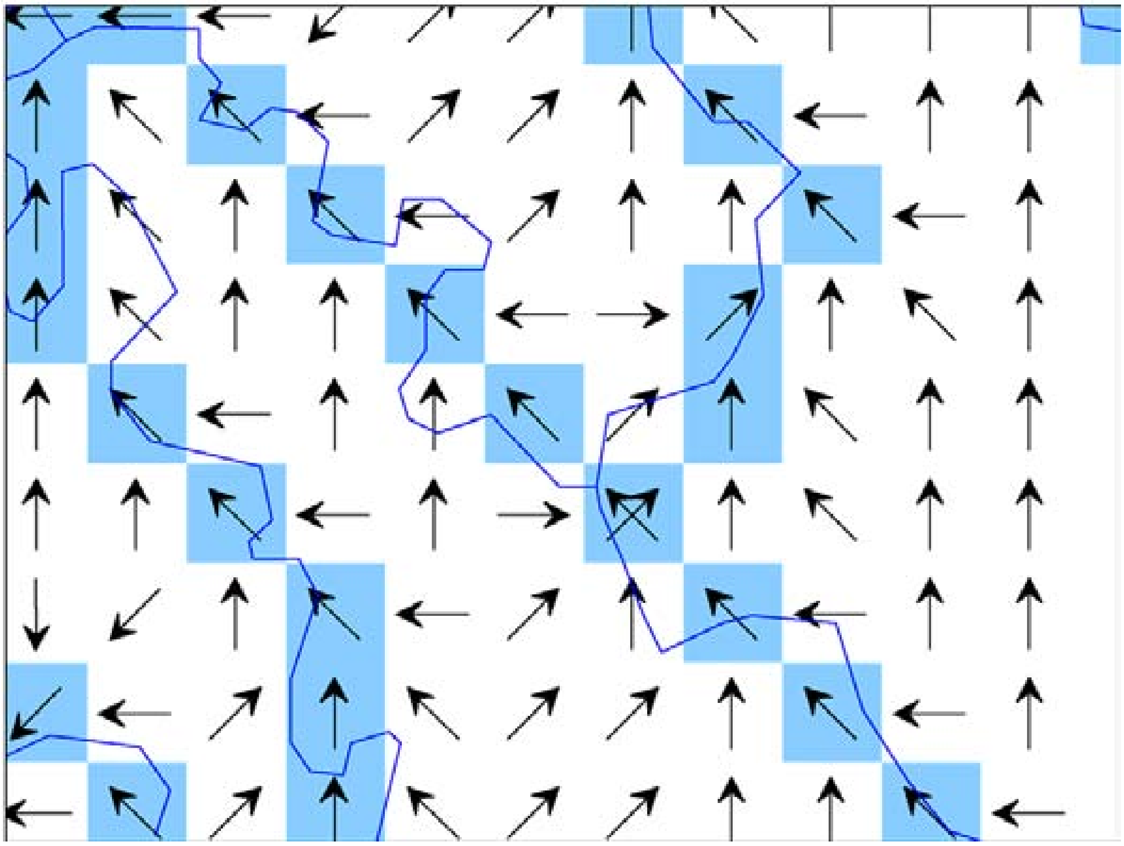

Figure 7.2. The flow direction grid showing multiple flow directions coded at distributary points in the channel network. Shown are the Geodata TOPO 250K vector streamlines (AUSLIG 1992b) and their gridded representation.

Loops were formed in the flow paths mostly along tile borders in areas of very low relief and ill-defined drainage. These were manually corrected either by altering the flow direction of one cell to flow out of the loop or by coding it as a sink. Spurious sinks (i.e. those not corresponding with a data (mapped) sink) were automatically cleared wherever possible by altering the flow direction of the sink cell to flow to a neighbouring stream cell (i.e. one through which a mapped stream passed) or otherwise to the lowest neighbouring cell that was not within the catchment of the sink. Remaining spurious sinks that were within 300 m of a mapped stream were cleared by manually altering the flow direction codes of grid cells in the vicinity of the sinks, guided by the 1:100,000 scale topographic maps. Elevation values were not altered.

Crossing flow paths, arising where the inter-cardinal flow directions of adjacent grid cells differ by 90 degrees (e.g. 45° and 315° or 135° and 225°), were occasionally formed along the tile borders when tiles were joined. These were also corrected by altering the flow direction of one of the grid cells, preferentially one not containing a mapped stream line.

Alterations were also made to the flow directions of occasional grid cells coded with multiple flow directions, principally to remove one of the flow directions where there was no evidence of a bifurcation in the mapped (data stream) channel network. This situation occurred where a grid cell contained more than one stream flowing in parallel. A rectangular neighbourhood of 5 by 5 cells around the multiple flow direction cell was searched for bifurcations in the mapped channel system. Bifurcations were identified from the arc – node topology of the mapped streamline vectors as nodes that occurred as the from (start) node for more than one arc. In erosional landscapes, as indicated by the Flatness Index of Gallant and Dowling (2003), the flow direction draining to the grid cell of the stream draining from the highest source was retained. Elsewhere, flow directions were removed from grid cells coded with multiple flow directions only where the flow pathways rejoined immediately downstream, upstream of any other confluence.

In some of the more complex braided or anastomosed sections of channel network it was also necessary to add flow directions to ensure the connectivity of flow pathways. An additional flow direction was added to a grid cell to direct the flow pathway to an adjacent, downstream grid cell with multiple flow directions that otherwise had no neighbouring cell coded as upstream. Where possible this was undertaken using automatic procedures, elsewhere with manual editing.

7.4 Delineating the stream network and its contributing catchment areas

A new national stream network was delineated based upon the stream network derived by ANUDEM. The ANUDEM stream network represents the input data streamlines, generalised to the 9 second grid resolution, and is consistent with the flow pathways defined in the flow direction grid. However, it also includes the numerous floodplain features such as ox bows or abandoned channels that exist among the input data streamlines as well as occasional spurious linkages between channels where a second flow direction was removed from a grid cell (see above).

A new 'DEM derived' stream network was delineated by tracing the flow pathways coded into the flow direction grid from channel heads to either a coastal outlet or inland sink (Figure 7.3). The location of channel heads was taken to be any grid cell that contained the head of a first order stream in the stream network produced by ANUDEM. Short (i.e. comprising less than 10 grid cells or about 2.5 km), unconnected channels exclusively located on valley bottom flats as defined by the Flatness Index, were assumed to be floodplain features and excluded.

The traced flow path joins each channel head to a sink or a coastal outlet and so produces a fully connected channel network. However, in many arid areas rainfall is insufficient for the maintenance of a connected channel system across the valley floors. Elsewhere tributary channels may terminate in wetlands or deltaic distributary systems of channels. A more realistic representation of the actual channelised flow network was derived by breaking the DEM derived stream network where there were disjunctions in the mapped streams as represented in the ANUDEM derived stream network.

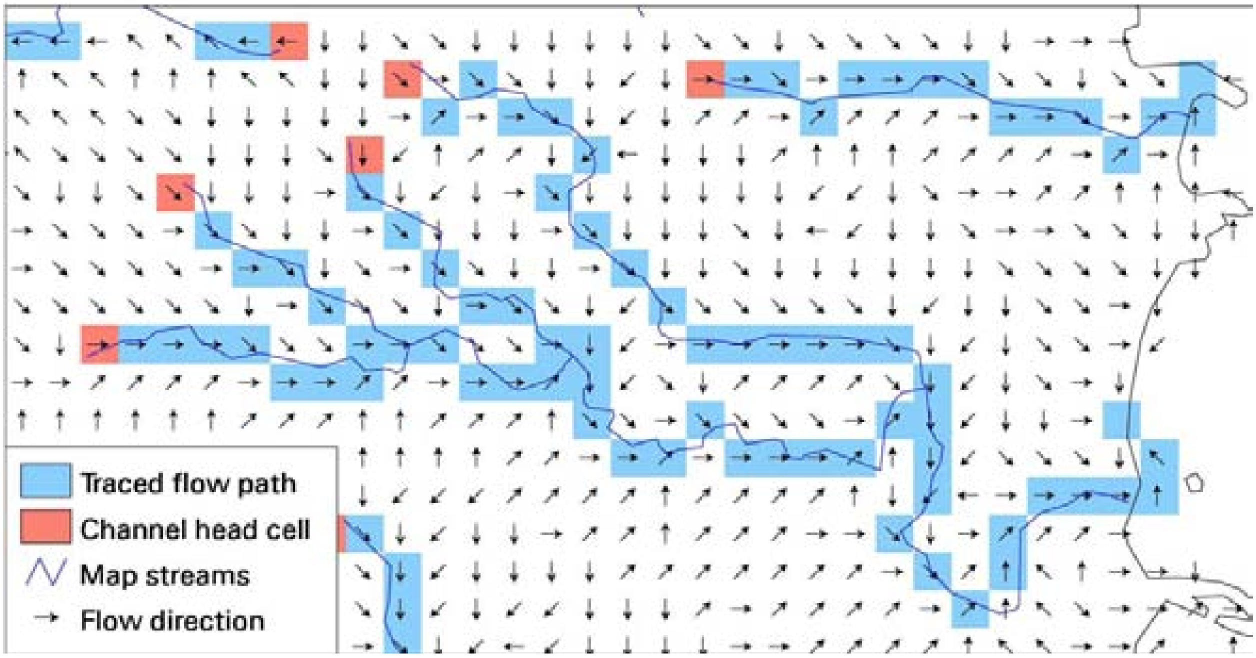

Figure 7.3. Tracing the stream network from identified channel head grid cells to an outlet on the coast.

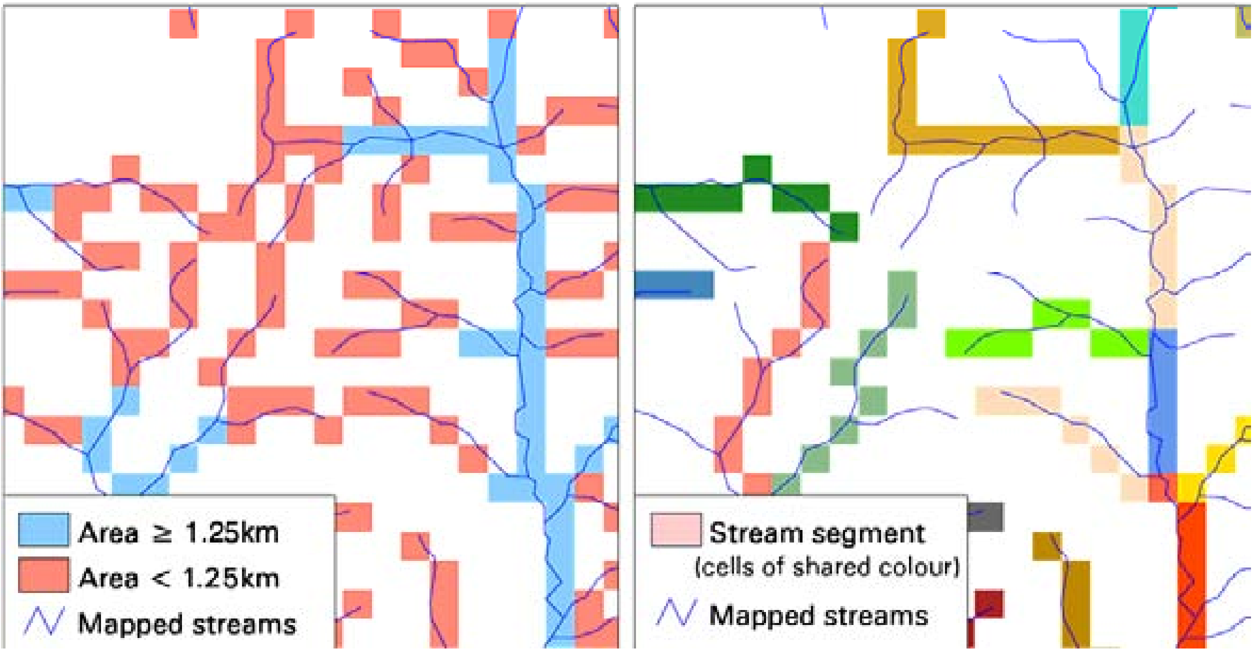

Figure 7.4. Clipping the stream network to remove source channels with a contributing area smaller than is reproducible from the 9 second DEM: the preliminary stream network, delineated by tracing flow pathways from channel heads (left) and the final stream network with stream segments indicated by shared colour (right). Compare this network with the truncated network (shown in blue on the left) that would be derived using just a contributing area threshold to delineate the network.

The resolution of the DEM limits the extent of the stream network and the size of the drainage features that can be extracted. Following the reasoning of Garbrecht and Martz (1994), Stein (2007) established that the smallest catchment area resolvable from the 9 second DEM, with a cell area of approximately 0.0625 km^2, would be 1.25 km^2. Thus, source channels with a contributing area of less than 1.25 km^2 at their pour-point were removed. However, main stem segments, defined as the segments draining the larger upstream contributing area, were retained to their source (Figure 7.4).

Stream segments (links), the section of the stream between tributary confluences, were uniquely identified and those longer than 20 km sub-divided into 10 km reaches. Segments were also divided where they flowed over a cliff so that the environmental characteristics of the sections of stream above and below the cliff could be individually attributed. Similarly, stream links were divided where the stream entered a large lake. Sub-catchment areas were delineated for each stream segment/reach in the derived stream network with the Arc/Info Grid WATERSHED function (ESRI 2007) seeded by the stream segment/reach grid cells. Grid cells were thus assigned the unique identifier of the stream segment to which they directly drained.

7.5 A spatial framework

A new national stream network was delineated with nearly 1.2 million stream segments. Segments average 2.5 km in length up to a maximum length of 161 km reflecting the natural variation in drainage density across the continent. Just over 1,000 segments of length greater than 20 km were sub-divided into shorter 10 km reaches. More than 100,000 distributary points were recognised and coded with multiple flow directions (
Figure 7.5).

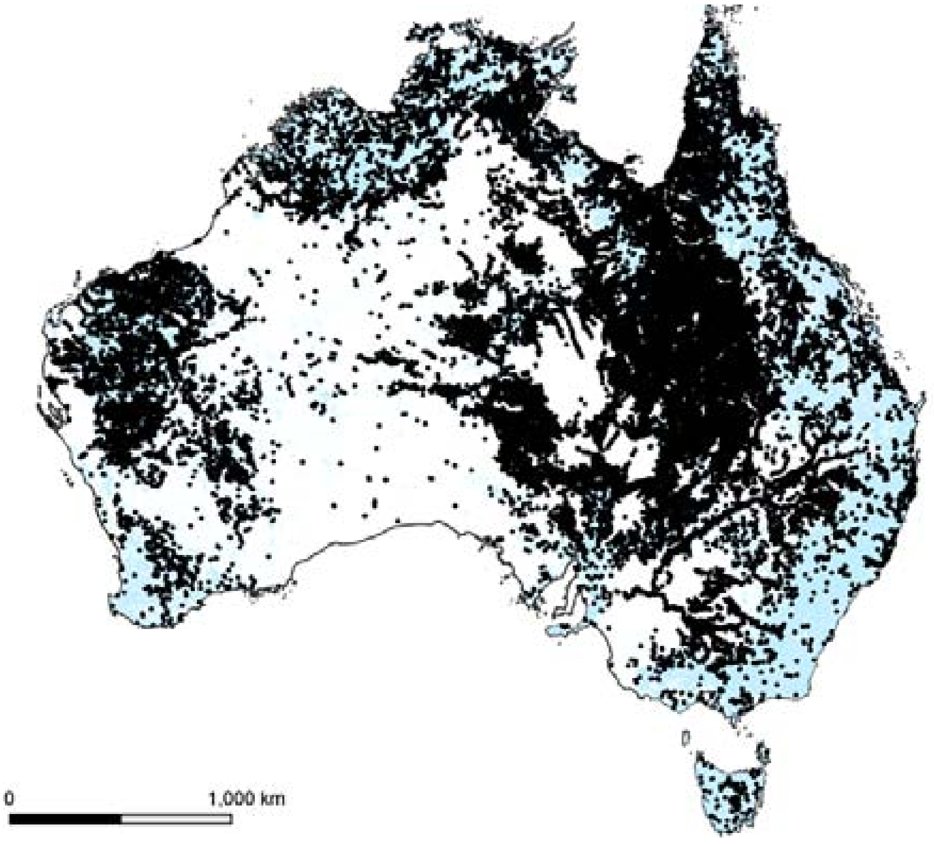

Figure 7.5. Location of distributary points in the stream network coded with multiple flow directions.

The stream network accurately represents streamlines at a map scale of about 1:250,000 including the extensively anabranching systems that occur in many inland areas (Figure 7.6). Its accuracy was assessed by calculating the distance from a set of points randomly selected along the DEM derived stream lines to the nearest input data stream line from Geoscience Australia's GEODATA 1:250,000 scale mapped streamlines (AUSLIG 1992b) (supplemented from 1:100,000 scale topographic mapping). To ensure consistent coverage 1,000 points were selected from the DEM derived stream lines for each of the 44 tiles that correspond with Geoscience Australia's 1:1 million scale map series. The forty-four thousand randomly selected points were found to be on average just 61.6 m from the mapped stream. This distance reflects the expected difference due to gridding and generalisation of the vector stream lines to the grid cell resolution of 9 seconds of latitude and longitude (about 270 m). Virtually all (99.9% or better) of these points were within 270 m of the mapped stream indicating the DEM derived stream network depicts realistic patterns of drainage density and will provide a suitable spatial framework for the task of developing an ecohydrological environment classification (Appendix 8). The stream network also supports a range of other river planning and management activities at regional to continental scales.

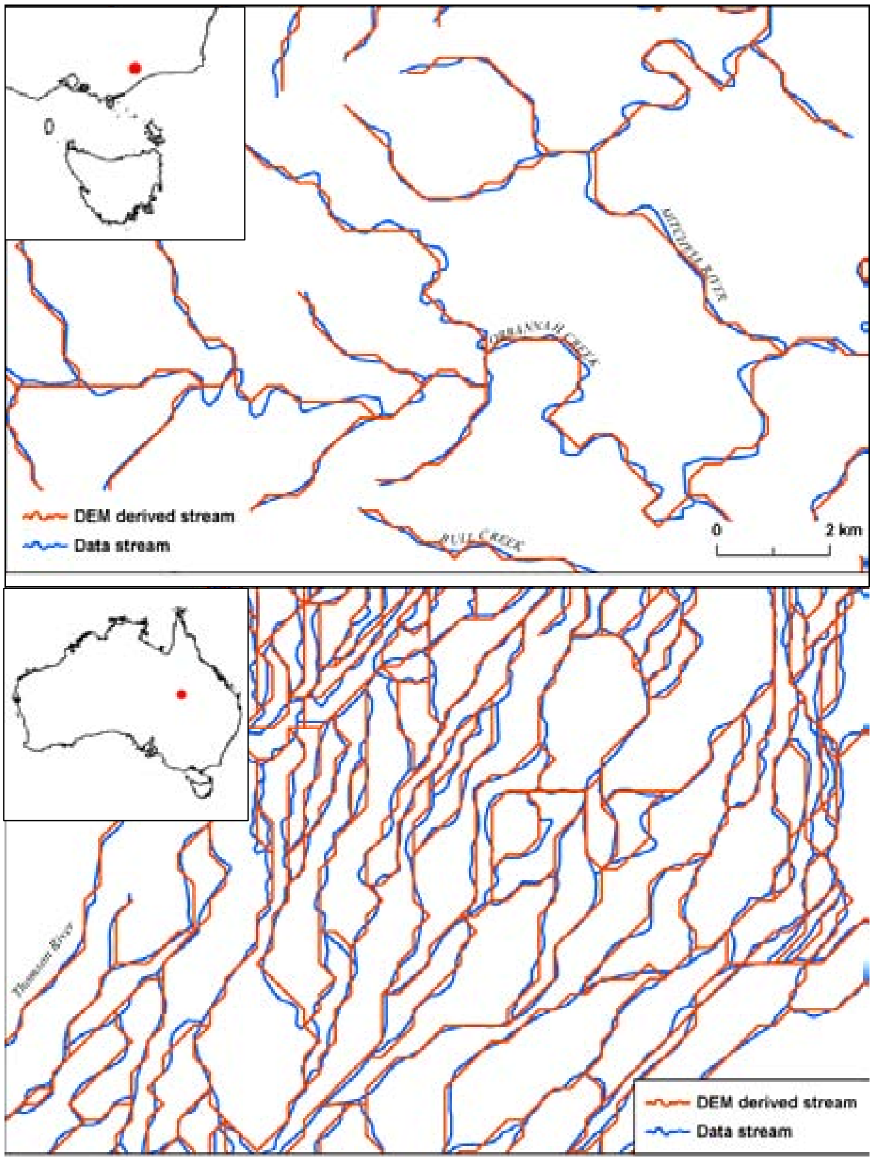

Figure 7.6. Comparing the DEM derived stream network and mapped (data) streamlines from the GEODATA TOPO-250K database version 1(AUSLIG 1992b) for a

section of the Mitchell River in Victoria (top) and the Thomson River in Queensland (bottom).

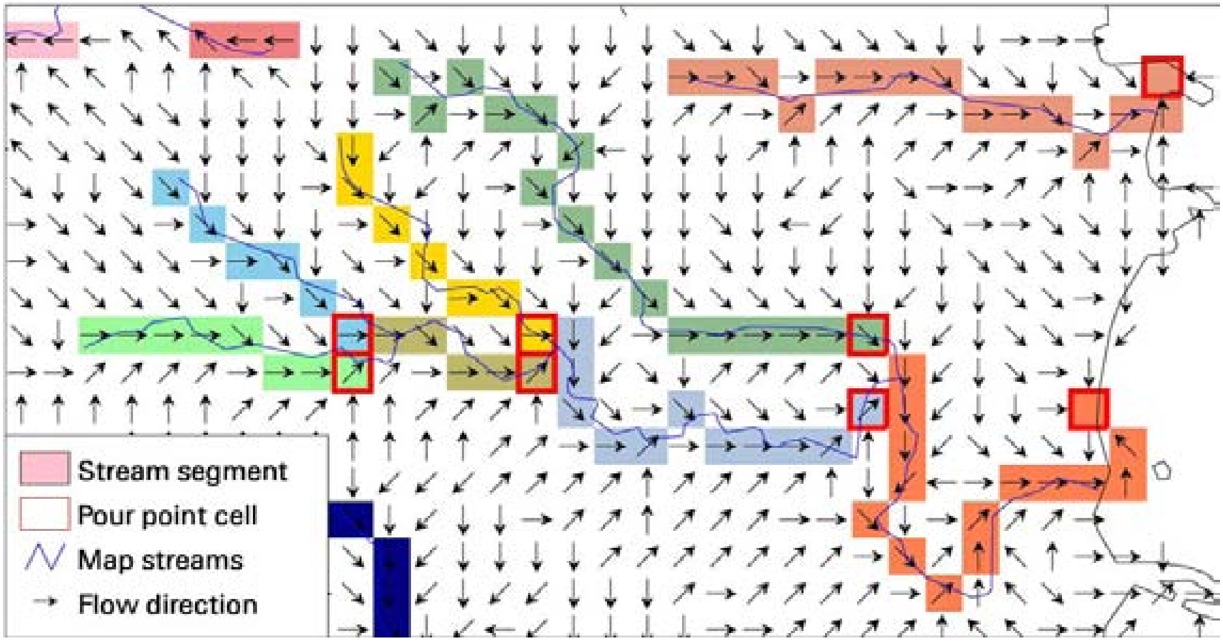

Figure 7.7. Reaches (segments) and pour-points. Stream reaches (segments) are shown as grid cells shaded with the same colour.

7.6 Spatial units

Appendix 8 refers to a number of spatial units including catchments, sub-catchments, reaches and pour-points. Reaches are the objects of the climate and landscape classification and as noted above are in most cases equivalent to a segment, the section of the stream between tributary confluences (Figure 7.7). Attribution of catchment environmental descriptors is done by considering the attribute value at the reach pour-point or outlet cell, that is, the cell on a stream reach immediately above a confluence that directly flows into the cell of a downstream reach (Figure 7.7). For terminal segments, the pour-point is the most downstream cell in the reach. This is often a sink or otherwise an outflow to the ocean. A sub-catchment is the area contributing directly to a stream segment (Figure **7.8**). The catchment is the entire area draining to a pour-point and thus also includes all of the sub-catchments upstream.

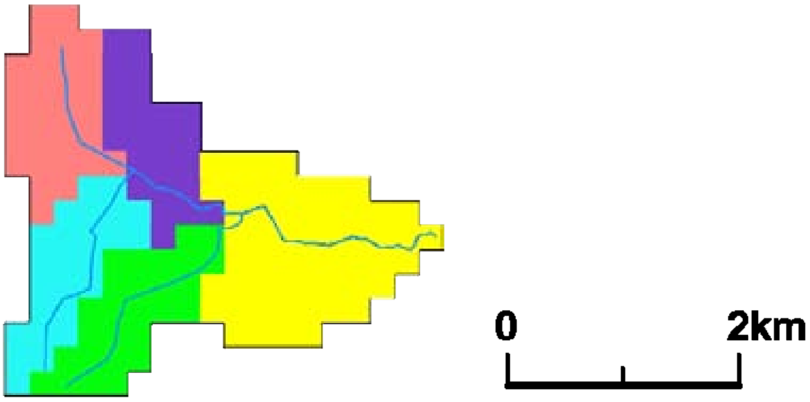

Figure 7.8. Catchments and sub-catchments. Each of the coloured areas is a sub-catchment i.e. the area contributing directly to a stream segment. The catchment is the entire area draining to a pour-point and thus also includes all of the sub-catchments upstream.

7.7 Acknowledgements

The maps shown in Figures 7.1 to 7.8 incorporate data which is © Commonwealth of Australia, Geoscience Australia 1992 and 2004.

7.8 References

AUSLIG. (1992a). *GEODATA COAST 100K* Australian Survey and Land Information Group, Canberra.

AUSLIG. (1992b). *GEODATA TOPO-250K User Guide*. Australian Survey and Land Information Group, Canberra.

AUSLIG. (1997). *River Basins of Australia*, Version 1.0. Australian Survey and Land Information Group, Canberra.

Australian Water Resources Council. (1976). *Review of Australia's water resources 1975*. Australian Water Resources Council, Australian Government Department of Natural Resources, Canberra. 170 pp.

ESRI. (2007). *Arc/Info*, Version 9.1. Environmental Systems Research Institute, Inc., Redlands.

Fenner School of Environment and Society ANU and Geoscience Australia. (2008). *GEODATA 9 Second DEM and D8. Digital Elevation Model Version 3 and Flow Direction Grid User Guide* [online]. Geoscience Australia. Available: http://www.ga.gov.au/nmd/products/digidat/dem_9s.jsp

Gallant, J. C. and Dowling, T. I. (2003). A multi-resolution index of valley bottom flatness for mapping depositional areas. *Water Resources Research* 39(12): 1347.

Gallant, J. C. and Wilson, J. P. (2000). Primary topographic attributes. Pp. 51–85. In Wilson, J. P. and Gallant, J. C. (eds), *Terrain analysis: principles and applications*. John Wiley & Sons, New York.

Garbrecht, J. and Martz, L. (1994). Grid size dependency of parameters extracted from digital elevation models. *Computers & Geosciences* 20(1): 85–87.

Geoscience Australia. (2003a). *Australian Surface Water Management Areas (ASWMA) 2000 Product User Guide*. Geoscience Australia, Canberra. 20 pp.

Geoscience Australia. (2003b). *GEODATA TOPO 250K Series 2 Topographic Data*. Geoscience Australia, Canberra.

Hellweger, F. (1997). *AGREE – DEM Surface Reconditioning System*. University of Texas, Austin, Texas. http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html

Hutchinson, M. F. (2006). *ANUDEM*, Version 5.2. Centre for Resource and Environmental Studies, Australian National University, Canberra. http://cres.anu.edu.au/outputs/anudem.php

Hutchinson, M. F., Stein, J. A. and Stein, J. L. (2001). *Upgrade of the 9 Second Australian Digital Elevation Model. A Joint Project of CRES and AUSLIG* [online]. Centre for Resource and Environmental Studies, Australian National University, Canberra. Available: http://cres.anu.edu.au/dem/index.php#4.

Hutchinson, M. F., Stein, J. L. and Stein, J. A. (2000). *Derivation of Nested Catchments and Sub-Catchments for the Australian Continent*. [online]. Centre for Resource and Environmental Studies, Australian National University, Canberra. Available: http://cres.anu.edu.au/outputs/audit/index.html

Jenson, S. K. (1991). Applications of hydrologic information automatically extracted from digital elevation models. *Hydrological Processes* 5: 31–44.

Jenson, S. K. and Domingue, J. O. (1988). Extracting topographic structure from digital elevation data for geographic system analysis. *Photogrammetric Engineering and Remote Sensing* 54: 1593–1600.

Jones, R. (2002). Algorithms for using a DEM for mapping catchment areas of stream sediment samples. *Computers & Geosciences* 28: 1051–1060.

Martz, L. W. and Garbrecht, J. (1998). The treatment of flat areas and depressions in automated drainage analysis of raster digital elevation models. *Hydrological Processes* 12: 843–855.

O'Callaghan, J. F. and Mark, D. M. (1984). The extraction of drainage networks from digital elevation data. Computer Vision. *Graphics and Image Processing* 28: 328–344.

Ryan, C. and Boyd, M. (2003). Catchment SIM: a new GIS tool for topographic geo-computation and hydrologic modelling. Presented at *28th International Hydrology and Water Resources Symposium*. Wollongong, NSW, 10–14 November 2003. The Institution of Engineers, Australia.

Saunders, W. C. (1999). Preparation of DEMs for use in environmental modeling analysis. Presented at *ESRI User Conference*. San Diego, California, 24–30 July 1999. Retrieved from: http://gis.esri.com/library/userconf/proc99/proceed/papers/pap802/p802.htm

Soille, P. (2004). Optimal removal of spurious pits in grid digital elevation models. *Water Resources Research* 40(12): W12509.

Stein, J. L. (2005). A national landscape framework for river and stream conservation: developing a new stream and catchment reference system. Pp. 548-552. Rutherford, I. D., Wiszniewski, I., Askey-Doran, M. and Glazik, R. (eds). Presented at *Fourth Australian Stream Management Conference: linking rivers to landscapes*. Launceston, Tasmania, 19–22 October 2004. Department of Primary Industries, Water and Environment.

Stein, J. L. (2007). *A continental landscape framework for systematic conservation planning for Australian rivers and streams.* PhD Thesis, Centre for Resource and Environmental Studies, Australian National University, Canberra.

Appendix 8

Ecohydrological classification based on landscape and climate data

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Summary

We grouped rivers and streams continent-wide on the basis of their multi-variate similarities using attributes that we expected would characterise the principal climatic and landscape factors that ultimately controlled ecologically relevant aspects of stream hydrology. A number of alternative classifications were generated using the ALOB non-hierarchical clustering method by varying the sets of attributes, weightings and transformations and numbers of groups. A 30 group classification was selected based on its greater capacity to recover the flow regime classes produced by the multi-metric classification of 830 gauges (Appendix 5) and explain meaningful variation in ecologically relevant descriptors of flow and for ease of communication. This 30 group ecohydrological environment classification was based on a set of 48 attributes describing the catchment climate, water balance, topography, substrate and vegetation cover of each of the 1.2 million stream reaches. No explicit weighting was applied to the attributes in this classification.

Stream reaches are not distributed evenly among the groups, the length of stream they contain varying by an order of magnitude between the smallest and largest groups. The diversity of types was also shown to vary greatly at a range of spatial scales. The groups are primarily differentiated by attributes describing the catchment climate and water balance and secondarily by attributes characterising the catchment morphology, substrate and vegetation cover. Ten spatially coherent meta-groups were recognised from a hierarchical clustering of the group means. There are broad similarities between this classification and an agro-climatic classification reinforcing the overriding influence of climate on the observed patterns. In contrast, there was little concordance between the ecohydrological environment classification and the Australian Water Resources Council Drainage Divisions.

The performance of the classification was assessed using the flow data compiled for the flow regime classification described in Appendix 5. The results were mixed. The classification strength was relatively high (75% of that for a comparable empirical classification) and better than that for alternative national classifications including the Interim Biogeographical Regionalisation of Australia (IBRA). The groups differentiated significant variation in many of the ecologically important descriptors of flow though less effectively for those metrics describing the frequency and duration of extreme events. However, the flow regime classes were only moderately well recovered by the ecohydrological environment groups.

We describe here the limitations and uncertainties in our classification. These might be addressed by alternative classificatory strategies and improved characterisation of some hydrological processes, notably those that control the groundwater contribution to streams. This would be the subject of future research. Despite these limitations, we expect the ecohydrological environment classification to effectively support applications at broad regional to continental scale. We suggested, for instance, that it might be applied to the task of designing a more representative network of gauging stations. It could also provide context for finer scale regional or catchment studies.

8.1 Introduction

The classification of 830 stream gauges Australia-wide, based on ecologically relevant attributes of their hydrology, enabled a detailed description and understanding of variability in the natural flow regime (Appendices 5 and 6) but is only applicable to gauged streams. Methods to extend flow parameters to ungauged streams are developing (see review in Croke 2002), but are confounded by the effects of flow regulation and catchment development.

On the other hand, environmental or landscape classification based on continent-wide environmental data can be applied to all streams and all sections of streams. Environmental classifications can be derived by drawing boundaries around relatively homogeneous geographic areas with a characteristic association of ecosystems (Bryce and Clarke 1996; Omernik and Bailey 1997) or by multivariate classification of spatially referenced objects described by the principal landscape factors responsible for the characteristics of interest ('driving' or 'controlling' variables) (O'Keefe and Uys 2000; Bourgeron *et al.* 2001).

Ecoregion classifications, including the Interim Biogeographical Regionalisation of Australia (IBRA) (Thackway and Cresswell 1995), are examples of the former approach and are widely used to support an ecosystem based approach to natural resource planning and management (Clarke *et al.* 1991; Warry and Hanau 1993; Omernik 1995; Bailey 1996; Bryce and Clarke 1996; Uhlig and Jordan 1996; Harding and Winterbourn 1997). However, ecoregion classifications have generally performed poorly when applied to freshwater ecosystems. Cited concerns include their inability to effectively partition variation in biological composition (Hawkins *et al.* 2000) or flow regimes among rivers (Snelder and Hughey 2005) and the often inconsistent application and poor communication of the decision rules for boundary placement(Kingsford *et al.* 2005).

Environmental domain analysis (Mackey *et al.* 1988; Mackey *et al.* 1989; Nix 1992, 1997; Mackey *et al.* 2001; Mackey *et al.* 2007) typifies the second approach to environmental classification using numerical clustering procedures to group spatial units on the basis of their shared multi-variate similarities across attributes describing meso-scale climate, substrate (regolith and soils) and topography that ultimately control landscape physical processes and biological function. Environmental domains are thus delineated in environmental rather than geographic space and do not necessarily form regions. While there are still subjective choices as to attributes, weightings, classificatory strategy and numbers of groups these are explicit and therefore transparent and repeatable. Commonly adopted to represent patterns of terrestrial biodiversity (Mackey *et al.* 1989; Lewis *et al.* 1991; Belbin 1993a; Kirkpatrick and Brown 1994; Mackey *et al.* 2000; Nix *et al.* 2000; Mackey *et al.* 2001; Leathwick *et al.* 2003; Trakhtenbrot and Kadmon 2005) the environmental domain approach has only recently been applied to rivers (Jerie *et al.* 2003; Stein 2007).

Here we apply the approach to develop an ecohydrological environment classification for all of the rivers and streams of Australia. We describe the environmental characteristics of the derived groups and the relationships between them. We also explore spatial variation in the diversity of ecohydrological environment groups at different scales and compare this classification with other national classifications. The performance of the classification is judged by its ability to recover the flow regime classes identified by the empirical classification of gauging stations (Appendix 5) and to discriminate meaningful variation in the ecologically relevant flow metrics on which these classes are based. We conclude with discussion of the limitations of the classification and suggestions for future improvement.

8.2 Methods

8.2.1. Classificatory strategy

Stream reaches (Appendix 7) were individually classified based on description of the environmental characteristics of their upstream catchment and local valley morphology (Section 8.2.2). The ecohydrological environment classes were derived using a numerical clustering procedure (ALOB) (Belbin 1993b). Classes are thus an emergent property of the data and reflect the shared similarities of key attributes (e.g. environmental domains Mackey *et al.* 1988). The alternative approach of specifying *a priori* the boundaries between classes as the outer limits of the features that characterise them (O'Keefe and Uys 2000) (e.g. New Zealand's River Environment Classification, Snelder and Biggs 2002) was not used as it assumes all possible types are already known.

We chose the ALOB non-hierarchical clustering method because it is well suited to classifying very large numbers of objects (Mackey *et al.* 1988; Mackey *et al.* 1989; Lewis *et al.* 1991; Nix, Stein and Stein 1992; Nix, Stein, Stein *et al.* 1992; Nix *et al.* 2000) and produces results that are at least comparable with traditional agglomerative hierarchical methods (Belbin 1987; Belbin and McDonald 1993). ALOB employs a simple iterative procedure to allocate objects into groups (Box 8.1). As ALOB is relatively insensitive to the choice of starting configuration (Belbin 1987) we applied the default option to use the first object (i.e. stream reach) as the initial group seed. Reaches that are more distant in data space than the specified allocation radius from this initial seed become the seeds for additional groups. We employed the Gower metric (Gower 1971) to measure this distance as it is appropriate for quantitative data (Belbin 1993b) and incorporates a range standardisation ensuring attributes with a larger range of values do not have undue influence on the classification. Thus the distance D_{ij} between reaches i and j for p variables x_k (k=1,….p) is given by:

$$D_{ij} = \sum_{k=1}^{p} \frac{|X_{ik} - X_{jk}|}{r_k}$$

Where r_k is the range of the kth variable (Belbin 1993b). The allocation radius that determines the number of groups derived was automatically set to the value that produced the result closest to the desired number of groups.

We generated a number of classifications by varying the set of attributes, attribute weightings and transformations and numbers of groups (Section 8.2.3) recognising that these choices are largely subjective. Our preferred ecohydrological environment classification was selected based on three criteria:

1) Its ability to recover the ecohydrological flow regime types generated by classification of the gauged data (Appendix 5) as judged by the Hubert-Arabie adjusted Rand Index.
2) Discrimination of variation in ecologically relevant descriptors of the flow regime within and across groups, as measured by its classification strength (Van Sickle 1997; Van Sickle and Hughes 2000).
3) The ease of interpretation and use.

The Hubert-Arabie adjusted Rand Index is generally accepted as the most reliable for measuring cluster recovery (Steinley 2004). It was calculated using the RIND module of the PATN software package (Belbin 1993b) and takes values in the range zero to one. An index value of one indicates a perfect match between the two groupings while a zero value implies an association no better than chance (Belbin 1993b).

Classification strength (CS) is calculated as the mean of all pairwise within group similarities $\left(\overline{W}\right)$ relative to the mean of all pairwise between group similarities $\left(\overline{B}\right)$ (Van Sickle 1997; Van Sickle and Hughes 2000). Average within group similarities are weighted by the number of objects within the group and only defined for groups with two or more members. CS may be expressed as the difference $\left(\overline{W}-\overline{B}\right)$ or the unitless ratio $\left(\overline{B}/\overline{W}\right)$. A large difference or a small ratio implies objects in the same group are substantially more similar to each other than they are to objects in other groups and hence is indicative of a strong classification (Van Sickle and Hughes 2000). CS was computed for each of the classifications with a modified version (Stein 2007) of the ASIM program from PATN version 3.6 (Belbin 1993b). The Gower measure was used to calculate the similarity between flow gauges across all 120 metrics. A test of the null hypothesis of 'no class structure' was also conducted using ASIM to randomly permute objects between groups and compare the randomised ratio ($\overline{B}/\overline{W}$) to that of the *a priori* classification. The test was applied by determining the number of times the ratio derived for the random grouping was less than that derived for the *a priori* classifications from the default 100 permutations.

To assist understanding of the relationships between the groups, the centroids of the groups generated with the ALOB non-hierarchical algorithm were themselves classified using the hierarchical agglomerative clustering routine, flexible UPGMA (Un-weighted Pair Group Mean Averaging), implemented in the FUSE module of PATN (Belbin *et al.* 1992). This clustering strategy weights objects equally as groups are successively combined. Belbin and colleagues (1992) demonstrated that this approach recovered simulated clusters better than an alternative option, flexible WPGMA, that weights groups equally, implicitly varying the weight of the object with the size of the group. Input to FUSE was the association matrix containing the dissimilarity between all pairs of group centroids produced by ALOB using the Gower metric and the specified attribute groupings. The β parameter, controlling the degree of dilation or contraction of the distance between groups as they join ('fuse'), was set to the recommended value of –0.1 (Belbin *et al.* 1992). A dendrogram depicts the fusion history graphically.

A 3-dimensional ordination of the group centroids was constructed with the semi-strong hybrid multi-dimensional ordination method available in PATN version 3.03 (Belbin and Collins 2004) as before using the Gower metric. For mapping, each group was assigned a colour based on its position in the configuration with each dimension aligned to a primary colour (Belbin *et al.* 1983). Box and whisker plots were produced using the R statistical software package (R Development Core Team 2004).

Box 8.1. The ALOB clustering algorithm (Belbin 1987).

1. Define a set of seed objects to act as a starting configuration
2. Create additional seeds from objects that are further (in data space) than the allocation radius from existing seeds
3. Generate an initial classification by allocating each object to the closest seed
4. Compute the centroid of each of the groups as the average of the attribute values for all objects in the group
5. Sequentially extract each object from its group and re-compute the group centroid. Calculate the distance from the object to each group centroid and (re-) allocate the object to its closest group
6. Recompute all group centroids and repeat steps 5 and 6 until there are no more objects to reallocate

8.2.2 Attributing environmental characteristics

Stream reaches were attributed with data for a broad set of environmental variables that we believed characterised potentially important landscape controls on the flow regime. Attribute selection was informed by a review of the landscape attributes used for river environment classifications elsewhere (Stein 2007) and professional judgement but was limited by the availability of suitable spatial data with consistent, continent-wide coverage. This set formed the basis for the final selection of attributes on which the ecohydrological environment classification was based.

Gridded data layers were derived for each of the selected landscape and climate attributes. Catchment average values were calculated by accumulating the values of all upstream grid cells according to the DEM-defined flow pathways and dividing by the number of upstream cells. Following Stein (2007), the accumulated totals and cell counts were distributed to anabranches in accordance with stream name in the ratio of 8 rivers: 4 creeks: 1 unnamed stream: 0.1 floodplain wetlands. Sub-catchment or reach scale attributes were derived by summarising the grid cell values of the stream reach and/or its sub-catchment only.

8.2.2.1 Climate

Climate ultimately controls many stream processes. The amount of runoff available for stream flow is a function of the precipitation falling within the catchment and is reduced by losses due to evaporation (among others) (Williamson 1998). Rainfall and temperature affect rates of weathering of rock and accordingly the rock's hydrogeological characteristics including its porosity and permeability (Ollier and Pain 1996; Knighton 1998; Nanson *et al.* 2005). Climatic parameters supply indicators for the critical environmental regimes (light, moisture, thermal) that control plant growth (Nix 1981, 1992, 1997) that in turn influence infiltration and runoff processes.

The climate of the catchment upstream of each stream reach was characterised by a sub-set of the bioclimatic parameters summarising annual and seasonal mean conditions, extreme values and intra-year seasonality (Nix 1986; Hutchinson *et al.* 2000). These were computed for each cell of the national 9 second DEM version 3 (Table 8.1). The rainfall erosivity R factor was included as an indicator of rainfall intensity, an important influence on processes of infiltration and runoff generation. It describes the potential for rainfall-induced soil loss based on storm kinetic energy and the maximum, 30-minute rainfall intensity (Lu and Yu 2002). Catchment average values of long-term monthly mean rainfall, minimum and maximum temperature and potential and actual evapotranspiration that had been derived from the Bureau of Meteorology Climate Atlas grids (Walsh *et al.* 2007) were also compiled to assist interpretation.

Table 8.1. Climatic attributes derived by calculating the average value of all grid cells upstream of the reach pour-point. Attributes indicated in bold were log10(x+1) transformed for classification. All were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.30).

Attribute	Units	Source
Annual mean rainfall	**mm**	**1**
Annual mean temperature	**degrees C**	**1**
Driest quarter mean rainfall	**mm**	**1**
Wettest quarter mean rainfall	**mm**	**1**
Coldest quarter mean rainfall	**mm**	**1**
Warmest quarter mean rainfall	**mm**	**1**
Annual mean solar radiation	**MJ/m^2/day**	**1**
Hottest month mean temperature	**degrees C**	**1**
Coldest month mean temperature	**degrees C**	**1**
Rainfall erosivity R factor	**(MJ mm)/(ha hr yr)**	**2**

Source data:ANUCLIM (Hutchinson et al. 2000); 2. NLWRA (National Land and Water Resources Audit 2000)

8.2.2.2 Catchment water balance

The catchment water balance attributes describe more directly the key aspects of the climatic influence on stream hydrology. They were derived from real time estimates of monthly runoff computed with the water balance module of the GROWEST program (Nix 1981; Hutchinson *et al.* 2004). This or similar models have been found to reasonably reproduce annual (Atkinson *et al.* 2002; Stein *et al.* 2002) or monthly flows (Lewis 1998; Xiong and Guo 1999; Jellett 2005). Unlike more complex rainfall-runoff models catchment specific calibration of model parameters could be avoided by setting the two required parameters based on broadly known soil attributes. It was thus suitable for continent-wide application.

GROWEST operates on a weekly time step, converting the monthly input rainfall and pan evaporation data to weekly values via cubic Bessel interpolation. The water balance module is conceptualised as a single 'bucket' model. It adds rainfall to the previous soil storage and removes it by means of evapotranspiration. The soil water surplus or 'runoff' is the rainfall exceeding 'bucket full' after allowing for actual evapotranspiration, calculated relative to potential evapotranspiration as a simple exponential function of the relative soil moisture content. For the purposes of a comparative study we assume that pan evaporation is the same as potential evapotranspiration achieved under a full canopy when water is non-limiting (Hutchinson *et al.* 1992). Monthly rainfall and pan evaporation estimates were generated at a grid spacing of 0.01 degrees (approximately 1 km) using elevation values derived by resampling the 9 second DEM version 3 with bilinear interpolation, and monthly climate surface coefficients (Kesteven *et al.* 2004) for a 30 year period from 1971 to 2000. This period matches as closely as possible that used for the classification of flow regimes that extends back to 1965 (Appendix 5). Evaporation data collected up to the early 1970s were less reliable as evaporation pans were not all fitted with bird guards (Bureau of Meteorology, private communication). The impact on the calculated 'runoff' was not significant.

GROWEST requires information for two soil parameters: the maximum available soil water capacity and the soil texture category (one of sandy loam, clay loam or clay) used to infer the relative water retention capabilities of the soil. Soil texture category was defined by classifying the values in the Australian Soil Resource Information System (ASRIS) grid of percent of clay in the A horizon (National Land and Water Resources Audit 2001d). Maximum available soil water parameters were derived by summing the ASRIS gridded values for the soil A and B horizons (National Land and Water Resources Audit 2001b, 2001c). Summary statistics derived from the monthly catchment water balance values (Table 8.2) were calculated from the reach pour-point accumulated totals of the upstream grid cell runoff estimates, converted to a volume by multiplying by the cell area.

Delayed runoff from precipitation that falls as snow during winter can produce significant flood peaks in spring. A simple indicator of the potential influence of snowfall on stream hydrology (Stein 2007) in south-eastern Australia was derived by calculating the proportion of the catchment long-term mean annual runoff generated above the snowline: 1400 m on the mainland (Hennessy *et al.* 2003) and 1100 m in Tasmania (Parkinson 1986). Only runoff generated in the alpine areas of south-eastern Australia (i.e. areas south of 34°12' S) was considered. Although snow falls occasionally elsewhere along the Eastern Highlands, it has little impact on stream flow characteristics (Warner 1986).

Table 8.2. Catchment water balance attributes derived from the monthly accumulated soil water surplus values (1971 to 2000) calculated in units of ML/month for each stream reach pour-point grid cell. As required for classification, the attributes shown in bold were standardised by dividing by the catchment area at the reach pour-point and $\log_{10}(x+1)$ transformed. Attributes indicated in italics were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.3).

Mean of the annual totals	Coefficient of variation of the annual maximum monthly
Coefficient of variation of the annual totals	Coefficient of variation of the annual minimum monthly
Minimum of annual totals	**Seasonal mean (summer, winter, autumn and spring)**
Maximum of annual totals	***Monthly means (January to December)***
Percentiles of annual totals **(5,10,20,30,40,*50*,60,70,80,90,*95*%),**	Coefficient of variation of the monthly totals
Mean of the annual minimum monthly	*Skewness (Median annual accumulated soil water surplus / mean annual accumulated soil water surplus)*
Mean of the annual maximum monthly	*Perenniality (proportional contribution to mean annual discharge by the six driest months of the year) (%)*
Proportion of mean annual accumulated soil water surplus generated above the snow line in south-eastern Australia (> 1400m elevation on the mainland, > 1100m in Tasmania) (%)	

8.2.2.3 Substrate

The hydrogeological properties of the substrate underlying the catchment plays a major role in shaping ecologically important properties of the stream hydrograph, such as the contribution from groundwater and the size of the peak flows (McMahon 1977; Goodwin 1996). To characterise this influence the areal proportion of bedrock lithology classes within the upstream catchment and the catchment average values of key soil hydrological properties (Table 8.3) were determined for each stream reach. The lithological classes were formed by grouping the mapping units from the digital 1:1 million scale Surface Geology of eastern Australia (Whitaker *et al.* 2005) and the Northern Territory (Liu *et al.* 2006) according to the broad lithological composition of the unit as coded in the gross rock descriptor field in the digital coverage. In Western Australia and South Australia where coverage of geology at this scale is not yet complete, the lithological classes were assigned based on the digital version of the 1976 Edition of Geology of Australia, 1:2,500,000 scale (Bureau of Rural Sciences 1991).

Table 8.3. Attributes describing the catchment and stream substrate. Attributes indicated in italics were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.3).

Attribute	**Source of data**	**Units**	**Description**
Catchment average saturated hydraulic conductivity	1	mm/h	Average value of all grid cells upstream of the reach pour-point
Stream and environs average saturated hydraulic conductivity	1	mm/h	Average value of all grid cells upstream of the reach pour-point
Catchment average solum plant available water holding capacity	1	mm	Average value of all grid cells upstream of the reach pour-point
Catchment percentage old bedrock	2,3,4	%	Areal proportion of all upstream grid cells overlying old rocks (>570My)
Catchment percentage siliciclastic/undifferentiated sedimentary rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying siliciclastic/undifferentiated sedimentary rocks (includes sandstones, conglomerate, mudstone, siltstone)
Catchment percentage carbonate sedimentary rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying carbonate sedimentary rocks (includes limestone, marl, dolomite)
Catchment percentage other sedimentary rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying other sedimentary rocks (includes volcanogenic sediments, non-carbonate chemical sediment, organic-rich rocks)
Catchment percentage igneous rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying igneous rocks
Catchment percentage mixed sedimentary and igneous rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying mixed sedimentary and igneous rocks
Stream and environs percentage unconsolidated rocks	2,3,4	%	Proportion of DEM derived stream reach grid cells and associated valley bottom cells overlying unconsolidated material (regolith)
Catchment percentage unconsolidated rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying unconsolidated material (regolith)

Source data:

1. Soil Hydraulic Properties of Australia (Western and McKenzie 2004)
2. Surface geology of eastern Australia (Whitaker *et al.* 2005)
3. Surface geology of the Northern Territory (Liu *et al.* 2006)
4. Geology of Australia (Bureau of Rural Sciences 1991)

An additional class, based on the age of the rocks underlying the catchment, was derived to reflect the increased porosity and permeability that accompanies weathering and fracturing of rocks over time (Table 8.3) (Le Moine *et al.* 2005; Le Moine *et al.* 2007). The hydraulic conductivity of the materials in the immediate environs of the stream is also an important influence on stream and aquifer connectivity (Ransley *et al.* 2007). Accordingly, the proportion of coarse grained unconsolidated materials in the immediate vicinity of the stream and its associated environs was taken to be an indicator of the potential for groundwater recharge. These materials generally have high conductivities (Cook 2003). We defined the stream and its environs to include the stream reach and any adjacent grid cells coded as valley bottom flats. Valley bottom flats were identified according to the Flatness Index of Gallant and Dowling derived from the values of their multi-resolution Valley Bottom Flatness Index and associated multi-resolution Ridge-top Flatness Index (Gallant and Dowling 2003).

8.2.2.4 Catchment and valley morphology

Eleven terrain parameters (Table 8.4) were computed from the national 9 second DEM to account for the influence of catchment and valley morphology on stream hydrology.

Measures of slope and relief are indicative of the energy available for the movement of water. Runoff is usually quicker in steeper catchments so hydrographs have larger and spikier peaks (Thorne 2004). Two measures of catchment relief were derived (Table 8.4). Catchment relief (Stewardson *et al.* 2005) considers the ratio of the average upstream relief relative to the total range in elevation while the Catchment relief ratio (Gordon *et al.* 1992) measures the total elevation range relative to the catchment length. Catchment length is the longest upstream path length, estimated by summing the distance to move across the surface, allowing for the change in elevation, from the centre of the grid cell to the centre of the next grid cell downstream in the direction of flow. Catchment average slope was computed from the grid cell estimates of slope calculated from the 9 second DEM using biquadratic spline interpolation with the SLPGRD program (Hutchinson unpublished).

Valley slope has a direct influence on channel slope and hence stream power and velocity (Knighton 1998). It was calculated by dividing the difference in elevation between the highest and lowest cells of the stream segment by its length. The length of the segment was computed as the sum of the distances to move to the next cell in the direction of flow for all cells in the segment. Very short stream segments of just one cell were assigned the average of the segment slope values computed for the upstream and downstream segments.

The size and shape of the catchment influence the water yield and its timing and distribution. The catchment elongation, for example, has a large bearing on the timing and magnitude of peak flows during flood events (Bárdossy and Schmidt 2002; Moussa 2003). A commonly used measure of catchment shape is the Elongation Ratio (R_e) (Gordon *et al.* 1992; Brierley *et al.* 1996; Davies *et al.* 2000; Parsons *et al.* 2002). It was calculated at each segment pour-point by dividing the diameter of a circle with the same area as the catchment above the pour-point by the maximum length of the catchment. The more elongated the catchment, the closer the value of this ratio is to zero. Catchment size is described by the total area that drains to the catchment outlet (Gordon *et al.* 2004). It was computed by accumulating the area of all grid cells upstream of the segment pour-point. The total area upstream of a flow bifurcation was included in the area of all downstream segments (i.e. it was not divided at the bifurcation).

Hydrograph properties including those related to baseflow and the timing and magnitude of stormflow events, have been shown to be strongly correlated with drainage density, the length of channel per unit area (e.g. Mwakalila *et al.* 2002; Brandes *et al.* 2005). Drainage density was calculated here by dividing the total length of all upstream reaches by the catchment area at the reach pour-point.

Table 8.4. Terrain attributes describing the catchment and valley morphology. Attributes indicated in italics were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.3). Catchment area and catchment length, $\log_{10}(x+1)$ transformed, were also included in the NOSTANDARDIZATION series classifications.

Attribute	**Units**	**Definition**
Indicator of valley confinement	%	Percentage of stream reach grid cells and their immediate neighbours that are not valley bottoms as defined by mrVBF and mrRTF indices
Valley slope	%	Stream reach slope: computed as the difference in elevation between the highest and lowest cells of the stream reach divided by its length
Catchment area	km^2	The contributing area upstream of the reach pour-point
Catchment length	km	Maximum flow path length upstream to the reach pour-point, calculated by incrementing the maximum upstream length of neighbouring contributing cells. Flow path distance is the distance to move across the surface, allowing for the change in elevation, from the centre of the grid cell to the centre of the next grid cell downstream in the direction of flow.
Maximum upstream elevation	m	Maximum elevation value of all upstream grid cells
Mean upstream elevation	m	Mean elevation value of all upstream grid cells
Minimum reach elevation	m	Minimum elevation value of all cells in reach
Catchment relief		(mean upstream elevation-pour -point elevation)/(max upstream elevation-pour-point elevation).
Catchment relief ratio		(maximum upstream elevation-pour-point elevation)/(flow path distance from source)
Catchment shape (elongation ratio)		$R_e = D_c / L$ where: D_c = the diameter of a circle with the same area as the catchment area upstream of the segment L = the maximum length of the catchment along a line basically parallel to the main stem (Gordon *et al.* 1992)
Catchment slope	%	Mean slope of all grid cells upstream of the reach pour-point (both valley and hillslope cells)
Drainage density	km/ km^2	Accumulated length of DEM derived stream upstream of the reach pour-point cell/upstream area

A primary differentiating criteria in many river classification schemes is valley confinement (e.g. Whiting and Bradley 1993; Rosgen 1994; Brierley and Fryirs 2000). The width of the valley relative to that of the channel controls the energy of inundating flows (Fagan and Nanson 2004). Confinement must be described relative to the width of the channel (Jerie *et al.* 2003), but neither valley nor channel width can be estimated reliably with the available continental-scale data. Instead, an indicator of valley confinement (Stein 2007) was derived by considering the Flatness Index class values derived from the values of the multi-resolution Valley Bottom Flatness (mrVBF) and multi-resolution Ridge Top Flatness (mrRTF) indices (Gallant and Dowling 2003) of the grid cells neighbouring the channel cells. It was computed as the percentage of the cells in the immediate 3 x 3 cell neighbourhood of the channel cell that were not classified as valley bottoms (i.e. cells that were classified as hillslope, ridge top flat or indeterminate). Small values of this indicator thus identify unconfined channels on wide floodplains. Intermediate values suggest the presence of smaller floodplain pockets. Valley confinement is indicative of the depositional environment and the potential for stream aquifer connectivity (Ransley *et al.* 2007) at the reach scale. The final terrain parameter, catchment storage, describes the relative proportion of depositional areas in the catchment, calculated simply as the proportion of grid cells in the catchment upstream of the segment pour-point that are valley bottoms.

8.2.2.5 Vegetation cover

The type and cover of vegetation in the catchment has an indirect but significant influence on stream hydrology through its effect on processes of infiltration and evapotranspiration. The catchment vegetation cover was described by the areal proportion of the catchment in each of three broad structural classes: trees, grasses and others, the latter including shrublands. These classes were formed by grouping the 23 major vegetation types of the National Vegetation Information System (NVIS) Version 3 pre-European vegetation layer supplied as a grid at 100 m resolution (National Land and Water Resources Audit 2001a). Pre-European vegetation, rather than present vegetation, was used to avoid confounding the classification with the effects of recent (post-European) industrial society (see Appendix 3).

8.2.3 Assigning stream gauges to the DEM derived stream network

To aid evaluation of the ecohydrological environment classifications, each of the 830 high and medium quality gauging stations compiled for the classification of flow regimes (Appendices 4 and 5) were assigned the identifier of the stream reach on which they were located. This enabled gauges to be allocated to an ecohydrological environment group and thus the flow characteristics of the group to be described. Kruskal-Wallis rank sum tests were used to test the null hypothesis that the distribution of the flow metric values was the same in each of the ecohydrological environment groups (R Development Core Team 2004). Kruskal-Wallis is a non-parametric statistic that is more robust to departures from normality than the F-statistic (Belbin and Collins 2004).

The reach assignment of each gauging station was verified by comparing the gauge name and supplied catchment area with the name and DEM-derived catchment area of the assigned stream reach. These comparisons uncovered occasional errors in gauge location as well as incorrect matching due to differences in mapping scale and generalisation of the DEM derived stream network, particularly for gauges located close to a confluence. Automatic procedures were developed to relocate these gauges to the closest position on a stream reach of the same stream name. Gauging stations for which matching locations could not be found automatically within 1 km of the given gauge location or those for which the DEM derived catchment area differed from that supplied by more than 5% were manually checked.

8.2.4 Classification series

Four series of classifications were generated with varying sets of attributes, weightings and transformations and numbers of groups (Table 8.5). Six classifications were generated for each series with the numbers of groups broadly between 10 and 60. In some cases, no value of the allocation radius would produce exactly the desired number of groups and so the numbers of groups tested incremented only approximately by ten.

Table 8.5. Classification series from which the ecohydrological environment classification was chosen.

Classification name	*No. of groups*	*Attributes*	*Transformations*	*Standardisation*	*Weighting of attributes*
MANTELSELECTED	10 20 29 41 51 61	As indicated in (in Table 8.6)	As selected using the procedure of Snelder *et al.* (2007)	As per Table 8.2	Implied by the number of times an attribute was selected
NO WEIGHTING	10 20 30 40 51 59	As indicated in tables 8.1 to 8.4 + vegetation cover attributes (Section 8.2.2.5)	As per tables 8.1 and 8.2	As per Table 8.2	None
EQWEIGHTING	10 20 31 40 49 58	As for NO-WEIGHTING	As per tables 8.1 and 8.2	As per Table 8.2	Equal weighting applied to each attribute group
NO STANDARDISATION	11 18 30 41 49 57	As for NO-WEIGHTING plus catchment area and catchment length	As per tables 8.1, 8.2 and 8.4	None	Equal weighting applied to each attribute group

The first ('MANTELSELECTED') was based on a set of attributes and transformations selected using the method of Snelder *et al.* (2007) described below and the 830 gauges compiled for the ecohydrological classification characterised by a set of 120 ecologically relevant flow metrics (Appendix 5.1). Each gauge was also attributed with a corresponding set of the 75 environmental attributes compiled for the stream reach. Following Snelder *et al.* (2007), a set of environmental variables was selected from this candidate set such that the pairwise distances between gauges in environmental space was maximally correlated with the pairwise distances based on the observed flow metrics. Both environmental and flow distances were calculated by the Manhattan distance after applying a range standardisation as for the Gower metric (Gower 1971). In a manner akin to forward stepwise regression, the variable that produced the largest increase (or smallest decrease) in the correlation between the distance matrices, as measured by the Mantel r statistic, was added iteratively (Snelder *et al.* 2007). A single variable could be added more than once as all were considered for selection at each step. A range of transformations of the variables was also tested: raising them to the power of 2, 0.5, 0.25 and $\log_{10}$. The procedure was implemented in R using the ecodist package (Goslee and Urban 2007) and allowed to run for 63 iterations. By this stage the change in the mantel r statistic for each additional attribute was very small (Figure 8.1) and no new attributes were being selected. To generate the MANTELSELECTED classification series we used the set of attributes that produced a Mantel r statistic value with confidence limits that included the maximum achieved over the 63 iterations (0.744) (Table 8.6).

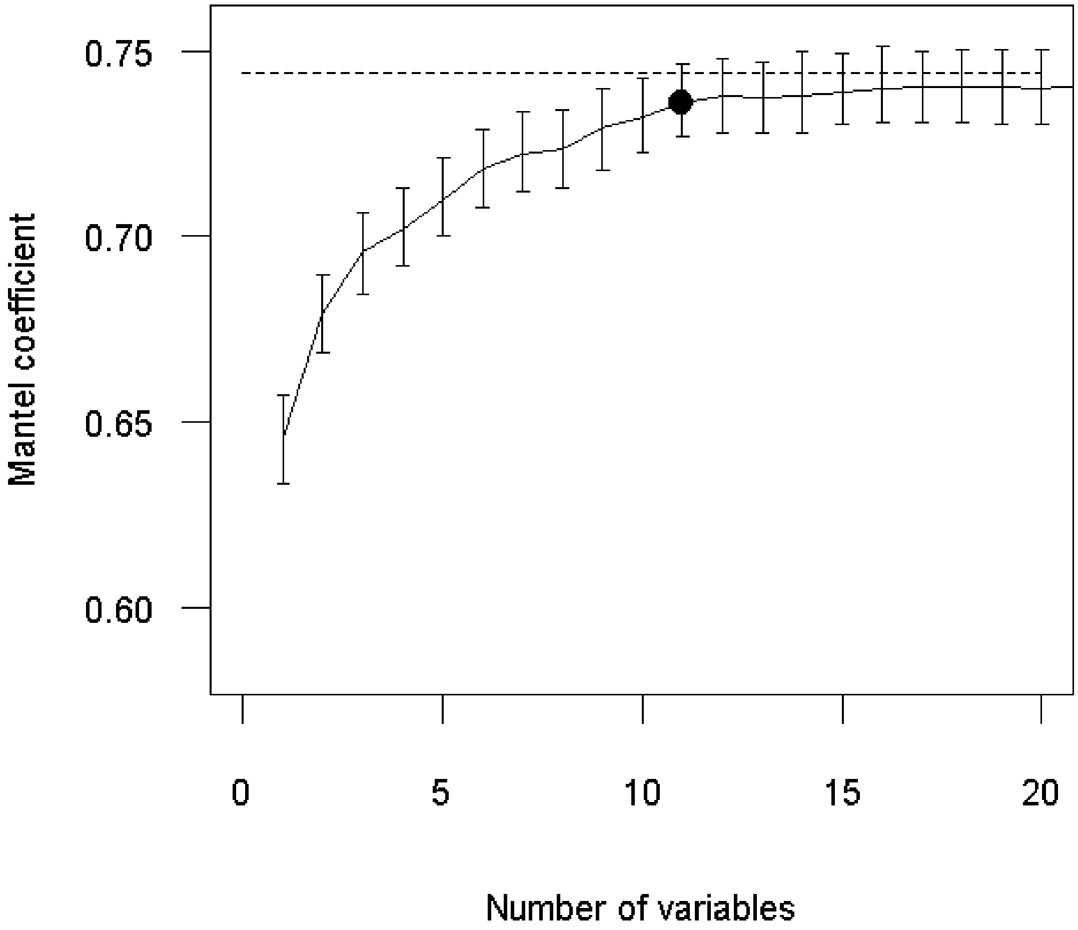


Figure 8.1. Mantel coefficient values with number of selected variables for the first 20 iterations. Error bars represent the 95% confidence limits while the dashed line show the maximum coefficient value obtained after 63 iterations. The circle indicates the minimum number of variables for which the confidence limits include the maximum coefficient value.

The attributes selected by the Mantel tests are based on a set of gauging stations that sample just 830 of the 1.2 million stream reaches and so may not be representative of those that influence stream hydrology in other environmental settings. Accordingly, a second series of classifications ('NOWEIGHTING') was generated based on attributes selected from literature review and our professional judgement. We excluded some of the reach scale attributes such as valley slope that we expected would be less important discriminators of the spatial variation in flow regimes and retained just five of the substrate attributes – those most likely to be indicative of greater potential for significant groundwater contributions to stream flow. A log10 (x+1) transformation was applied to attributes with particularly skewed distributions. In this series of classifications, no weighting was applied to attributes so correlated attributes would have a greater influence on the outcomes. The same set of attributes was selected for the third series of classifications ('EQWEIGHTING') but in this case the five attribute groups (climate, catchment water balance, catchment/valley morphology, substrate and vegetation) were equally weighted in the calculation of the dissimilarity measure regardless of the number of attributes in the attribute group. The final series ('NOSTANDARDIZATION') also weighted the attribute groups equally but allowed for a catchment size effect, using the catchment water balance attributes expressed as volumes (i.e. not standardised by catchment area) and including additional attributes of catchment area and catchment length.

Table 8.6. Mantel test results for the first 15 iterations. The attributes shown in bold were selected for the MANTELSELECTED classification series.

Iteration number	*Mantel coefficient*	*Selected attribute*	*Transformation*	*Lower confidence limit*	*Upper confidence limit*
1	0.646	**C of annual runoff**	$\log_{10}$	0.634	0.657
2	0.679	**Catchment average annual mean temperature**	$\log_{10}$	0.669	0.690
3	0.696	**CV of annual runoff**	0.5	0.685	0.706
4	0.702	**Drainage density**	0.25	0.692	0.713
5	0.710	**Catchment average driest quarter rainfall**	none	0.700	0.721
6	0.719	**CV of annual runoff**	0.5	0.708	0.729
7	0.722	**Catchment average saturated hydraulic conductivity**	$\log_{10}$	0.712	0.733
8	0.723	**Mean September runoff**	0.25	0.713	0.734
9	0.729	**Proportion of catchment under natural tree cover**	0.25	0.718	0.740
10	0.732	**Skewness of annual runoff**	0.25	0.722	0.742
11	0.736	**Catchment average warmest quarter rainfall**	$\log_{10}$	0.727	0.747
12	0.738	Catchment average driest quarter rainfall	2	0.728	0.748
13	0.738	Catchment average solum plant available water holding capacity	$\log_{10}$	0.728	0.747
14	0.738	CV of annual runoff	0.5	0.728	0.750
15	0.739	Catchment maximum elevation	$\log_{10}$	0.730	0.749

8.3 Results

8.3.1 Classification selection

Twenty four classifications were generated grouping the 1.2 million stream reaches into between 10 and 61 classes. The different classification series varied in both their ability to recover the flow regime types generated by the classification of gauging stations (Appendix 5) and their classification strength as measured by the similarity of flow metric values within and between groups.

Classification strength (CS), expressed as the difference $\left(\overline{W}-\overline{B}\right)$, generally increased with the number of groups in the classification across all classification series (Figure 8.2). In all cases, the randomised ratio ($\overline{B}/\overline{W}$) was greater than that for the environmental classification so the null hypothesis of 'no class structure' could be rejected. However, with increasing numbers of groups the proportion of groups sampled by the gauges decreases as does the number of gauges within each group (Table 8.7) increasing the likelihood that CS values are affected by random sampling effects associated with small sample sizes (Hawkins *et al.* 2000; Heino *et al.* 2004; Snelder *et al.* 2005). The CS values of the MANTELSELECT and NOWEIGHTING series are consistently higher than those of the EQWEIGHTING series classifications. Not surprisingly, all are higher than the values for the NOSTANDARDIZATION series where stream size has a direct influence on the groupings.

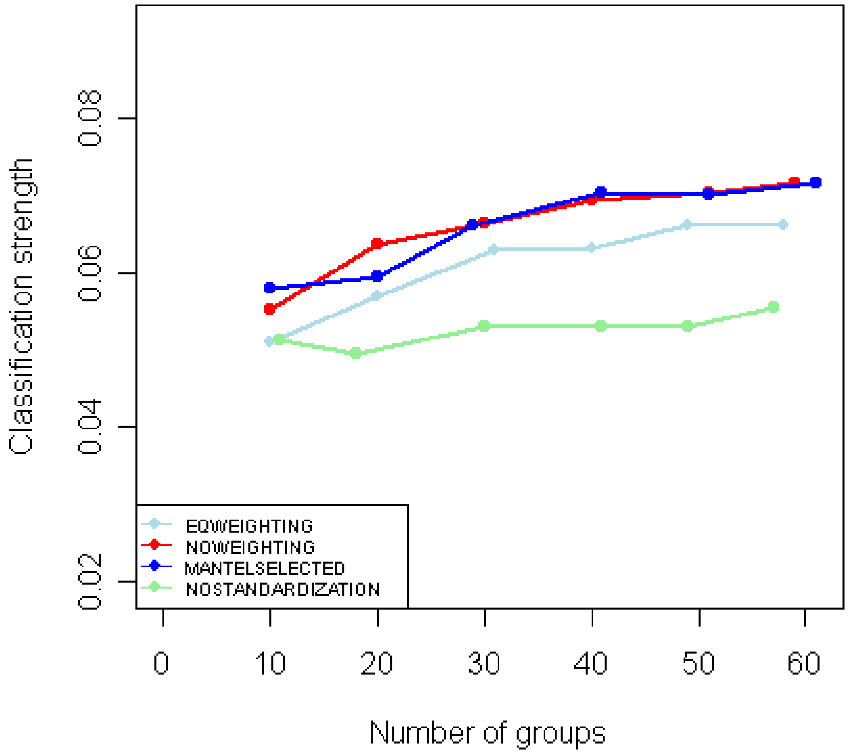


Figure 8.2. Classification strength of environmental classifications evaluated using 120 ecologically relevant flow metrics derived for 830 gauging stations. Classification strength is expressed as the difference between average within and between group similarities $\left(\overline{W}-\overline{B}\right)$.

Table 8.7. Classification strength as measured by the similarity of flow metric values within and between groups for environmental classifications. A higher difference ($\overline{W} - \overline{B}$) or lower ratio ($\overline{B}/\overline{W}$) indicates a stronger classification.

Classification	*No. groups*	*No. groups tested (i.e. > 1 gauge)*	*No. groups with less than 5 gauges*	*Mean no. gauges/ group*	$\overline{W} - \overline{B}$	$\overline{B}/\overline{W}$
NOWEIGHTING	10	9	1	83.0	0.0551	0.937
	20	18	2	41.5	0.0637	0.928
	30	26	3	28.6	0.0663	0.925
	40	34	6	23.1	0.0692	0.923
	51	40	8	19.3	0.0702	0.922
	59	49	13	15.7	0.0715	0.920
EQWEIGHTING	10	9	1	83.0	0.051	0.941
	20	16	4	46.1	0.0569	0.935
	31	23	5	31.9	0.0629	0.929
	40	25	10	25.9	0.063	0.929
	49	31	11	22.4	0.066	0.926
	58	37	15	18.9	0.0661	0.926
NOSTANDARDISATION	11	11	2	75.5	0.0512	0.940
	18	11	5	46.1	0.0495	0.943
	30	11	9	33.2	0.0529	0.939
	41	11	14	25.2	0.053	0.939
	49	8	18	21.3	0.053	0.939
	57	8	18	20.8	0.0555	0.937
MANTELSELECTED	10	9	1	83.0	0.0578	0.934
	20	17	5	43.7	0.0595	0.932
	29	24	8	33.2	0.066	0.926
	41	32	7	24.4	0.0704	0.921
	51	37	18	19.3	0.07	0.922
	61	43	17	16.6	0.0716	0.920

Similarly, the Hubert Arabie Rand Index values indicated the environmental classifications derived using the standardised catchment water balance attributes, better recovered the 12 group classification of gauging stations based on standardised flow metrics (Figure 8.3). The index reached a maximum value of 0.23 for the 31 group EQWEIGHTING classification. This is only slightly higher than that for the 30 group NOWEIGHTING and the 29 group

MANTELSELECTED classifications though much lower than the value of 0.8 suggested by Steinley (2004) to be indicative of good recovery of given clusters. However, it compared reasonably with the Hubert Arabie Rand Index value of 0.37 for an alternative 12 group classification of the gauges that was generated using the UPGMA hierarchical agglomerative clustering strategy, and the Gower dissimilarity measure based directly on the flow metrics. Communicating the characteristics of more than thirty groups is unwieldy whether by graphical or other means. A greater number of classes will also be more difficult to comprehend (DeVellis 1991 in Schunemann *et al.* 2003). We chose therefore to focus our analysis on a 30 group classification, the 30 group classification from the NOWEIGHTING series, henceforth referred to as the 'ecohydrological environment classification'. Although performing comparably, the MANTELSELECTED classifications were based on a limited number of attributes (Table 8.6) omitting many that our literature review had indicated played an important role in shaping flow regimes. In particular, geology is known to be a major control on the magnitude of the groundwater contribution to a stream yet none of the attributes that described the catchment geology were selected.

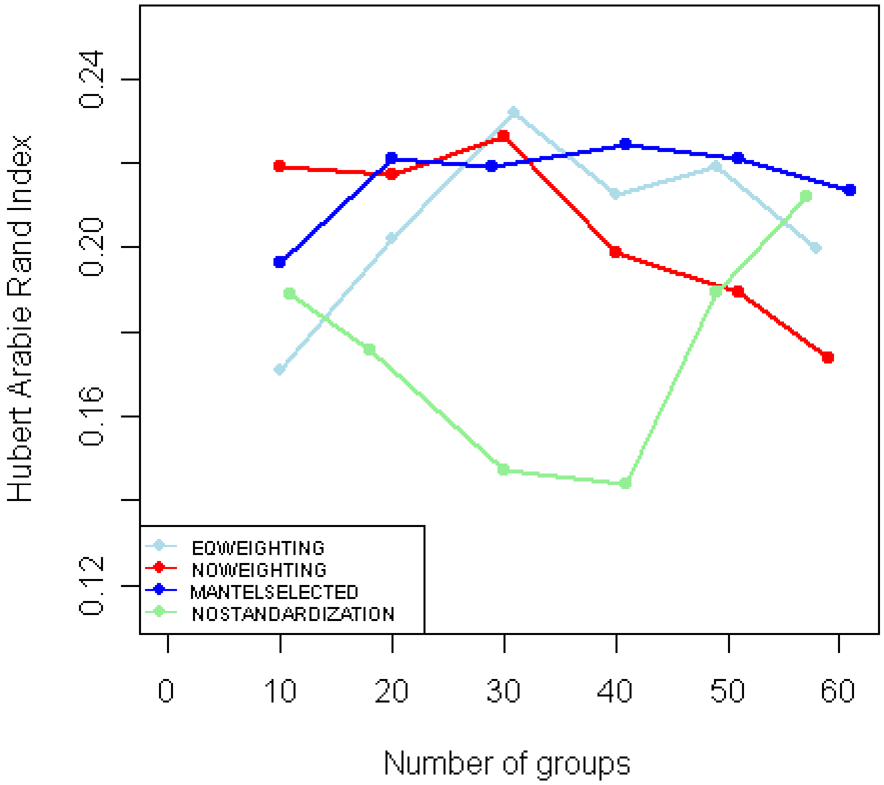


Figure 8.3. Recovery of the 12 groups generated by classification of gauging stations by the environmental classifications as measured by the Hubert Arabie Rand Index.

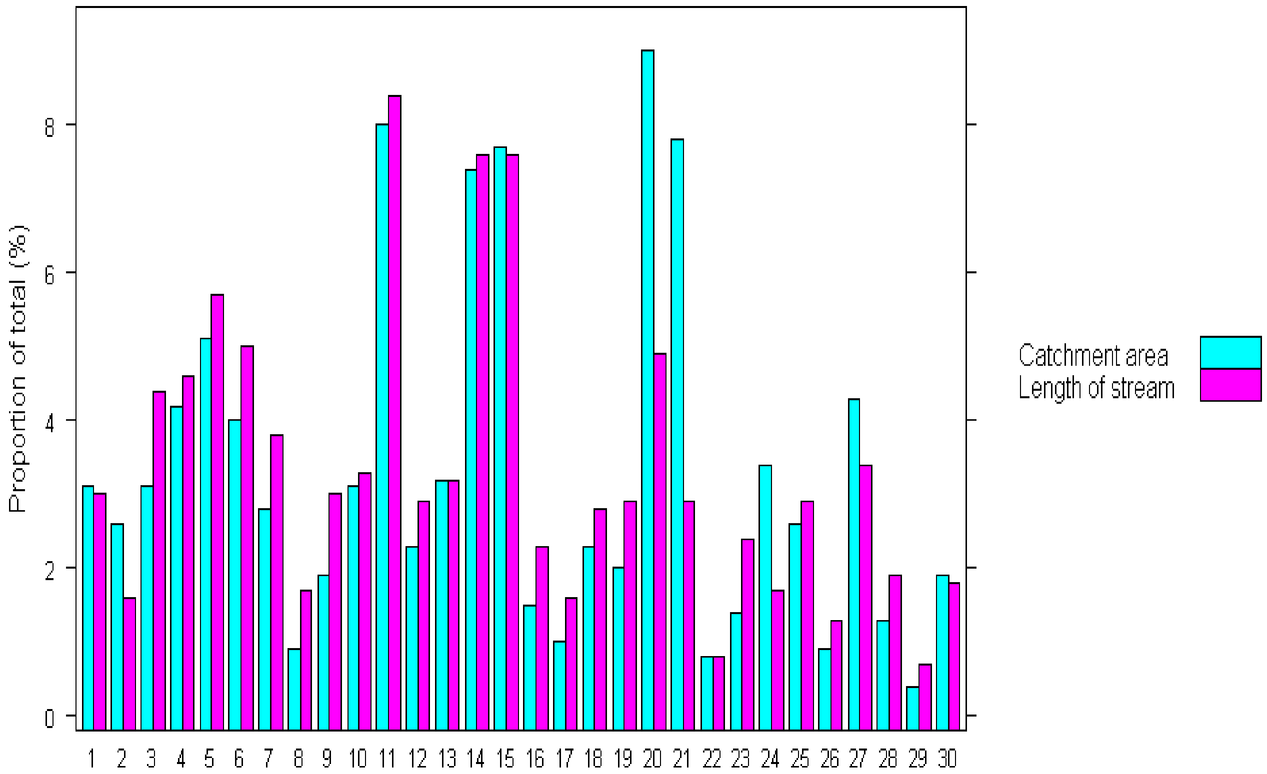


Figure 8.4. Total length of stream and catchment area (stream reach contributing area) by ecohydrological environment group.

8.3.2 The ecohydrological environment classification

Streams reaches are not evenly distributed among the ecoecohydrological environment groups (Figure 8.4). The number of stream reaches, their total length and catchment area vary by an order of magnitude. The largest group (20) includes reaches totalling more than 246,500 kilometres of stream and drains a total area of 516,437 km^2 while the reaches within the smallest group (29) total just 20,508 km and have a catchment area of 25,573 km^2. A few groups (20, 21 and 24 in particular) drain proportionally more area than the length of channel they contain reflecting a lower drainage density while the reverse is true for some other groups (e.g. 6 and 7) that contain a relatively higher proportion of the channel length than of catchment area. The groups include streams with a wide range of catchment sizes (Figure 8.5) though five groups (numbers 2, 21, 24 and 27 and to a lesser extent, 4) more often contain stream reaches of larger catchments.

The groups are displayed in colours that reflect their shared similarity (Figure 8.6) highlighting the strong north-south latitudinal gradient in the distribution of the ecohydrological environment groups and a clear separation of streams along the coastal fringe from those inland.

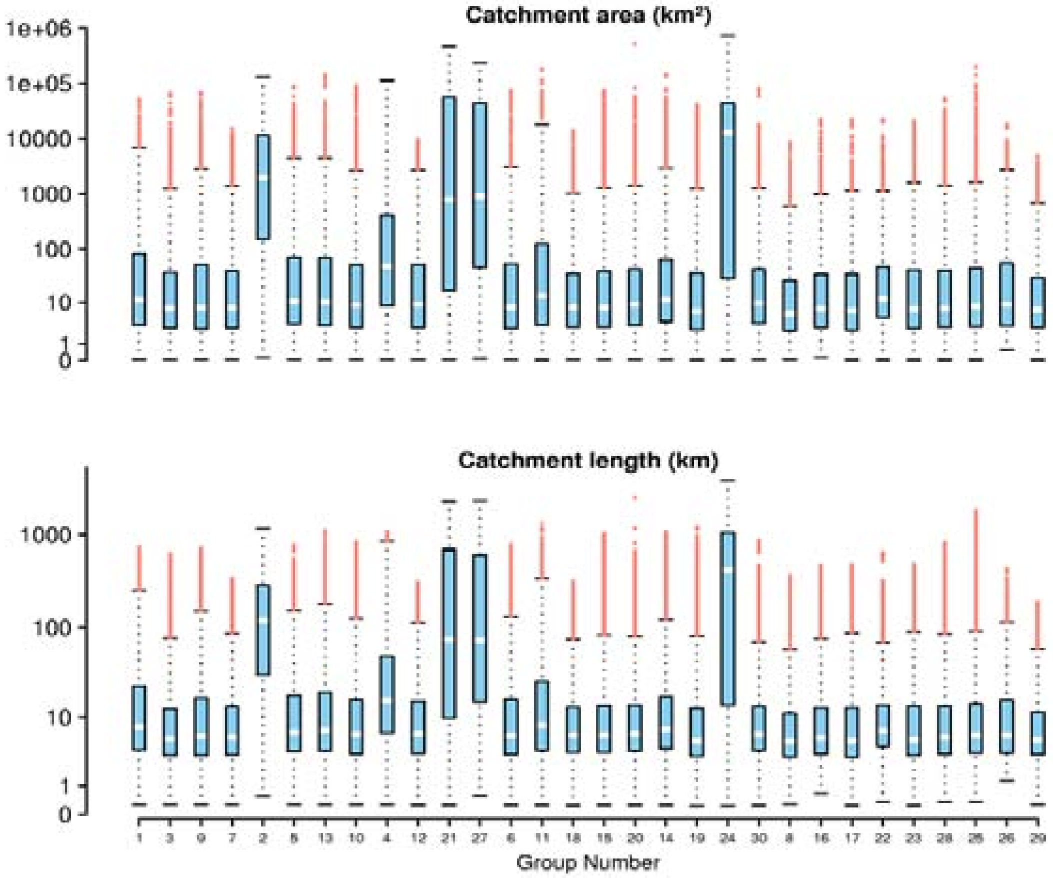


Figure 8.5. The catchment size of stream reaches by ecohydrological environment group. The boxes indicate the inter-quartile range with the central bar signifying the median value. Whiskers are drawn to include all data points that are not more than 1.5 times the inter-quartile range from the box with outliers portrayed in red.

A single river may traverse more than one of the ecohydrological environment groups. The main stem of the Darling River in western New South Wales, for instance, flows through five of the groups (20, 21, 24, 26 and 27) and even more if its tributaries are also considered. The Murray-Darling Basin, in fact, contains some of the greatest diversity of ecohydrological environment groups at spatial scales ranging from drainage divisions (Figure 8.7a) through drainage basins (Figure 8.7c) and 1 degree grid cells (~110x110 km) (Figure 8.7b).

High flow regime diversity in the Murray-Darling Basin was also a feature of the empirical classification (Appendix 6) although in this case, the larger streams were not included due to regulation. However, when considered as a function of drainage basin area, it is the higher relief, coastal draining basins that exhibit the greater diversity (Figure 8.7d). The Snowy River basin for instance contains 11 of the ecohydrological environment types, compared to the 20 found in the Murray-Darling Basin, though occupying less than 2% of the area. The small, internally draining basins that occur across much of the Western Plateau Drainage Division and the lower reaches of the Murray-Darling Basin Drainage Division also display a relatively high diversity in comparison to their area though in absolute terms the number of types is very low.

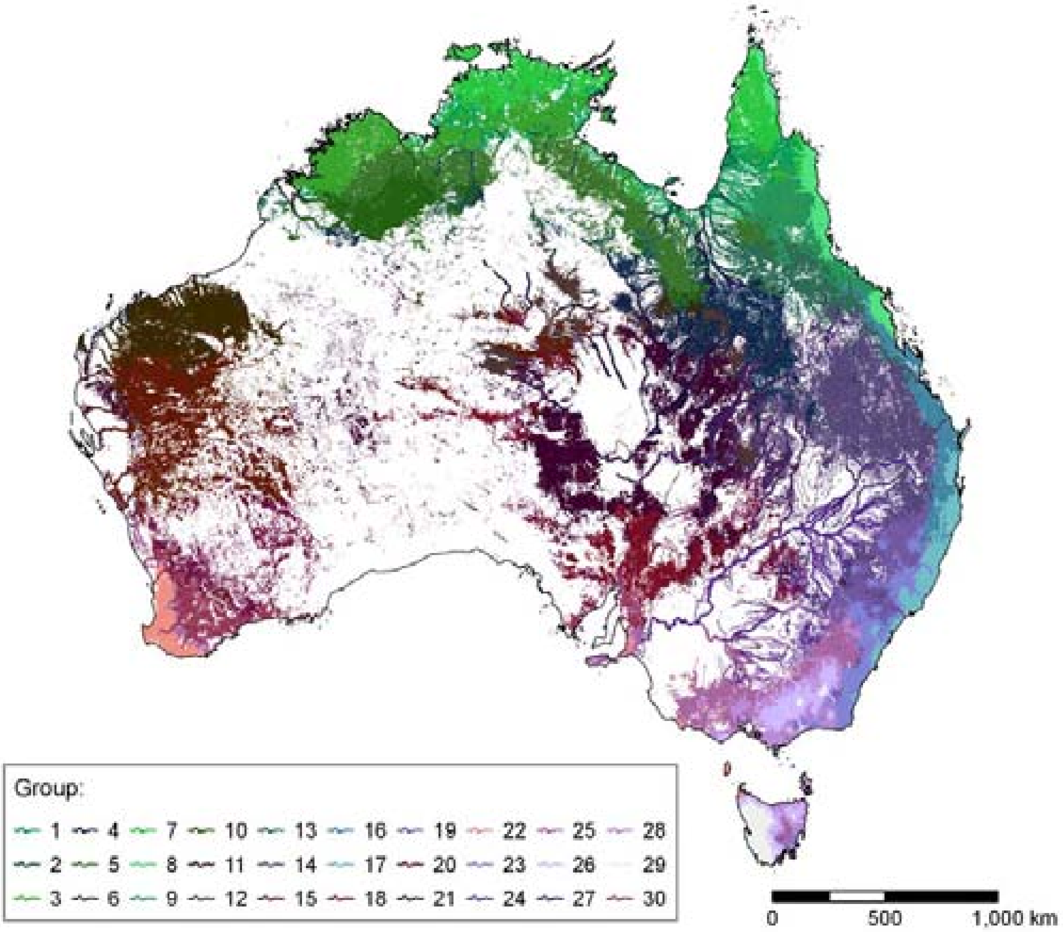


Figure 8.6. The ecohydrological environment classification. Colours used to map the groups were derived by aligning the ordination axes of a 3-dimensional ordination of the group centroids with the three primary colours and assigning a colour to each group based on its position in the configuration (Belbin *et al.* 1983). Thus groups that are similar in environmental space share similar colours.

There are broad similarities between the ecohydrological environment classification and the agro-climatic classification of Australia (Hutchinson *et al.* 2005), modelled from a global classification of agro-climatic data (Hutchinson *et al.* 1992) (Figure 8.8a). However, the catchment signal is clearly evident when compared to the smoothed boundaries of the agro-climatic regions. Thus, the agro-climatic class that coincides with the ecohydrological environment grouping of a stream reach is that of its upper catchment rather than the agro-climatic region in which it flows. Similarly, a number of the Interim Biogeographical Classification of Australia (IBRA) regions (version 6.1) (Department of Environment, Water, Heritage and the Arts 2007) are aligned with major groupings in the ecohydrological environment classification though other regions (e.g. the Brigalow Belt North in Queensland) encompass quite dissimilar ecohydrological environment groups (Figure 8.8b). IBRA was developed for the National Reserves System program (Pigram and Sundell 1997). It is a regionalisation delineated from regional and continental-scale data on climate, geomorphology, landform, lithology and expert knowledge of characteristic flora and fauna (Thackway and Cresswell 1995). In contrast, there is little concordance between the ecohydrological environment classification and the Australian Water Resources Council (AWRC) Drainage Divisions (Australian Water Resources Council 1976; AUSLIG 1997; Geoscience Australia 2003) (Figure 8.8c) derived by aggregating the catchments of the major river systems and neighbouring small coastal or inland drainage systems according to geographic proximity or shared discharge points.

The ecohydrological environment groups are primarily differentiated by climatic and catchment water balance attributes and secondarily by attributes describing the catchment morphology, substrate or vegetation cover. This is shown in the box and whisker plots presented in Appendix 8.1 (Figures A8.1 to A8.8). For any group the values of climatic and catchment water balance attributes occupy a reasonably narrow range. However, the range of values for the attributes describing the catchment morphology, substrate and vegetation cover is generally much wider and often overlapping.

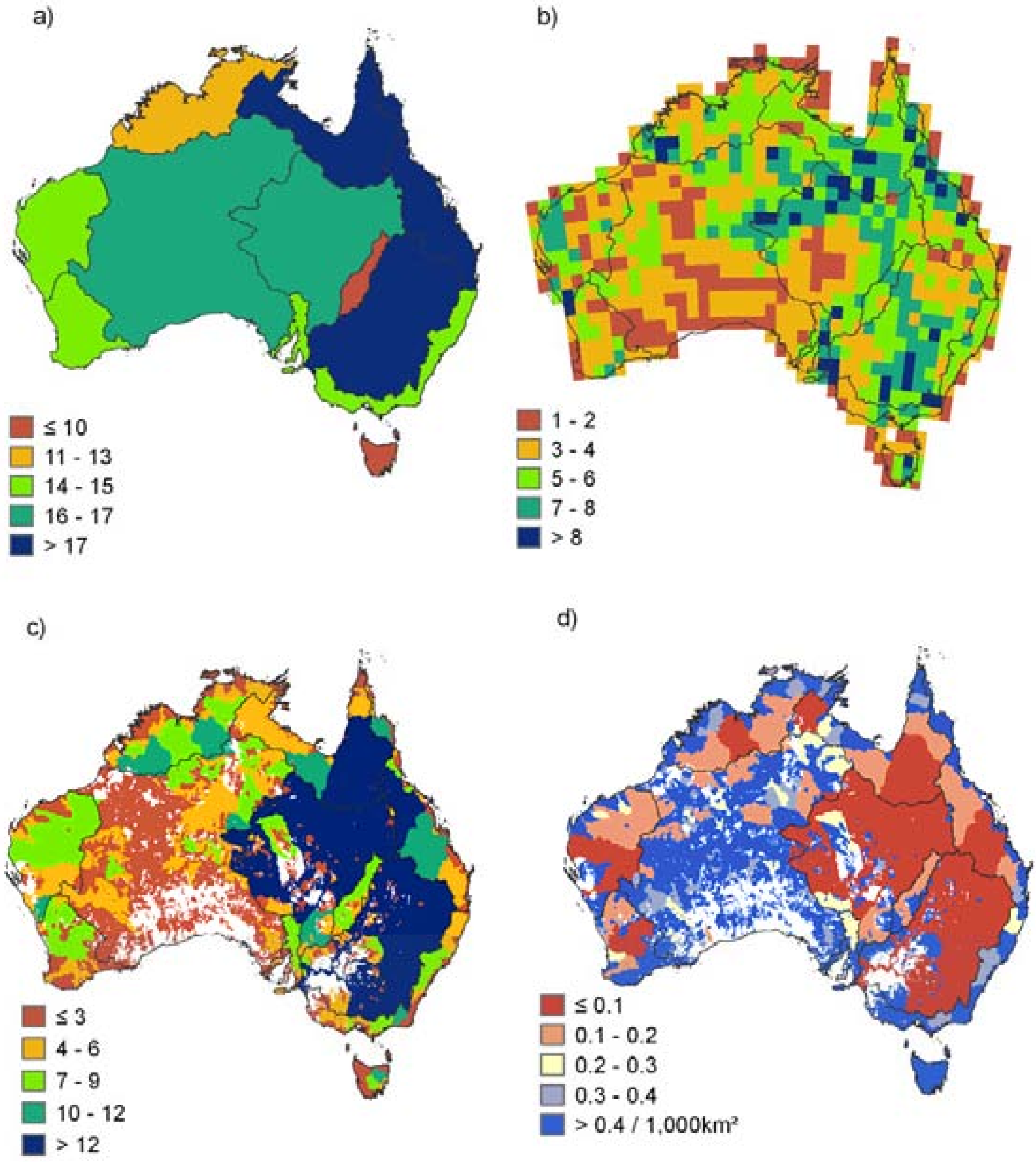
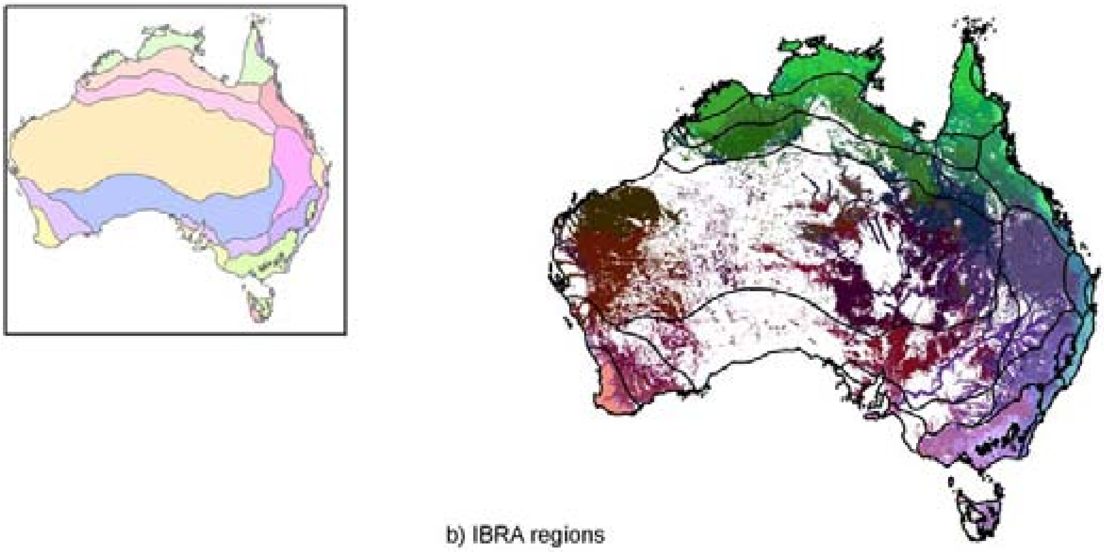
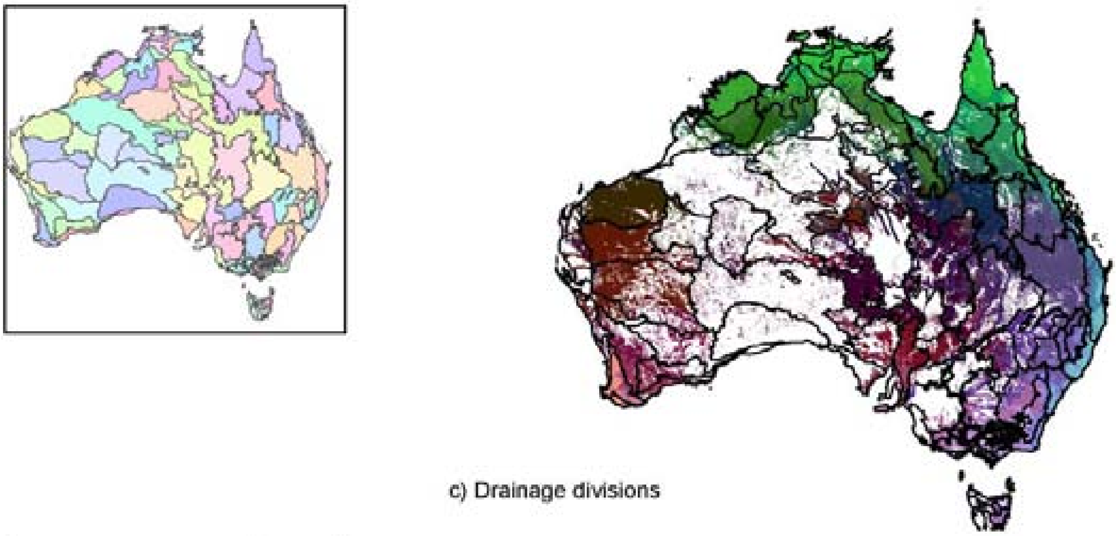


Figure 8.7. Number of ecohydrological environment types per (a), AWRC drainage division, (b) 1 degree grid cell, (c) topographically defined drainage basin and (d) relative to drainage basin area (number/1,000 km^2).

a) Agroclimatic classes



b) IBRA regions



c) Drainage divisions

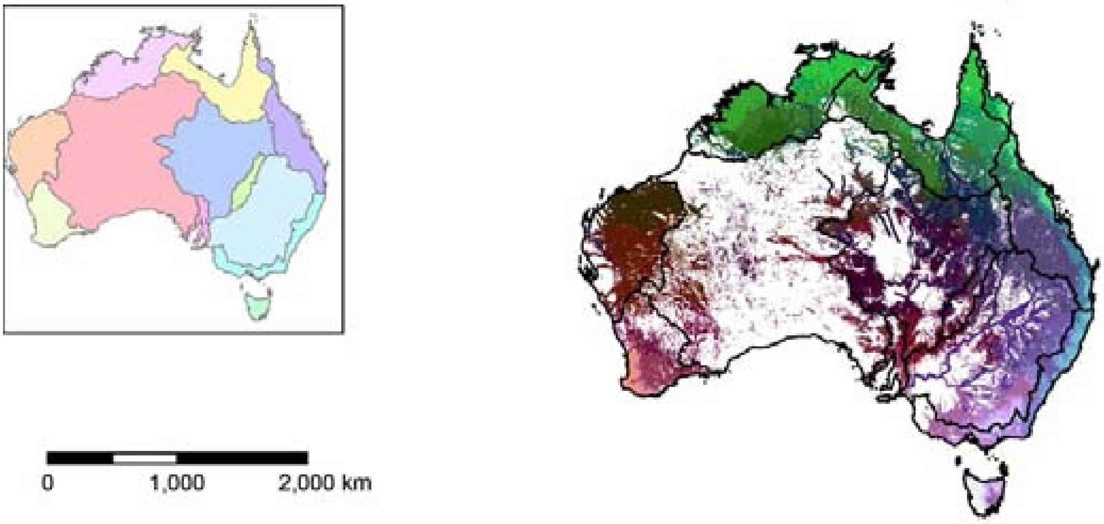


Figure 8.8. Concordance between the ecohydrological environment classification and the boundaries of regions delineated by other national classification schemes. a) Agro-climatic regions (Hutchinson *et al.* 2005); b) IBRA 6.1 regions (Department of Environment Water Heritage and the Arts 2007) and c) Drainage Divisions (Geoscience Australia 2003). Inset maps show the alternative classification.

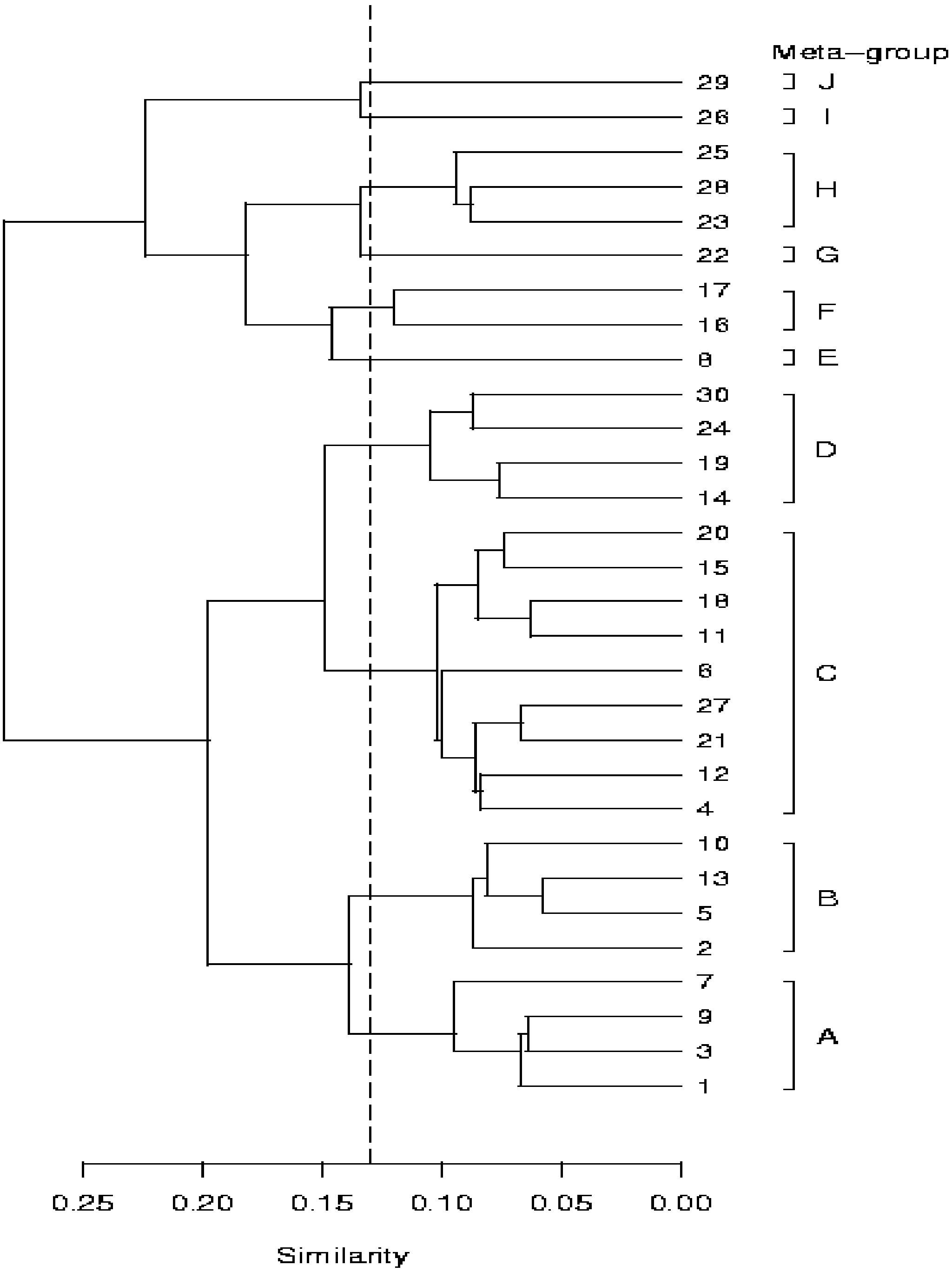


Figure 8.9. Dendrogram showing the relationship among the ecohydrological environment groups derived by clustering group centroids. The dashed line shows the 10 meta-groups delineated by cutting the dendrogram at a similarity value of 0.13.

The hierarchical clustering of the group centroids indicates the 30 ecohydrological environment groups form 10 distinct meta-groups (Figure 8.9) with strong spatial coherence (Figure 8.10). At the broadest scale these cluster into three broad regions: i) a northern cluster with strong seasonal wet/dry rainfall and runoff patterns (meta-groups A and B); ii) a much drier cluster of streams across inland Australia with highly variable runoff characteristics (meta-groups C and D); and iii) streams draining wetter catchments with less variable runoff along the east coast, in south-eastern and south-western Australia (meta-groups E to J). The major gradients are summarised in the 3-dimensional ordination (Figure 8.11). It shows a clear separation of the 10 meta-groups.

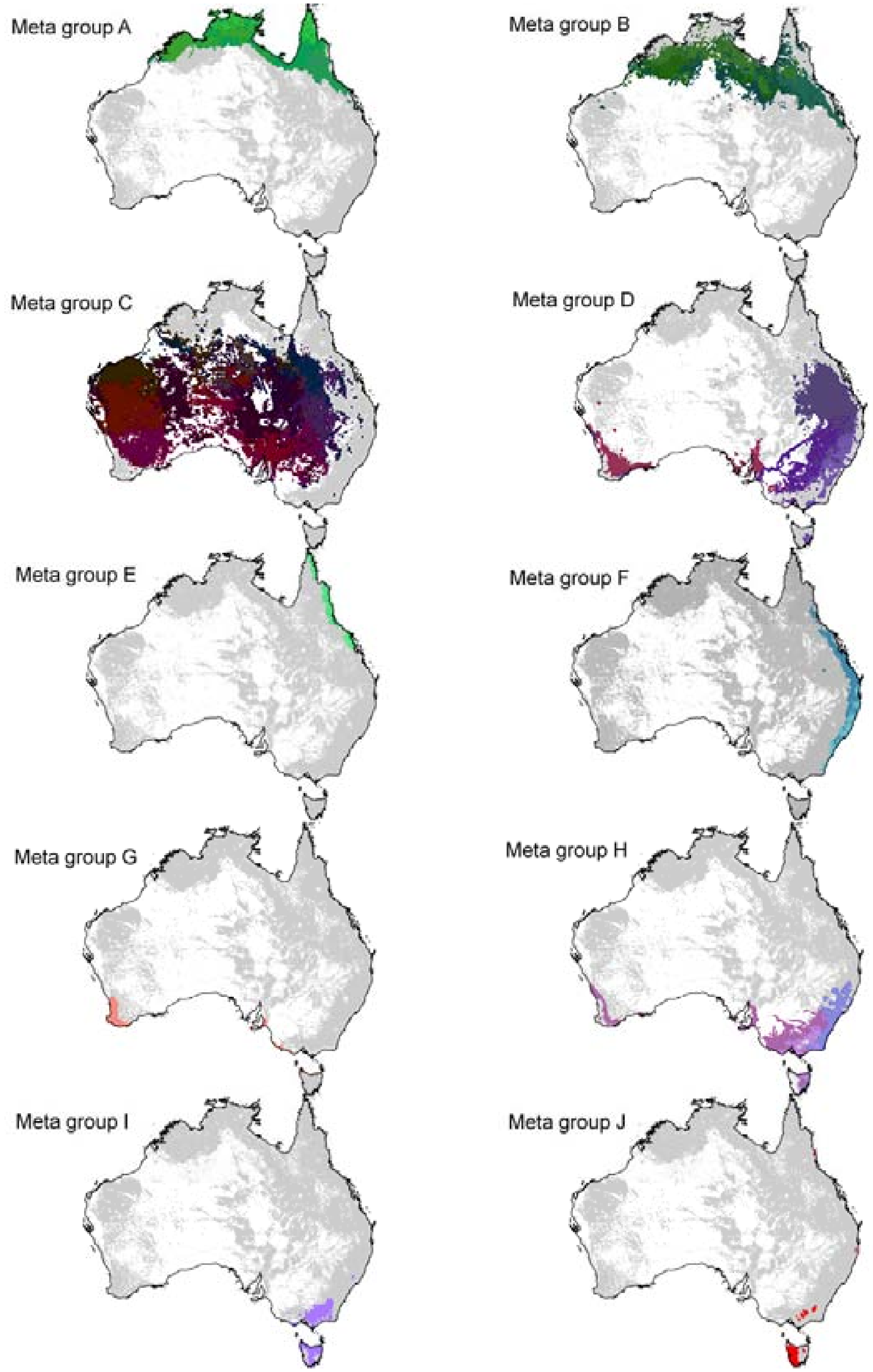


Figure 8.10. Geographic extent of ecohydrological environment meta-groups. Individual groups are coloured as in Figure 8.6 with the exception of the single group (29) that comprises meta-group J, here shown in red for easier discrimination.

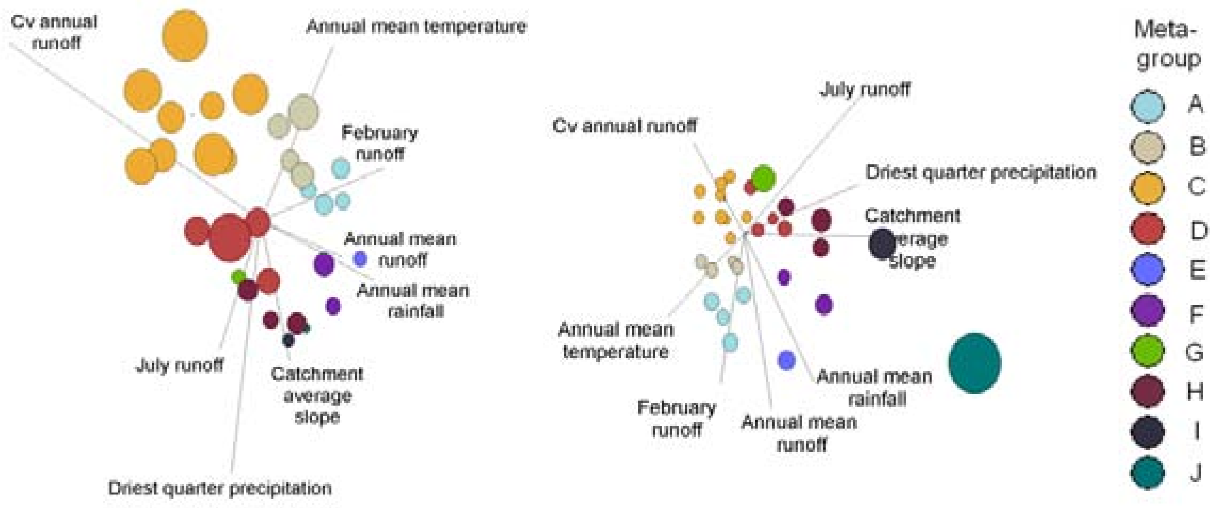


Figure 8.11. Two rotated views of the 3-dimensional ordination of ecohydrological environment groups with groups coloured according to meta-group membership. Vectors indicate a gradient of increasing values of the labelled attributes from the centroid of all the groups in the ordination space.

Meta-group A includes four of the groups (1, 3, 9 and 7) distributed across the top end of Australia (Figure 8.10). The catchments of streams in these groups experience high temperatures throughout the year and a strong seasonal wet-dry rainfall pattern. Rainfall tends to be highly erosive and leads to high annual runoff totals generated almost entirely over the period December to April. Group 9 streams are distinguished from others in this meta-group by slightly cooler minimum temperatures in the colder months and less marked differences in precipitation between the wettest and driest quarters. Group 7 streams exhibit less variability and higher minimums in annual totals of runoff. In contrast to the other meta-group A streams, the ecohydrological environment group 1 streams typically have a low proportion of the catchment underlain by siliclastic sedimentary rocks but a high proportion of unconsolidated sediments while group 3 streams more often have a large proportion of old rocks underlying the catchment.

Stream reaches found in a band lying immediately to the south and inland of those in meta-group A belong to the four groups (2, 5, 10 and 13) that form meta-group B (Figure 8.10). They too experience strongly seasonal rainfall patterns though tend to be drier and cooler in the colder months than those in meta-group A and have more variable runoff. Group 2 streams are distinguished by catchment morphological descriptors. They typically have a lower elongation ratio implying a more elongated catchment but relatively larger proportions of flat depositional areas as indicated by the catchment storage values and reflected in the lower catchment relief. These streams also have lower annual runoff totals. Vegetation cover is the primary attribute discriminating group 10 streams from others in meta-group B. Grasses, not trees, dominate the catchment of these streams. Group 13 streams are generally draining catchments that are cooler during the hottest months and have lower radiation while group 5 streams differ most from others in this meta-group by the geology that underlies the majority of their catchments most often comprising older rocks.

Meta-group C contains nine member groups from the ecohydrological environment classification. It is the largest of the meta-groups representing a total length of 1,248,652 km of stream and occupying a catchment area of 2,836,723 km^2 across central Australia (Figure 8.10). These are the streams in the most arid parts of the continent with the lowest precipitation and high radiation. They experience a greater temperature range than streams in either meta-group A or B with high temperatures in the hottest months and cool to warm temperatures in the colder months. Runoff is highly variable. While average monthly runoff is low all year round, annual totals are highly skewed. Runoff may be substantial in some years, most notably for streams in groups 4 and 12, but negligible in many others. Member groups can also be distinguished by their dominant vegetation cover (trees: groups 12, 20 and 27; grasses: groups 4, 6, 21, 11 and 18; shrublands: group 15) and catchment average soil hydraulic conductivity. Groups 21 and 27 also have lower values of catchment relief.

Clustered with the meta-group C streams are the four ecohydrological environment groups (14, 19, 24, and 30) that form meta-group D (Figure 8.9). They are common across the northern areas of the Murray-Darling Basin and include group 30 streams in south-west Western Australia, the latter group corresponding with the ancient or old drainage zone identified by Mulcahy and Bettenay (1972). Meta-group D streams experience moderate to low precipitation similar to that of streams in meta-group B but with less marked seasonality and cooler temperatures. Monthly runoff magnitude is highest in winter but generally low. Although less variable than meta-group C streams, annual runoff totals vary considerably from year to year though consistently higher for group 14 and 19 streams than others in this meta-group. Group 14 is distinguished further by catchments with a high proportion of unconsolidated sediments while those in group 19 experience cooler temperatures and drain catchments with higher average slopes and greater relief. Group 24 stream reaches are usually in lower catchment positions distant from their source and drain large, elongated catchments (Figure 8.4). Catchment storage values indicate that more of their catchment is classed as a valley bottom flat reflected also by their typically lower catchment relief.

Ecohydrological environment group 8, the sole member of meta-group E, is distributed along the coastal fringe in Queensland (Figure 8.10). It is distinguished by high summer rainfall that is highly erosive and temperatures that are warm to hot all year. Annual runoff totals are also high with low year to year variability though considerable intra-year variability with a strong seasonal wet/dry pattern in average monthly runoff totals.

Most similar to this group are the two ecohydrological environment groups (16 and 17) that comprise meta-group F (Figure 8.9).They are found along the east coast of Australia and represent a transition zone between the streams with a summer dominant rainfall/runoff pattern in the north and those with a winter dominant pattern in the south (Figure 8.10). Rainfall is high even in the driest period of the year and temperatures warm. The northern streams in this meta-group belong to ecohydrological environment group 16 and differ from the southern group 17 streams principally in the magnitude and seasonality of rainfall and runoff. Group 16 streams are wetter overall though group 17 streams experience more winter rainfall. The runoff of group 16 streams is also more variable both inter- and intra-year and their catchments experience warmer temperatures.

Meta-group G is another with just one member group (22) and is found on the Fleurieu Peninsula in South Australia and in south-west Western Australia (Figure 8.10) where it overlaps with the ‘mature drainage’ zone of Mulcahy and Bettenay (1972). This group has a typical Mediterranean climate with hot summers, mild winters and a strongly seasonal pattern of winter dominated rainfall and runoff. Runoff totals vary little from year to year. Streams in this group are most similar to those in meta-group H (Figure 8.9). They are differentiated primarily by a more pronounced rainfall seasonality and generally lower relief and average catchment slopes.

Meta-group H comprises three of the ecohydrological environment groups (23, 25 and 28) that are distributed across southern Australia (Figure 8.10). They are characterised by a cool, wet climate and the absence of a seasonal dry period. Group 25 streams are distinguished from the others in this meta-group by lower values of catchment average slope and relief ratio and warmer temperatures while runoff is higher, especially in winter and spring in group 28 streams. Streams in both of these groups have lower values of perenniality but higher values of skewness than do streams in group 23.

Ecohydrological environment group 26 is the single member of meta-group I. It is found in areas of higher slope and relief in south-eastern Australia, including Tasmania. The catchments of these streams experience cool temperatures, lower radiation and winter dominant rainfall patterns like those in meta-group H, but are wetter and streams may receive a contribution to runoff from snow melt.

Streams in south-west Tasmania and the highest parts of the Great Dividing Range are members of the ecohydrological environment group 29 that forms the final meta-group, J. They share similar climate and runoff characteristics with those in meta-group I but typically are even wetter and colder and have the lowest year to year variability in runoff of all groups. They also differ in catchment vegetation cover. Unlike meta-group I streams, grasses and other non-tree vegetation types may cover a substantial portion of the catchment of these streams.

8.3.3 Performance of the ecohydrological environment classification

8.3.3.1 Recovery of flow regime classes

The 830 gauging stations used to test classification performance are unevenly distributed across the ecohydrological environment groups. One group (11) is not represented at all while three other groups (12, 18, and 21) are gauged at just one location. Another eight of the groups are represented by less than 10 gauging stations. In contrast, more than 80 gauges are located on streams in ecohydrological environment groups 22 and 28.

The ability of the ecohydrological environment classification to recover the 12 flow regime classes generated by the classification of these gauging stations (Appendix 5) is mixed. While the streams of some ecohydrological environment groups are readily assigned a flow regime class others are shared among a number of flow regime classes (Figure 8.12). This is confirmed by the value of the Hubert Arabie Rand Index of 0.226 indicative of a fairly weak recovery of the flow regime classes (Steinley 2004).

None of the groups sampled by more than one gauging station are exclusively linked to a single flow regime class. However, for 19 of the 30 ecohydrological environment groups, a majority (> 50%) of the gauges were of a single flow regime class. In particular, gauging stations on streams in the cool, wet groups were predominantly of either the perennial flow regime class 11 or 5. Five of the six gauges on the group 29 streams were flow regime class 11, the other class 5. This situation was reversed for streams in the other closely associated cool, wet group 26 where 41 of the 61 gauges belong to flow regime class 5 and another 14 are flow regime class 11.

Similarly, at the other ends of the environmental spectrum the arid group 6 streams were gauged at six locations of which five were of the extremely intermittent flow regime class 4 while all but one of the 34 gauges on streams in ecohydrological environment group 7 (hot, wet, summer rainfall) were of the flow regime class 2 (highly intermittent, summer dominant) (23 gauges) or 6 (perennial, summer dominant, high baseflow contribution) (10 gauges).

Other ecohydrological environment groups include gauging stations from as many as eight flow regime classes. This is the case for both groups 25 and 28, gauged at 48 and 86 locations, respectively. Both are members of meta-group H. This, however, is the meta-group containing the greatest variety of flow regime classes (Table 8.8). The majority of gauges of most other meta-groups are members of just two or three flow regime classes. Table 8.8 also shows that the flow regime classes typically occur across several of the ecohydrological environment meta-groups though the majority may be restricted to just one or two. For instance, 47 of the 56 gauges of flow regime class 6 (intermittent, winter dominant) are found on streams in ecohydrological environment group 22 (meta-group G) the remainder are scattered across three other meta-groups D, H and I. The Hubert Arabie Rand Index value of 0.232 is only slightly better than that for the comparison with the 30 group classification.

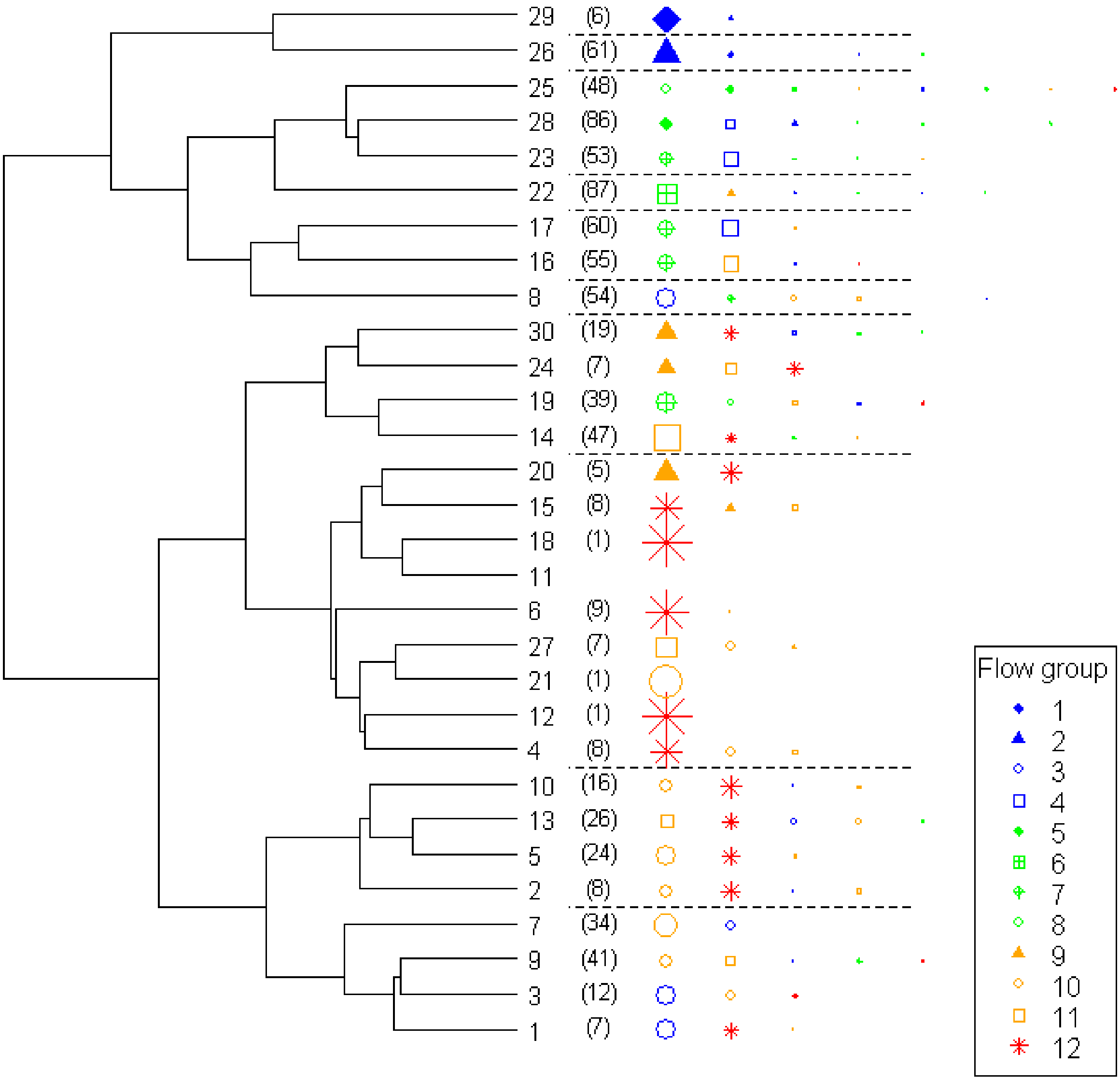


Figure 8.12. Flow regime class membership of the ecohydrological environment groups. The size of symbols is drawn proportional to the total number of gauges within each environment group (shown in parenthesis) while their colour and shape derives from their flow regime class as in Figure 5.9 in Appendix 5 (i.e. blue=Perennial, green=Intermittent, Orange=Highly intermittent, red=Extreme intermittent). Dashed lines show the 10 meta-groups formed by clustering of the ecohydrological environment groups. Environment group 11 streams were not gauged.

Table 8.8. Number of gauging stations by flow regime class and ecohydrological environment meta-group.

Meta-group	**Flow regime class**											
	Perennial				**Intermittent**			**Highly intermittent**				**Extreme intermittent**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	1		27				6			46	10	4
B			6				1			28	13	26
C									6	6	6	22
D						1	25	7	14	1	42	18
E	1		30				10			8	4	
F	1			31			57				25	1
G	4	11			6	47		1	18			
H	1	18		45	54	7	26	25	6		3	2
I	14	41		2	3	1						
J	5	1										

8.3.3.2 Discriminating variation in flow regime characteristics

While not being able to consistently predict the flow regime class membership of a stream, the ecohydrological classification is able to discriminate meaningful variation among streams in a number of the ecologically relevant characteristics of the flow regime. This is shown by the box and whisker plots presented for selected flow metrics describing major facets of the flow regime (Figures 8.13 to 8.16). To assist comparison, the hydrologic indices selected are those used to show variation among the flow regime classes in Figure 5.9 in Appendix 5, calculated for each of the 830 gauging stations.

The ability of the ecohydrological environment groups to differentiate the values of the hydrologic indices varies between the indices and among groups, though no group appears to be consistently more variable across all flow metrics. For instance, the mean number of zero flow days is well predicted by group membership for some groups including those at the extremes of the climate gradient (e.g. the cool, wet groups 26 and 29 and the arid groups 6 and 27) but poorly so for many others (e.g. group 1) (Figure 8.13). In contrast, within group variation in the values of the hydrologic index, predictability of mean daily flow, is similar for all groups and relatively modest.

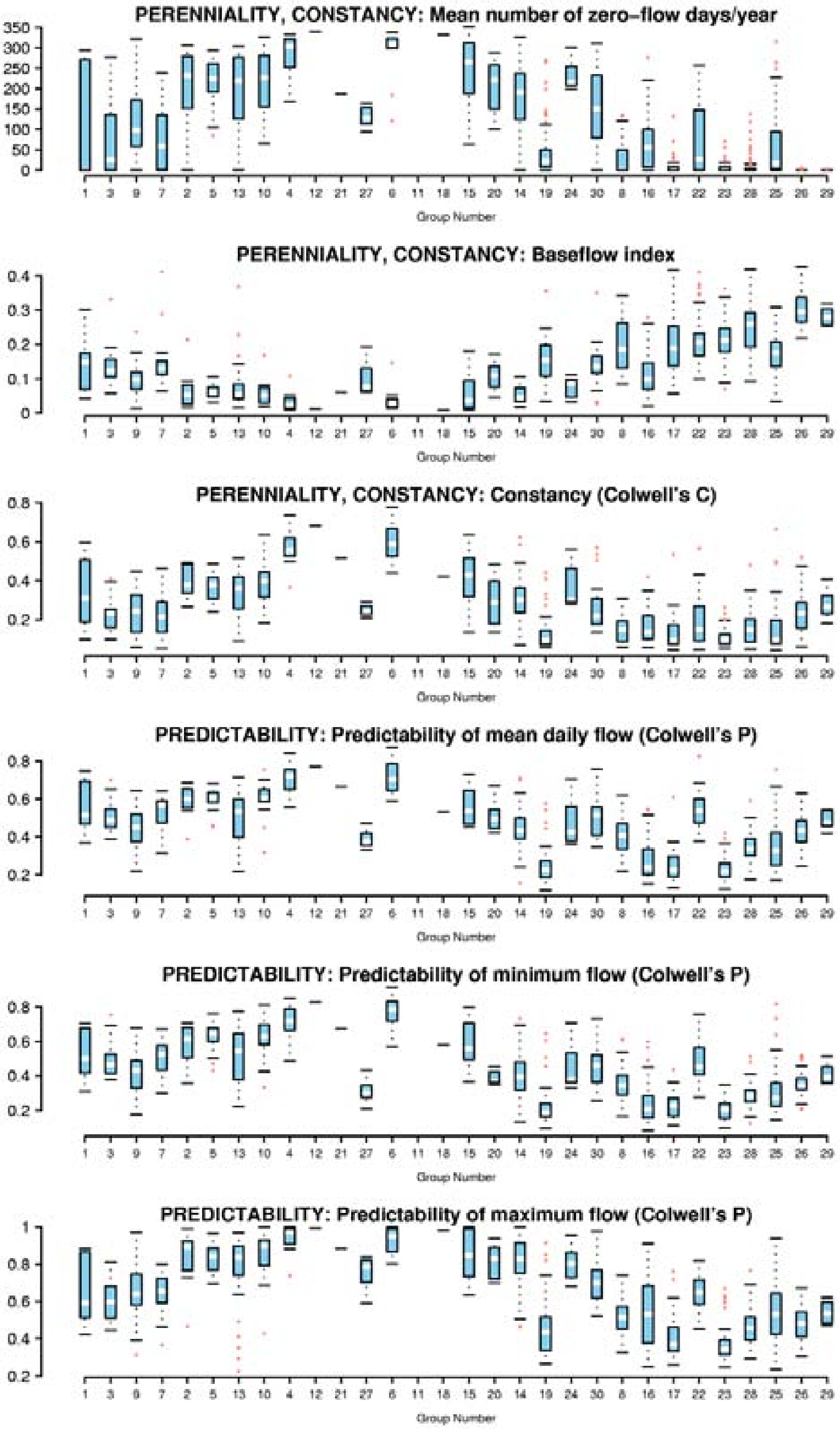


Figure 8.13. Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 1: perenniality, constancy and predictability.

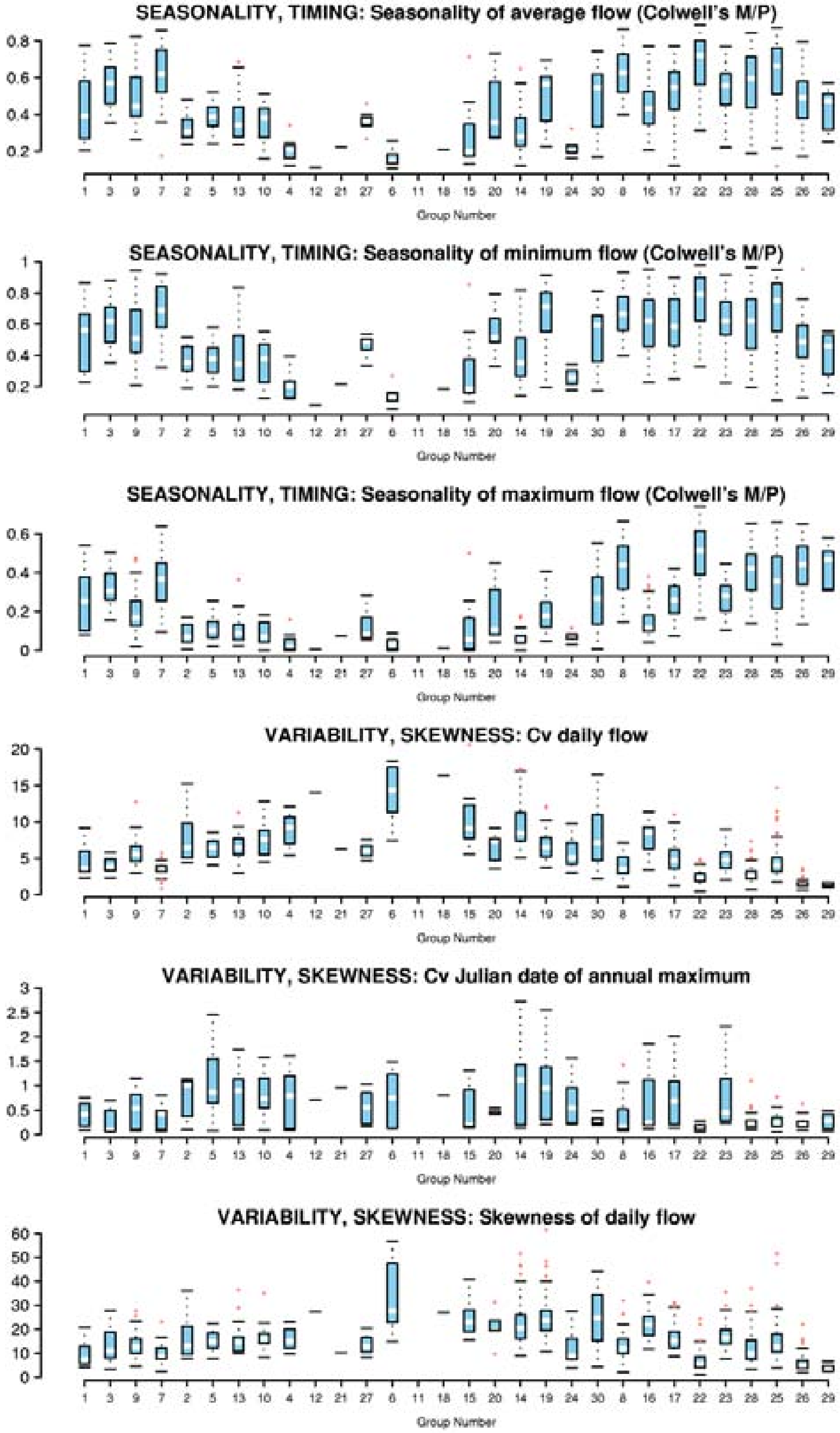
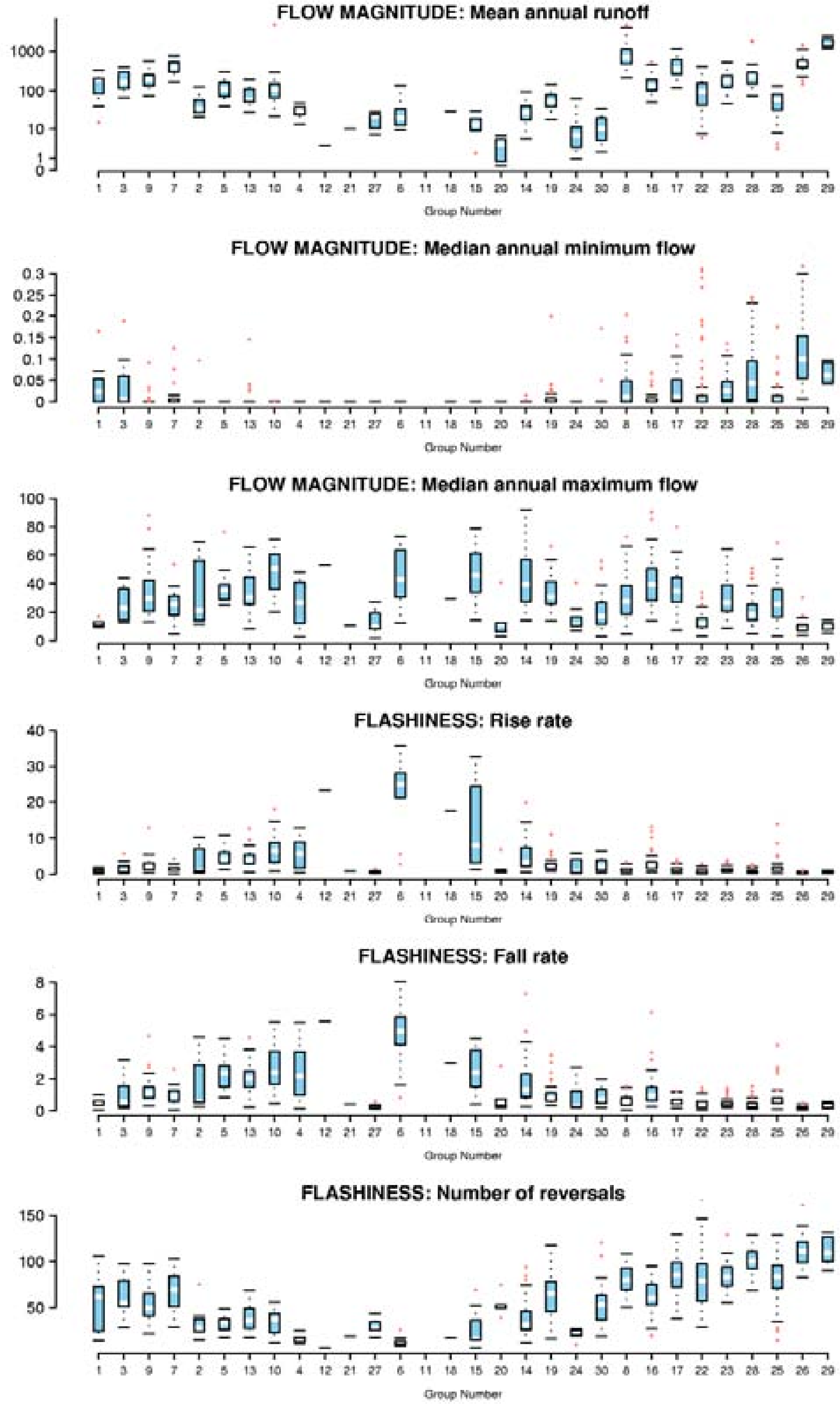


Figure 8.14. Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 2: seasonality, timing, variability and skewness.



FLOW MAGNITUDE: Mean annual runoff

FLOW MAGNITUDE: Median annual minimum flow

FLOW MAGNITUDE: Median annual maximum flow

FLASHINESS: Rise rate

FLASHINESS: Fall rate

FLASHINESS: Number of reversals

Figure 8.15. Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 3: magnitude and flashiness.

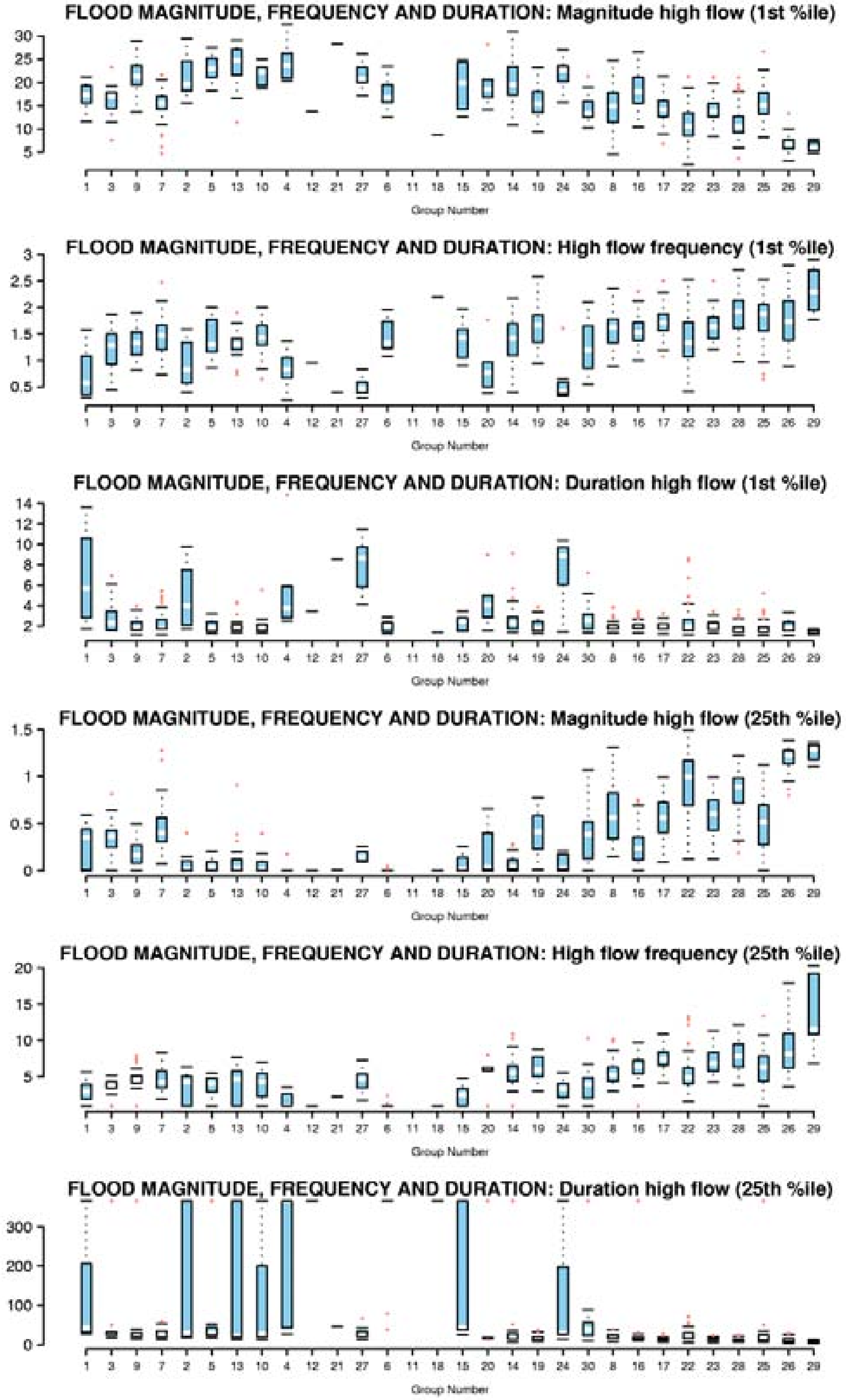


Figure 8. 16. Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 4: flood magnitude, frequency and duration.

The results are similarly mixed for the indices describing the seasonality, timing and variability of flow (Figure 8.14). Perhaps best discriminated by the ecohydrological environment classification among these indices, are the skewness of daily flow and the C_v of daily flow. In contrast, the gauging station values of the C_v of the Julian date of the annual maximum are quite variable for most groups with some notable exceptions for several groups of streams from the southern half of the continent. Interestingly, this hydrologic index also exhibited a wide range of values for five of the flow regime classes (0, 1, 3, 4 and 6) (see Figure 5.9 in Appendix 5).

The gauged values of annual mean runoff are very well discriminated by all of the ecohydrological environment classification (Figure 8.15) (though note log scale). The results are more inconsistent for the median annual minimum and median annual maximum flows. However, group membership reliably predicts where the median annual minimum flow is typically zero. Variation within groups for the hydrologic indices describing the rate of rise and fall is also less for streams in the cooler, wetter groups in southern Australia than it is for streams in meta-groups B and C in particular (Figure 8.15).

Similarly, the groups differ in the level of within group variation for the flow metrics describing characteristics of the high flows (Figure 8. 16). While the indices describing the flood magnitude and frequency are, in most cases, reasonably well discriminated by the ecohydrological environment groups, those describing the duration of high flows are very poorly differentiated by several groups in northern Australia.

For all hydrologic indices the probability value of the Kruskall-Wallis test was very close to zero, confirming that the ecohydrological environment classification did indeed discriminate significant variation in their values. However, as seen in the box and whisker plots, this varied between hydrologic indices (Figure 8.17). Indices describing flow components related to the duration and frequency of events (both high and low) and the timing of low flow events are typically less well discriminated than other components of flow.

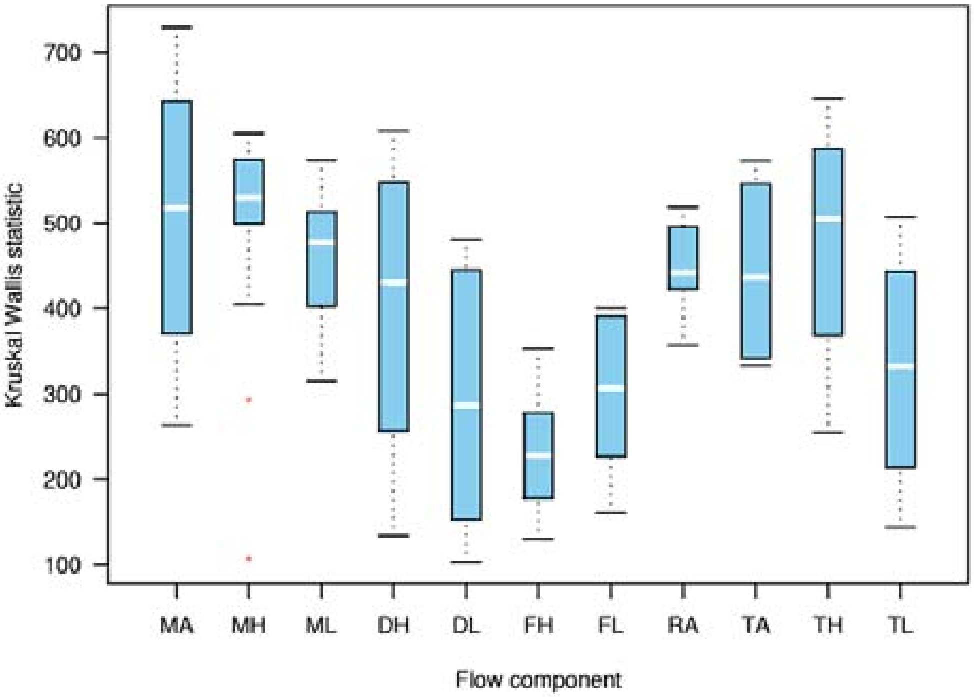


Figure 8.17. Ecohydrological Environment Types Kruskal Wallis statistic for hydrologic indices by flow component: MH – Magnitude average, MH – Magnitude high, ML – Magnitude low, DH – Duration high, DL – Duration low, FH – Frequency high, FL – Frequency low, RA – Rate of change, TA – Timing average, TH – Timing high, TL – Timing low.

8.3.3.3 Classification strength

The Kruskal-Wallis statistic tested classification performance against each of the hydrologic indices independently. A more integrated measure of performance is provided by the Classification Strength (CS). We showed earlier (Section 8.3.1, Table 8.7) that the CS value of the 30 group ecohydrological environment classification derived from the NOWEIGHTING classification series was less than that of the flow regime classification of gauging stations, though better than any random grouping of gauging stations. Here we compare the CS of the ecohydrological environment classification with those of alternative landscape classification schemes: the IBRA regionalisation and sub-regionalisation (Department of Environment, Water, Heritage and the Arts 2007), the AWRC Drainage Divisions (Australian Water Resources Council 1976; Geoscience Australia 2003) topographically defined drainage basins (all of the catchment area draining to a river mouth or inland sink) (Stein 2007, unpublished) and the agro-climatic classification (Hutchinson *et al.* 2005). Gauging stations were allocated to a region in each classification by overlay. We also explore variation in hydrologic similarity within groups.

Classification strength was computed for each of the alternative classifications based on the hydrologic similarity of the gauges measured by the Gower metric across all 120 hydrologic indices. The classification strength derived directly from *a posteriori* classification of the gauges suggests an upper bound to that achievable by any landscape classification for the same number of groups (Van Sickle and Hughes 2000). To compare the strength of different classifications the relative CS (Snelder *et al.* 2004) was calculated by expressing CS as a percentage of the CS of *a posteriori,* spatially neutral classifications of the gauging station data. These *a posteriori* classifications were generated with the flexible beta UPGMA clustering algorithm ($\beta = -0.1$) (Belbin *et al.* 1992) as implemented in PATN (Belbin 1993b) for a number of groups equal to the number of landscape classification groups represented by at least two sites, that is, the number of groups included in the calculation of $\overline{W}$. For example, a 26 group classification of gauging stations produced a CS ($\overline{W} - \overline{B}$) value of 0.0887. Thus, the ecohydrological environment classification that also tests 26 groups has a relative CS value of 75% (0.0663/0.0887).

The ecohydrological environment classification provides the strongest landscape classification when expressed as relative CS (Table 8.8). The agro-climatic classification also performs well with a relative CS value of 69%. Topographically defined drainage basins provide the weakest classification with CS values just 35% of that achievable for *a posteriori* classification with an equivalent number of groups.

Table 8.8. Classification strength of alternative landscape classifications. Relative CS values are calculated as for *a posteriori* classifications of the gauges are also included.

Classification	***Number of groups***	***Number of groups sampled by > 1 gauge***	$\overline{W}-\overline{B}$	$\overline{B}/\overline{W}$	***Relative CS (%)***
Landscape classification					
IBRA 6.1 regions (Department of Environment, Water, Heritage and the Arts 2007)	85	56	0.0578	0.935	60
IBRA 6.1 sub-regions (Department of Environment, Water, Heritage and the Arts 2007)	403	145	0.0674	0.925	62
AWRC Drainage Divisions (Geoscience Australia 2003)	12	11	0.0379	0.956	49
Topographically defined drainage basins (Stein 2007 unpublished)	1250[1]	93	0.0357	0.99	35
Agro-climatic classification of Australia (Hutchinson *et al.* 2005)	18	17	0.0579	0.934	69
Ecohydrological environment classification (this study)	30	26	0.0663	0.925	75
Classification of gauging stations					
Flow regime classes (Appendix 5)	12	12	0.0764	0.915	98

Notes:

1. Basins of named streams

Mean similarity dendrograms (Van Sickle 1997) were produced using a routine written in the R statistical software scripting language (R Development Core Team 2004) (Figure 8.18). Relatively long branches of the mean similarity dendrogram are indicative of a strong classification (Van Sickle and Hughes 2000). However, while within group similarity W_i was greater than between class similarity for all but one of the Drainage Divisions (Bullo-Bancannia), none of the classifications presented, including the *a posteriori* classification of flow regime classes (Appendix 5) displayed the long arms that would suggest a strong classification. Moreover, W varies between groups. The values of the hydrologic indices were most similar among gauging stations in the cool, wet ecohydrological environment groups 26 and 29 (values of W of 0.914 and 0.917 respectively) and least similar for gauges in group 30, the drier of the south-west Western Australian groups (W=0.8346). The greatest variation in W is observed for groups gauged at less than 15 locations (

Figure **8.**19) suggesting at least some of the variation in W between groups may be attributed to sampling effects (Hawkins and Vinson 2000; Heino *et al.* 2004).

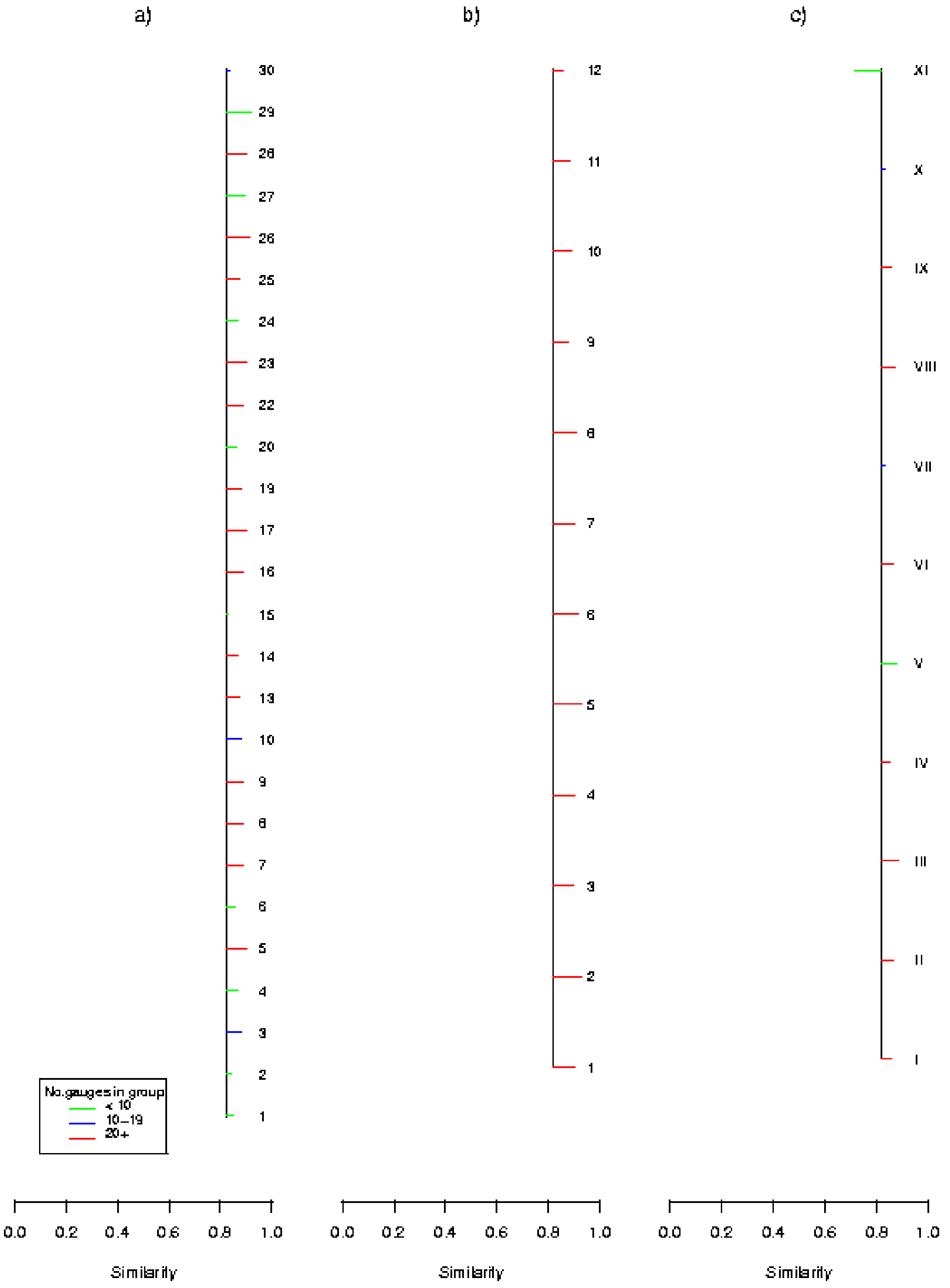


Figure 8.18. Mean similarity dendrograms for alternative groupings of gauging stations: a) the ecohydrological environment classification; b) Autoclass clustering of gauges (Appendix 5); c) AWRC Drainage Divisions (I – North-east coast, II – South-east coast, III – Tasmania, IV – Murray-Darling, V – South Australian coast, VI – South-west coast, VII – Indian Ocean, VIII – Timor Sea, IX – Gulf of Carpentaria, X – Lake Eyre, XI – Bulloo-Bancannia). The dendrogram node is plotted at $\overline{B}$, the average between group similarity, with branches for each group

of length W_i where W_i is the within group mean similarity for group *i*.

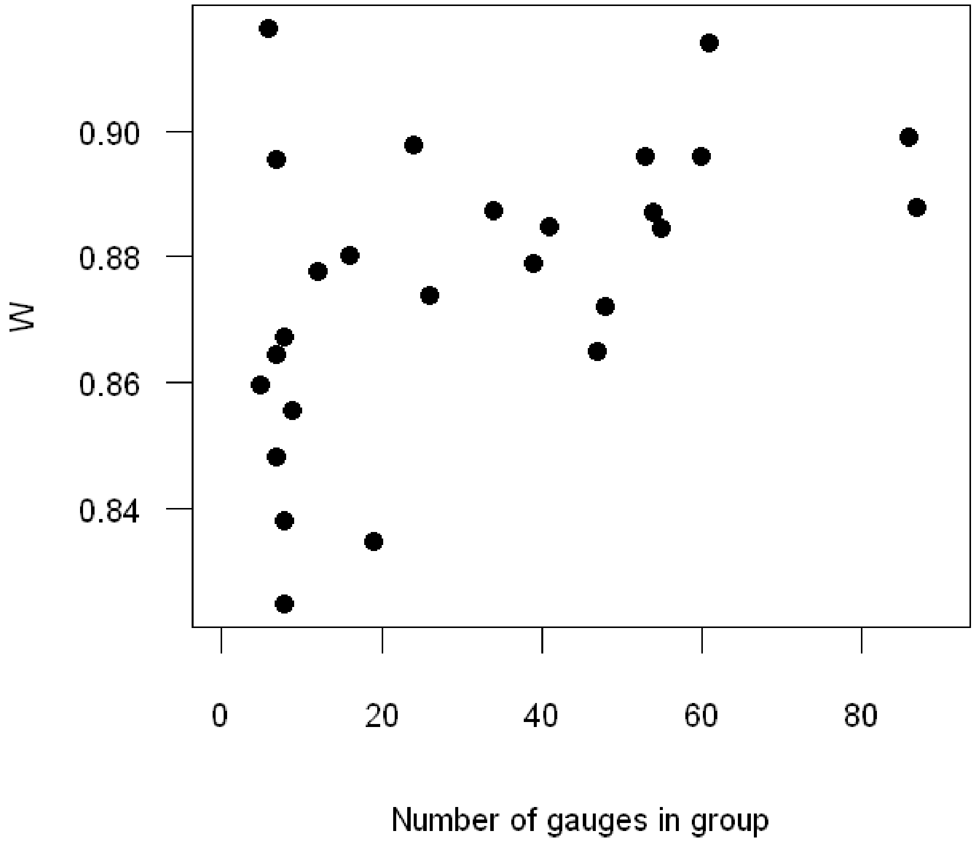


Figure 8.19. Within group similarity (W) for ecohydrological environment groups with number of gauging stations.

8.4 Discussion

We classified all of the streams (that are mapped at a scale of 1:250,000) to derive an ecohydrological environment classification for Australia. The classification describes variation in the landscape and climate variables that shape the flow regime. Climate, both directly, and indirectly through the catchment water balance attributes, exerts a major influence on these patterns. At finer spatial scales, groups exemplify the separate and/or combined influences of substrate, terrain and vegetation cover.

8.4.1 Classification performance

Our classification is also able to discriminate meaningful variation in many of the ecologically relevant descriptors of the flow regime. It provides a stronger classification than other national classifications including the AWRC Drainage Divisions, IBRA and the agro-climatic classification. The CS value for the topographically defined drainage basins was particularly low, suggesting there is considerable within basin heterogeneity in flow regimes relative to that between – a finding supported by the high diversity of ecohydrological environment types observed for many basins.

The relative CS value of 75% of that for a comparable *a posteriori* classification of the gauging stations compares favourably with that reported by Snelder *et al.* (2005) for New Zealand's River Environment Classification from an analysis of 335 gauges (a best CS of 60%). Like Snelder *et al.* (2005) we found between group similarities $\left(\overline{B}\right)$ to be relatively large when compared to the within group similarities among gauging stations ($\overline{W}$). Accordingly, absolute CS values were reasonably low. This however, was also true of the classification of flow regime classes. The low $\overline{B}$ values implies that each pair-wise combination of gauging stations share similar values for at least some flow metrics, thus constraining the range of possible values of B. The distribution of the pair-wise similarity values confirms this to be the case. These have a mean value of 0.827 (standard deviation: 0.061, median: 0.834) on a scale of zero, indicating the gauging stations are maximally dissimilar, to one, implying identical values across all hydrologic indices. Even the most dissimilar gauges have a Gower metric value of 0.503 implying some overlap in flow metric values.

CS is an integrated measure of classification performance. However, it masks considerable variability in the classification's ability to discriminate meaningful variation between hydrologic indices. Interestingly, some of the components of flow least well discriminated (low flow magnitude, duration and timing) were also some of those that were found to be least accurately described by the gauged data (Appendix 4). Since baseflow characteristics are an important distinguishing attribute of the flow regime classes (Appendix 5) it was not surprising that the ecohydrological environment classification did not reliably predict class membership.

8.4.2 Classificatory strategy

The classification might have been tailored to better recover these flow regime classes by seeding it with the flow regime class means derived from the values of the environmental attributes at the gauging station location. Thus, each stream reach would be allocated to the flow regime class to which it was most similar in this environmental space. However, we were also interested to discover whether there was additional variation in the ecohydrological characteristics of streams that might not be captured by the reasonably limited set of gauging stations available. Accordingly, we derived our environmental classification independently and used the gauged data to test its performance. We thus identified four groups of streams with potentially different ecohydrological characteristics that were either not gauged at all, or gauged at only one location. Not unexpectedly, these streams are all found across the arid centre of Australia and hence have been of very little interest to hydrologists.

There are a number of other aspects of our classificatory strategy that will influence the outcomes. These include our choices of clustering method, attributes, weightings, numbers of groups and hierarchical organisation.

We employed the ALOB non-hierarchical clustering procedure to generate the ecohydrological environment classification based on its successful application to many other environmental domain analyses and its ability to handle the very large data matrix that we generated (i.e. 1.2 million stream reaches x 48 attributes). The inter-group association matrix it produces also enables exploration of the relationship between groups and their higher level clustering. However, it does not explicitly incorporate data uncertainty into the algorithm though this might be approximated by appropriate variable weightings. More seriously, it produces hard boundaries between classes that may not reflect gradual change. Probabilistic methods such as that used to generate the flow regime classes overcome the problem of indeterminate boundaries and might be assessed for future revisions of the ecohydrological environment classification.

There are no widely accepted criteria for determining an appropriate number of groups (Belbin 1993a). Moreover the different criteria may not agree (Mufti *et al.* 2005). For ease of interpretation and use and because it better recovered the grouping of gauging stations we chose to focus our analysis on a 30 group classification. Classifications with a larger number of groups will differentiate greater variation in the environmental characteristics of streams and their catchments. However, as the number of groups increases, the differences between them increasingly approach the measurement error of the attributes, or is so small as to be ecologically meaningless. Still, streams in the two most similar groups of the 40 group NOWEIGHTING classification series differed significantly across at least one attribute: the average proportion of natural tree cover in the catchment (values of 5 and 74% respectively). It remains to be tested, however, whether this explains any additional, ecologically meaningful, variation in their flow regime. Such testing would likely require additional gauging stations to ensure adequate sampling of each group.

Our attribute weighting was implicitly defined by the number of variables that we used to describe the major landscape controls on stream hydrology. These were heavily weighted to the climatic and catchment water balance descriptors, many of them highly correlated, so not surprisingly, these are the major discriminators of variation among the groups. This is, however, consistent with the wide recognition of the primary role that climate plays in controlling stream ecosystem patterns and processes at broad spatial scales (Bailey 1996; Cleland *et al.* 1997; Calvert *et al.* 2001; Snelder and Biggs 2002) but reduces the influence of other important controlling factors. This could be one of the reasons the classification was unable to discriminate those streams with a significant baseflow contribution associated with the geology of its catchment. Assigning equal weighting to each of the major attribute groups (climate, catchment water balance, catchment morphology, substrate and vegetation cover), however, produced a weaker classification.

A hierarchical classification structure provides an alternative method of organising the classification that better reflects the different scales at which the controlling factors operate. Thus, for instance, one could derive five separate classifications, one for each of the major attribute groups, and then combine these hierarchically (e.g. Snelder and Biggs 2002; Stein 2007). The major disadvantage of this approach is the large number of combinations it can produce making validation and testing problematic. For example, there are 10^5 possible combinations for a five level hierarchical classification of ten groups though of course, many of the potential combinations may not exist.

The attributes selected by the Mantel tests raise some interesting questions about the nature of the landscape controls on stream hydrology. These too, down-weighted the influence of substrate, selecting none of the attributes describing the catchment lithology. Similarly, the classification trees (CART) models (Appendix 5) did not include geological attributes as significant predictors of flow regime class membership. This, however, is likely to be more a reflection of the limitations of the geological data and the method of attribution than an indication of the relative influence of catchment geology on stream hydrology.

8.4.3 Characterisation of landscape processes

Categorical map data such as lithology are difficult to attribute in ways that suitably reflect their influence on stream hydrology. This task was made more difficult by the nature of the geological mapping. The new, 1:1 million scale, Geology of Australia mapping was not finished in time for this project. Differences in the mapping scale and the coding and lithological description of map units between this, and the older, 1:2,500,000 scale mapping used to complete the continental coverage, produced inconsistencies across state borders and potentially artefacts in the classification. The mapping units also combine lithologies with very different hydrogeological properties. For example, shales and other fine grained clastic rocks, typically with extremely low permeabilities, were mapped with highly permeable sandstones (Fitts 2002). Moreover, a lithology's hydrogeological behaviour may vary considerably depending on the age of the bedrock and the degree of weathering and faulting (Le Moine *et al.* 2007). Even if expert assistance was available to characterise the hydrogeological properties of each of the many thousands of mapping units (a major undertaking) there remains the problem of integrating these values across the catchment. Catchment averages may be uninformative and even misleading, especially in large catchments.

Catchment averages were also used to characterise the catchment climate and similarly, may not adequately represent the heterogeneous climatic conditions of a large catchment. This might be improved by weighting the average according to the potential contribution of an area to stream flow (e.g. as indicated by the monthly runoff estimates). An even better solution would be to model directly the physical processes that shape the character and behaviour of the stream hydrology although in many cases this is likely to be precluded by the coarse scale of national mapping of essential data layers.

The catchment water balance model attempted to do this. Clearly, it greatly simplifies the processes of converting rainfall into runoff. This avoided the need for calibration for individual catchments and complex parameterisation with concomitant demands on data thus enabling continental-scale application. It was computed from monthly rainfall totals rather than actual rainfall events and does not account for transmission losses in streamflow routing. Contributions to streamflow from surface (overland and interflow) and groundwater are not partitioned though work is now underway to introduce a slow flow component into the water balance model (M. Hutchinson, pers. comm. 31/1/08). The results will also be sensitive to the coarse resolution (~1 km) of the soils data that sets the size of the soil water storage capacity and the way the accumulated runoff is apportioned in anabranching systems.

8.5 Conclusions

We recognised limitations and uncertainties in our classification. Some of these could be readily addressed by testing alternative classificatory strategies such as the use of probabilistic clustering algorithms or a hierarchical classification structure. Others relate to our ability to capture the critical landscape controls on stream hydrology and will require a greater investment in research. In particular, it will be important to address shortcomings in the methods available to characterise the influence of catchment geology and the geological mapping on which it is based. The inability of the classification to discriminate streams with a significant groundwater contribution might be largely attributed to these shortcomings.

Even so, we have shown that the consistent, continent-wide characterisation of climate and landscape variation that our ecohydrological environment classification describes differentiates many of the other ecologically relevant components of the flow regime, including those describing its magnitude, seasonality and variability. At the highest level, the classification splits streams into three broad clusters, differentiating streams in the north from those in the south and inland. Further divisions produce groupings of streams that are generally spatially coherent. The overriding influence of climate on these patterns is reinforced by the relative strength of an independent agro-climatic classification.

The ecohydrological environment classification will support applications at broad regional to continental scale while supplying the context for finer scale regional or catchment studies. We showed, for instance, how it might be used to explore patterns of diversity in the ecohydrological characteristics of streams at a range of spatial scales. We also identified several ecohydrological environment types that were very poorly gauged. Thus, our classification may also be applied to the task of designing a more representative network of gauging stations.

8.6 Acknowledgements

The maps shown in Figures 8.6, 8.7, 8.8 and 8.10 incorporate data which is © Commonwealth of Australia Geoscience Australia 1997 and 2004.

8.7 References

Atkinson, S.E., Woods, R.A. and Sivapalan, M. (2002). Climate and landscape controls on water balance model complexity over changing timescales. *Water Resources Research* 38(12): 1314.

AUSLIG. (1997). *River Basins of Australia* Version 1.0. Australian Survey and Land Information Group, Canberra.

Australian Water Resources Council. (1976). *Review of Australia's water resources 1975*. Australian Water Resources Council, Australian Government Department of Natural Resources, Canberra. 170 pp.

Bailey, R.G. (1996). *Ecosystem Geography*. Springer-Verlag, New York. 204 pp.

Bárdossy, A. and Schmidt, F. (2002). GIS approach to scale issues of perimeter-based shape indices for drainage basins. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 47(6): 931–942.

Belbin, L. (1987). The use of non-hierarchical allocation methods for clustering large sets of data. *Australian Computer Journal* 19(1): 32–41.

Belbin, L. (1993a). Environmental representativeness – regional partitioning and reserve selection. *Biological Conservation* 66(3): 223–230.

Belbin, L. (1993b). *PATN* Version 3.6. CSIRO Division of Wildlife and Ecology, Canberra.

Belbin, L. and Collins, A. (2004). *PATN* Version 3.03. Blatant Fabrications, Hobart. http://www.patn.com.au/

Belbin, L., Faith, D.P. and Milligan, G.W. (1992). A comparison of two approaches to beta-flexible clustering. *Multivariate Behavioral Research* 27(3): 417–433.

Belbin, L., Marshall, C. and Faith, D.P. (1983). Representing relationships by the automatic assignment of colour. *Australian Computer Journal* 15(4): 160–163.

Belbin, L. and McDonald, C. (1993). Comparing three classification strategies for use in ecology. *Journal of Vegetation Science* 4(3): 341–348.

Bourgeron, P.S., Humphries, H.C. and Jensen, M.E. (2001). Elements of ecological land classifications for ecological assessments. Pp. 321–337. In Jensen, M.E. and Bourgeron, P.S. (eds), *A Guidebook for Integrated Ecological Assessments.* Springer-Verlag, New York.

Brandes, D., Hoffmann, J.G. and Mangarillo, J.T. (2005). Base flow recession rates, low flows, and hydrologic features of small watersheds in Pennsylvania, USA. *Journal of the American Water Resources Association* 41(5): 1177–1186.

Brierley, G.J. and Fryirs, K. (2000). River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management* 25(6): 661–679.

Brierley, G.J., Fryirs, K. and Cohen, T. (1996). *Geomorphology & river ecology in southeastern Australia: An approach to catchment characterisation. Part One. A geomorphic approach to catchment characterisation.* Graduate School of the Environment, Macquarie University, North Ryde. 54 pp.

Bryce, S.A. and Clarke, S.E. (1996). Landscape-level ecological regions: Linking state-level ecoregion frameworks with stream habitat classifications. *Environmental Management* 20(3): 297–311.

Bureau of Rural Sciences. (1991). *Digital Version of the 1976 Edition of Geology of Australia, 1:2 500 000 Scale (ARC/INFO vector format)*. Available: http://www.brs.gov.au/datasets

Calvert, S., Erskine, W. and Junor, B. (2001). *Development of a National River Classification System – Final Report. Consultancy report prepared by PPK Environment and Infrastructure*. Murray-Darling Basin Commission, Environment Australia and the Land and Water Resources, Research and Development Corporation, Sydney, Australia. 68 pp.

Clarke, S.E., White, D.S. and Schaedel, A.L. (1991). Oregon, USA, ecological regions and subregions for water quality management. *Environmental Management* 15: 847–856.

Cleland, D. T., Avers, P.E., McNab, W.H., Jensen, M.E., Bailey, R.G., King, T. and Russell, W.E. (1997). National hierarchical framework of ecological units. Pp. 181–200. In Boyce, M.S. and Haney, A. (eds), *Ecosystem Management: Applications for Sustainable Forest and Wildlife Resources.* Yale University Press, New Haven.

Croke, B. (2002) *Hydrological Parameterisation of SedNet. Technical Report I for the Basin-wide mapping of sediment and nutrient exports in dryland regions of the Murray-Darling Basin (Project D10012).* Integrated Catchment Assessment and Management Centre (iCAM), Australian National University, Canberra. 51 pp.

Davies, N.M., Norris, R.H. and Thoms, M.C. (2000). Prediction and assessment of local stream habitat features using large-scale catchment characteristics. *Freshwater Biology* 45: 343–369.

Department of Environment, Water, Heritage and the Arts. (2007). *Interim Biogeographic Regionalisation of Australia (IBRA) Version 6.1.* Department of Environment, Water, Heritage and the Arts, Canberra. Retrieved from: http://www.deh.gov.au/parks/nrs/ibra/version5-1/summary-report/pubs/ibrav5-summary-report.doc

DeVellis, B. (1991). *Scale development: theory and applications.* Sage Publications, Newbury Park, California.

Fagan, S.D. and Nanson, G.C. (2004). The morphology and formation of floodplain-surface channels, Cooper Creek, Australia. *Geomorphology* 60(1–2): 107–126.

Fitts, C.R. (2002). *Groundwater science*. Academic Press, Amsterdam. 450 pp.

Gallant, J.C. and Dowling, T.I. (2003). A multi-resolution index of valley bottom flatness for mapping depositional areas. *Water Resources Research* 39(12): 1347.

Geoscience Australia. (2003). *Australian Surface Water Management Areas (ASWMA) 2000 Product User Guide*. Geoscience Australia, Canberra. 20 pp.

Goodwin, C. (1996). *Watershed Analysis and Management: The Importance of Geology* [online]. U.S. Environmental Protection Agency. Available: http://www.epa.gov/owow/watershed/Proceed/goodwin.htm

Gordon, N.D., McMahon, T.A. and Finlayson, B.L. (1992). *Stream hydrology. An introduction for ecologists.* John Wiley & Sons, Chichester. 526 pp.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. and Nathan, R.J. (2004). *Stream hydrology. An introduction for ecologists.* 2nd edition. John Wiley & Sons, Chichester. 429 pp.

Goslee, S. and Urban, D. (2007). *ecodist: Dissimilarity-based functions for ecological analysis. R package* Version 1.1.2.

Gower, J.C. (1971). A general coefficient of similarity and some of its properties. *Biometrics* 27(4): 857–871.

Harding, J.S. and Winterbourn, M.J. (1997). An ecoregion classification of the South Island, New Zealand. *Journal of Environmental Management* 51(3): 275–287.

Hawkins, C.P., Norris, R.H., Gerritsen, J., Hughes, R.M., Jackson, S.K., Johnson, R.K. and Stevenson, R.J. (2000). Evaluation of the use of landscape classifications for the prediction of freshwater biota: synthesis and recommendations. *Journal of the North American Benthological Society* 19(3): 541–556.

Hawkins, C.P. and Vinson, M.R. (2000). Weak correspondence between landscape classifications and stream invertebrate assemblages: implications for bioassessment. *Journal of the North American Benthological Society* 19(3): 501–517.

Heino, J., Louhi, P. and Muotka, T. (2004). Identifying the scales of variability in stream macroinvertebrate abundance, functional composition and assemblage structure. *Freshwater Biology* 49(9): 1230–1239.

Hennessy, K., Whetton, P., Smith, I., Bathols, J., Hutchinson, M. and Sharples, J. (2003). *The impact of climate change on snow conditions in mainland Australia.* CSIRO Atmospheric Research, Aspendale, Victoria. 50 pp. Retrieved from: http://www.cmar.csiro.au/e-print/open/hennessy_2003a.pdf

Hutchinson, M.F., Houlder, D.J., Nix, H.A. and McMahon, J.P. (2000). *ANUCLIM Users Guide Version 5.1.* Centre for Resource and Environmental Studies, Australian National University, Canberra.

Hutchinson, M.F., McIntyre, S., Hobbs, R.J., Stein, J.L., Garnett, S. and Kinloch, J. (2005). An agro-climatic classification incorporating bioregional boundaries in Australia. *Global Ecology and Biogeography* 14: 197–212.

Hutchinson, M.F., Nix, H.A. and McMahon, J.P. (1992). Climate constraints on cropping systems. Pp. 37–58. In Pearson, C.J. (ed), *Field Crop Systems, Vol. 18.* Elsevier, Amsterdam.

Hutchinson, M.F., Nix, H.A. and McTaggart, C. (2004). *GROWEST Version 2.0.* Centre for Resource and Environmental Studies, Australian National University, Canberra. Available: http://cres.anu.edu.au/outputs/growest.php

Jellett, D.R. (2005) *Parameter efficient prediction of unconfined groundwater levels and streamflow.* PhD Thesis, Centre for Resource and Environmental Studies, Australian National University, Canberra. 286 pp.

Jerie, K., Household, I. and Peters, D. (2003). *Tasmania's river geomorphology: stream character and regional analysis. Volume 1*. Nature Conservation Report No. 03/50. Department of Primary Industries, Water and Environment, Tasmania. 126 pp.

Kesteven, J., Landsberg, J. and URS Australia (2004). *Developing a national forest productivity model.* National Carbon Accounting System Technical Report No. 23. Australian Greenhouse Office, Canberra. 104 pp.

Kingsford, R.T., Dunn, H., Love, D., Nevill, J., Stein, J.L. and Tait, J.T. (2005). *Protecting Australia's rivers, wetlands and estuaries of high conservation value*. Department of Environment and Heritage Australia, Canberra. Retrieved from: http://www.environment.gov.au/water/publications/environmental/protecting-rivers.html

Kirkpatrick, J.B. and Brown, M.J. (1994). A comparison of direct and environmental domain approaches to planning reservation of forest higher plant communities and species in Tasmania. *Conservation Biology* 8(1): 217–224.

Knighton, D. (1998). *Fluvial forms and processses. A new perspective.* Arnold, London.

Le Moine, N., Andréassian, V., Michel, C. and Perrin, C. (2005). How to account for groundwater exchanges in rainfall-runoff models. Presented at *MODSIM 2005 International Congress on Modelling and Simulation*. Melbourne, December, 12–15. Zerger, A. and Argent, R.M. (eds), pp. 2932–2938. Modelling and Simulation Society of Australia and New Zealand.

Le Moine, N., Andréassian, V., Perrin, C. and Michel, C. (2007). How can rainfall-runoff models handle intercatchment groundwater flows? Theoretical study based on 1040 French catchments. *Water Resources Research* 43: W06428.

Leathwick, J.R., McOverton, J. and McLeod, M. (2003). An environmental domain classification of New Zealand and its use as a tool for biodiversity management. *Conservation Biology* 17(6): 1612–1623.

Lewis, A., Stein, J.L., Stein, J.A., Nix, H.A., Mackey, B.G. and Bowyer, J.K. (1991). *An assessment of regional conservation adequacy: Tasmania*. Resource Assessment Commission, Forest and Timber Inquiry Consultancy Series No., Canberra, 106 pp.

Lewis, F. (1998) *Modelling Direct Episodic Recharge in the Western Australian Wheatbelt.* Resource Management Technical Report No. FTC91/17. Department of Agriculture, Western Australia. 46 pp. Retrieved from: http://agspsrv38.agric.wa.gov.au/pls/portal30/docs/folder/ikmp/lwe/water/watres/tr168.pdf

Liu, S.L., Raymond, O.L., Stewart, A.J., Sweet, I.P., Duggan, M., Charlick, C., Phillips, D. and Retter, A.J. (2006). *Surface geology of Australia 1:1,000,000 scale, Northern Territory [Digital Dataset]*. The Commonwealth of Australia, Geoscience Australia, Canberra. Available: http://www.ga.gov.au

Lu, H. and Yu, B. (2002). Spatial and seasonal distribution of rainfall erosivity in Australia. *Australian Journal of Soil Research* 40(6): 887–901.

Mackey, B.G., Berry, S.L. and Brown, T. (2007). Reconciling approaches to biogeographical regionalization: a systematic and generic framework examined with a case study of the Australian continent. *Journal of Biogeography* 35(2): 213–229.

Mackey, B.G., Nix, H.A. and Hitchcock, P. (2001). *The natural heritage significance of Cape York Peninsula*. ANUTECH, Canberra. 194 pp.

Mackey, B.G., Nix, H.A., Hutchinson, M.F., MacMahon, J.P. and Fleming, P.M. (1988). Assessing representativeness of places for conservation reservation and heritage listing. *Environmental Management* 12(4): 501–514.

Mackey, B.G., Nix, H.A., Stein, J.A. and Cork, S.E. (1989). Assessing the representativeness of the Wet Tropics of Queensland World Heritage Property. *Biological Conservation* 50: 279–303.

Mackey, B.G., Stein, J.A., Stein, J.L. and Gilles, J. (2000). *A scientific assessment of the conservation value of Monga and Buckenbowra State Forests, NSW, Australia – with a particular emphasis on adequacy and representativeness*. Centre for Resource and Environmental Studies/ Department of Geography, Faculty of Science, Australian National University, Canberra. ISBN 086740518X.

McMahon, T.A. (1977). The relief and land form map of Australia: Does it show rock types and land forms of hydrologic significance? *Catena* 4(1–2): 189–199.

Moussa, R. (2003). On morphometric properties of basins, scale effects and hydrological response. *Hydrological Processes* 17: 33–58.

Mufti, G.B., Bertrand, P. and Moubarki, L.E. (2005). Determining the number of groups from measures of cluster stability. Presented at *XIth. International Symposium on Applied Stochastic Models and Data Analysis (ASMDA 2005)*. Brest, France, 17–20 May. Pp. 405–413. Retrieved from: http://asmda2005.enst-bretagne.fr/IMG/pdf/proceedings/404.pdf

Mulcahy, M.J. and Bettenay, E. (1972). Soil and landscape studies in Western Australia. (1) The major drainage divisions. *Journal of the Geological Society of Australia* 18(4): 349–357.

Mwakalila, S., Feyen, J. and Wyseure, G. (2002). The influence of physical catchment properties on baseflow in semi-arid environments. *Journal of Arid Environments* 52(2): 245–258.

Nanson, G.C., Jones, B.G., Price, D.M. and Pietsch, T.J. (2005). Rivers turned to rock: Late Quaternary alluvial induration influencing the behaviour and morphology of an anabranching river in the Australian monsoon tropics. *Geomorphology* 70(3–4): 398–420.

National Land and Water Resources Audit. (2000). *Rainfall erosivity (R factor).* National Land and Water Resources Audit, Canberra. http://data.brs.gov.au/asdd/index.php

National Land and Water Resources Audit. (2001a). *Australian Native Vegetation Assessment 2001.* National Land and Water Resources Audit, Canberra.

National Land and Water Resources Audit. (2001b). *Available water capacity for Australian areas of intensive agriculture of Layer 1 (A-Horizon – Top-soil) (derived from soil mapping).* National Land and Water Resources Audit, Canberra. http://data.brs.gov.au/asdd/index.php

National Land and Water Resources Audit. (2001c). *Available water capacity for Australian areas of intensive agriculture of Layer 2 (B-Horizon – Sub-soil) (derived from soil mapping).* National Land and Water Resources Audit, Canberra. http://data.brs.gov.au/asdd/index.php

National Land and Water Resources Audit. (2001d). *Soil Clay Content for Australian areas of intensive agriculture of Layer 1 (A-Horizon – Top-soil) (derived from soil mapping).* National Land and Water Resources Audit, Canberra. http://data.brs.gov.au/asdd/index.php

Nix, H.A. (1981). Simplified simulation models based on specified minimum data sets: The CROPEVAL concept. Pp. 151–169. In Berg, A. (ed), *Application of remote sensing to agricultural production forecasting.* Commission of the European Communities, Luxembourg.

Nix, H.A. (1986). A biogeographic analysis of Australian elapid snakes. Pp. 4–15. In Longmore, R. (ed), *Atlas of Elapid Snakes of Australia. Australian Flora and Fauna Series No. 7.* Australian Government Publishing Service, Canberra.

Nix, H.A. (1992). Environmental domain analysis. Presented at *Environmental Regionalisation. Establishing a Systematic Basis for National and Regional Conservation Assessment and Planning*. Canberra, 11–12 May 1992. R.Thackway (ed). Environmental Resources Information Network.

Nix, H.A. (1997). Management of parks and reserves for the conservation of biological diversity. Pp. 11–36. In Pigram, J.J. and Sundell, R.C. (eds), *National Parks and Protected Areas: Selection, Delimitation, and Management.* Centre for Water Policy Research, University of New England, Armidale.

Nix, H.A., Faith, D.P., Hutchinson, M.F., Margules, C.R., West, J., Allison, J., Kesteven, J.L., Natera, G., Slater, W., Stein, J.L. and Walker, P. (2000). *The BioRap Toolbox. A National Study of Biodiversity Assessment and Planning for Papua New Guinea. Consultancy Report to the World Bank.* Centre for Resource and Environmental Studies, Australian National University, Canberra. 48 pp.

Nix, H.A., Stein, J.A. and Stein, J.L. (1992). *Developing an environmental geographic information system for Tasmania: an application to assessing the potential for hardwood plantation forestry.* Consultant's report to the Land Resources Division and Bureau of Rural Resources, Department of Primary Industries and Energy. Centre for Resource and Environmental Studies, Australian National University, Canberra. 174 pp.

Nix, H.A., Stein, J.L., Stein, J.A. and Tassell, G. (1992). *Generation of an environmental domain classification for the Northern Territory. A report to the Northern Territory Conservation Commission*. Centre for Resource and Environmental Studies, ANU, Canberra.

O'Keefe, J.H. and Uys, M.C. (2000). The role of classification in the conservation of rivers. Pp. 445–458. In Boon, P.J., Davies, B.R. and Petts, G.E. (eds), *Global perspectives on river conservation: Science, policy and practice.* John Wiley & Sons, Chichester.

Ollier, C. and Pain, C. (1996). *Regolith, soils and landforms.* John Wiley & Sons, Chichester. 316 pp.

Omernik, J.M. (1995). Ecoregions: A spatial framework for environmental management. Pp. 49–65. In Davis, W.S. and Simon, T.P. (eds), *Biological assessment and criteria : tools for water resource planning and decision making.* Lewis Publisher, Boca Raton.

Omernik, J.M. and Bailey, R.G. (1997). Distinguishing between watersheds and ecoregions. *Journal of the American Water Resources Association* 33: 935–950.

Parkinson, G. (ed). (1986). *Climate.* Division of National Mapping, Canberra.

Parsons, M., Thoms, M. and Norris, R. (2002). *Australian River Assessment System: AusRivAS Physical Assessment Protocol.* Monitoring River Health Initiative Technical Report No. 22. Commonwealth of Australia and University of Canberra, Canberra. Retrieved from: http://ausrivas.canberra.edu.au/Geoassessment/Physchem/Man/Protocol/index.html

Pigram, J.J. and Sundell, R.C. (1997). Introduction. Pp. 1–3. In Pigram, J.J. and Sundell, R.C. (eds), *National Parks and Protected Areas: Selection, Delimitation, and Management.* Centre for Water Policy Research, University of New England, Armidale.

R Development Core Team. (2004). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Ransley, T., Tottenham, R., Sundaram, B. and Brodie, R. (2007). *Development of Method to Map Potential Stream-Aquifer Connectivity: a case study in the Border Rivers Catchment.* Bureau of Rural Sciences, Canberra. 25 pp. Retrieved from: http://www.affashop.gov.au/PdfFiles/method_map_stream_aquifer_connectivity.pdf

Rosgen, D.L. (1994). A classification of natural rivers. *Catena* 22: 169–199.

Schunemann, H.J., Best, D., Vist, G., Oxman, A.D. and The Grade Working Group. (2003). Letters, numbers, symbols and words: how to communicate grades of evidence and recommendations. *CMAJ* 169(7): 677–680.

Snelder, T.H. and Biggs, B.J.F. (2002). Multi-scale river environment classification for water resources management. *Journal of the American Water Resources Association* 38(5): 1225–1239.

Snelder, T.H., Biggs, B.J.F. and Woods, R.A. (2005). Improved eco-hydrological classification of rivers. *River Research and Applications* 21: 609–628.

Snelder, T.H., Cattanéo, F., Suren, A.M. and Biggs, B.J.F. (2004). Is the River Environment Classification an improved landscape-scale classification of rivers? *Journal of the North American Benthological Society* 23(3): 580–598.

Snelder, T.H., Dey, K.L. and Leathwick, J.R. (2007). A procedure for making optimal selection of input variables for multivariate environmental classifications. *Conservation Biology* 21(2): 365–375.

Snelder, T.H. and Hughey, K.F.D. (2005). The use of an ecologic classification to improve water resource planning in New Zealand. *Environmental Management* 36(5): 741–756.

Stein, J.L. (2007). *A continental landscape framework for systematic conservation planning for Australian rivers and streams.* PhD Thesis, Centre for Resource and Environmental Studies, Australian National University, Canberra.

Stein, J.L., Stein, J.A. and Nix, H.A. (2002) Spatial analysis of anthropogenic river disturbance at regional and continental scales: identifying the wild rivers of Australia. *Landscape and Urban Planning* 60(1): 1–25.

Steinley, D. (2004). Properties of the Hubert-Arabie Adjusted Rand Index. *Psychological Methods* 9(3): 386–396.

Stewardson, M., DeRose, R. and Harman, C. (2005). *Regional Models of Stream Channel Metrics.* Technical Report No. 05/16. Cooperative Research Centre for Catchment Hydrology, Melbourne, 52 pp.

Thackway, R. and Cresswell, I. (1995). *An Interim Biogeographic Regionalisation for Australia: a framework for setting priorities in the National Reserves System Cooperative Program Version 4.* Australian Nature Conservation Agency, Canberra.

Thorne, C.R. (2004). *Basin, Microsoft Encarta Online Encyclopedia* [online]. Available: http://uk.encarta.msn.com

Trakhtenbrot, A. and Kadmon, R. (2005). Environmental cluster analysis as a tool for selecting complementary networks of conservation sites. *Ecological Applications* 15(1): 335–345.

Uhlig, P.W.C. and Jordan, J.K. (1996). A spatial hierarchical framework for the co-management of ecosystems in Canada and the United States for the upper Great Lakes region. *Environmental Monitoring and Assessment* 39(1–3): 59–73.

Van Sickle, J. (1997). Using mean similarity dendrograms to evaluate classifications. *Journal of Agricultural, Biological, and Environmental Statistics* 2: 370–388.

Van Sickle, J. and Hughes, R.M. (2000). Classification strengths of ecoregions, catchments, and geographic clusters for aquatic vertebrates in Oregon. *Journal of the North American Benthological Society* 19(3): 370–384.

Walsh, C., Stewardson, M., Stein, J. and Wealands, S. (2007). *Sustainable Rivers Audit Filters Project Stage 2. Report to Murray-Darling Basin Commission.* University of Melbourne, Melbourne, 54 pp.

Warner, R.F. (1986). Hydrology. Pp. 49–79. In Jeans, D. N. (ed), *Australia – A Geography Volume One. The Natural Environment,* 2nd edition. Sydney University Press, Sydney

Warry, N.D. and Hanau, M. (1993). The use of terrestrial ecoregions as a regional-scale screen for selecting representative reference sites for water-quality monitoring. *Environmental Management* 17(2): 267–276.

Western, A. and McKenzie, N. (2004). *Soil hydrological properties of Australia* Version 1.0.1. CRC for Catchment Hydrology, Melbourne.

Whitaker, A.J., Raymond, O.L., Liu, S., Champion, D.C., Stewart, A.J., Retter, A.J., Percival, D.S., Connolly, D.P., Phillips, D. and Hanna, A.L. (2005). *Surface geology of Australia 1:1,000,000 scale, eastern States [Digital Dataset]*. The Commonwealth of Australia, Geoscience Australia, Canberra. http://www.ga.gov.au

Whiting, P.J. and Bradley, J.B. (1993). A process-based classification system for headwater streams. *Earth Surface Processes and Landforms* 18: 603–612.

Williamson, D.R. (1998). Land degradation processes and water quality effects: waterlogging and salinisation. Pp. 162–190. In Williams, J., Hook, R.A. and Gascoigne, H.L. (eds), *Farming Action. Catchment Reaction: the effect of dryland farming on the natural environment.* CSIRO Publishing, Melbourne.

Xiong, L. and Guo, S. (1999). A two-parameter monthly water balance model and its application. *Journal of Hydrology* 216: 111–123.

Appendix 8.1

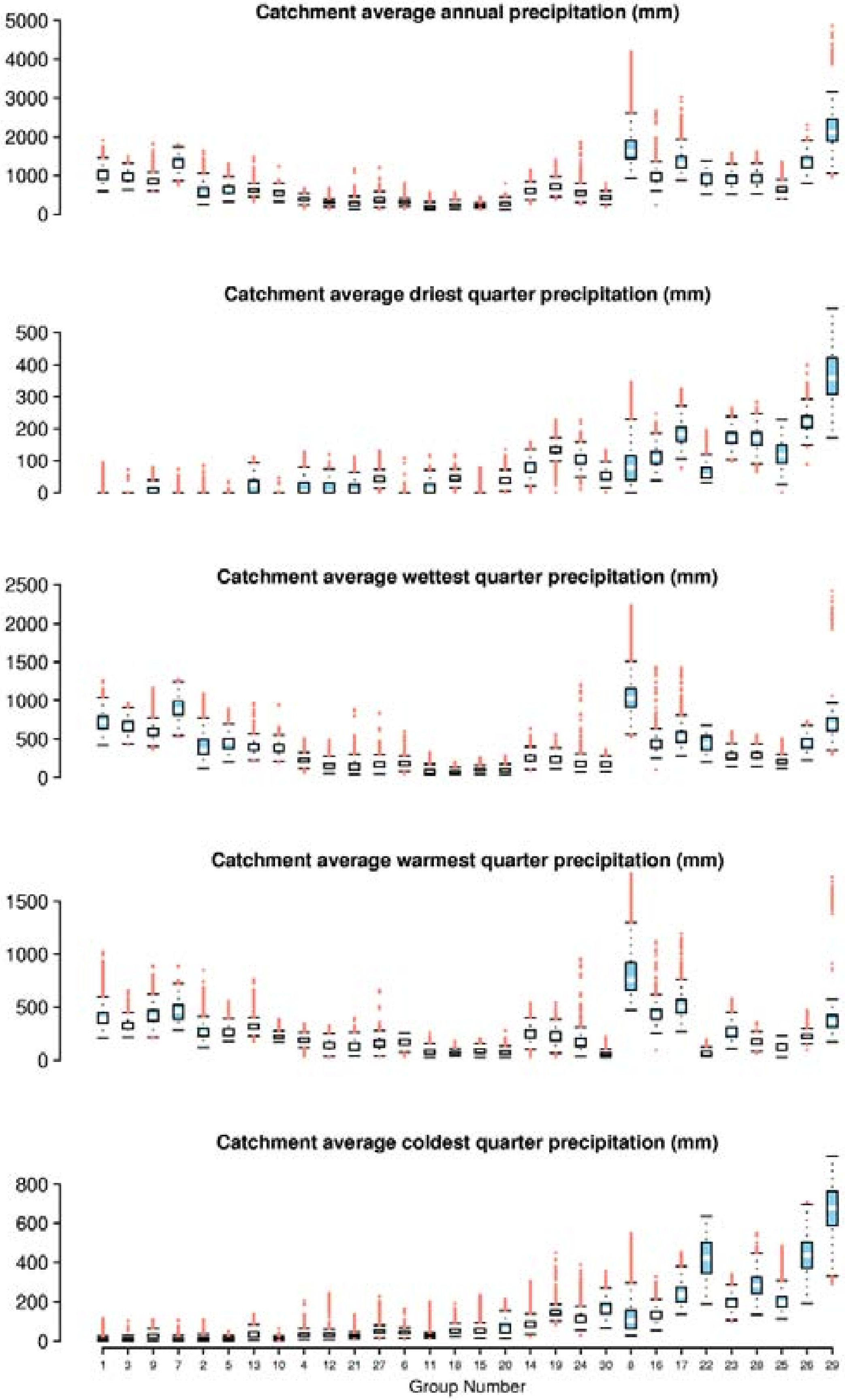


Figure A8.1. Distribution of rainfall attributes by ecohydrological environment group. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

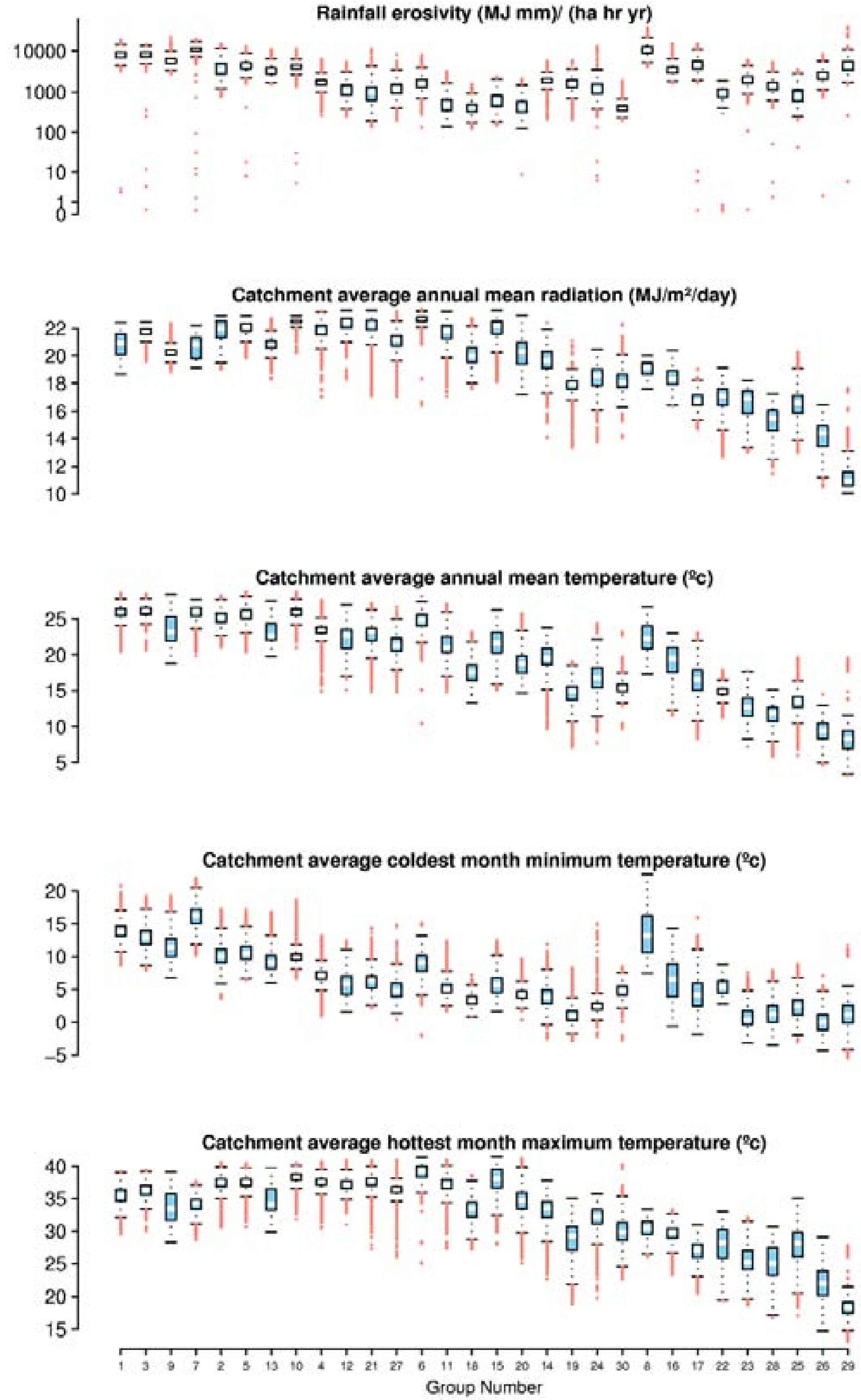


Figure A8.2. Distribution of other climatic attributes by ecohydrological environment group. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

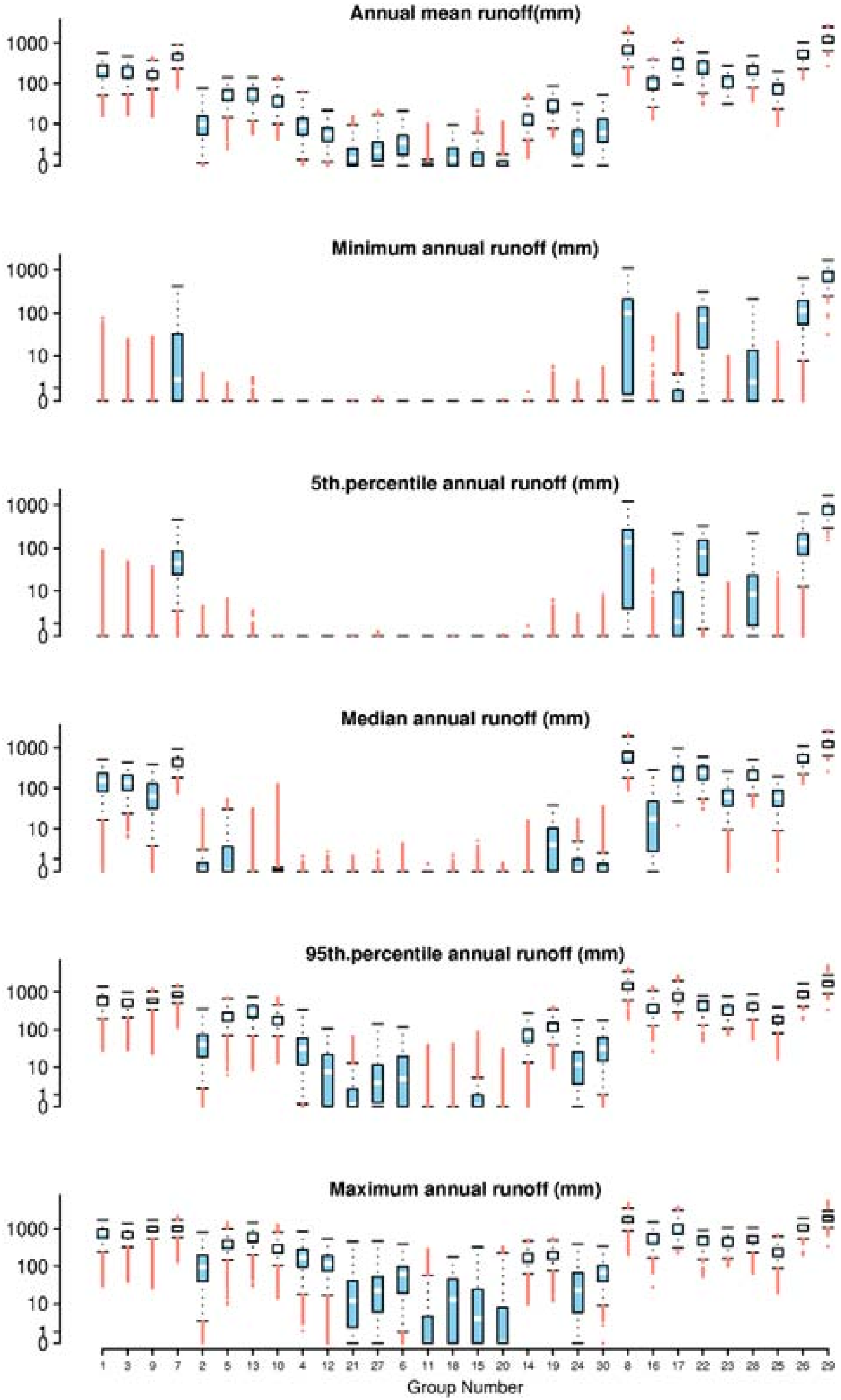


Figure A8.3. Distribution of values for catchment water balance attributes by ecohydrological environment group 2. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

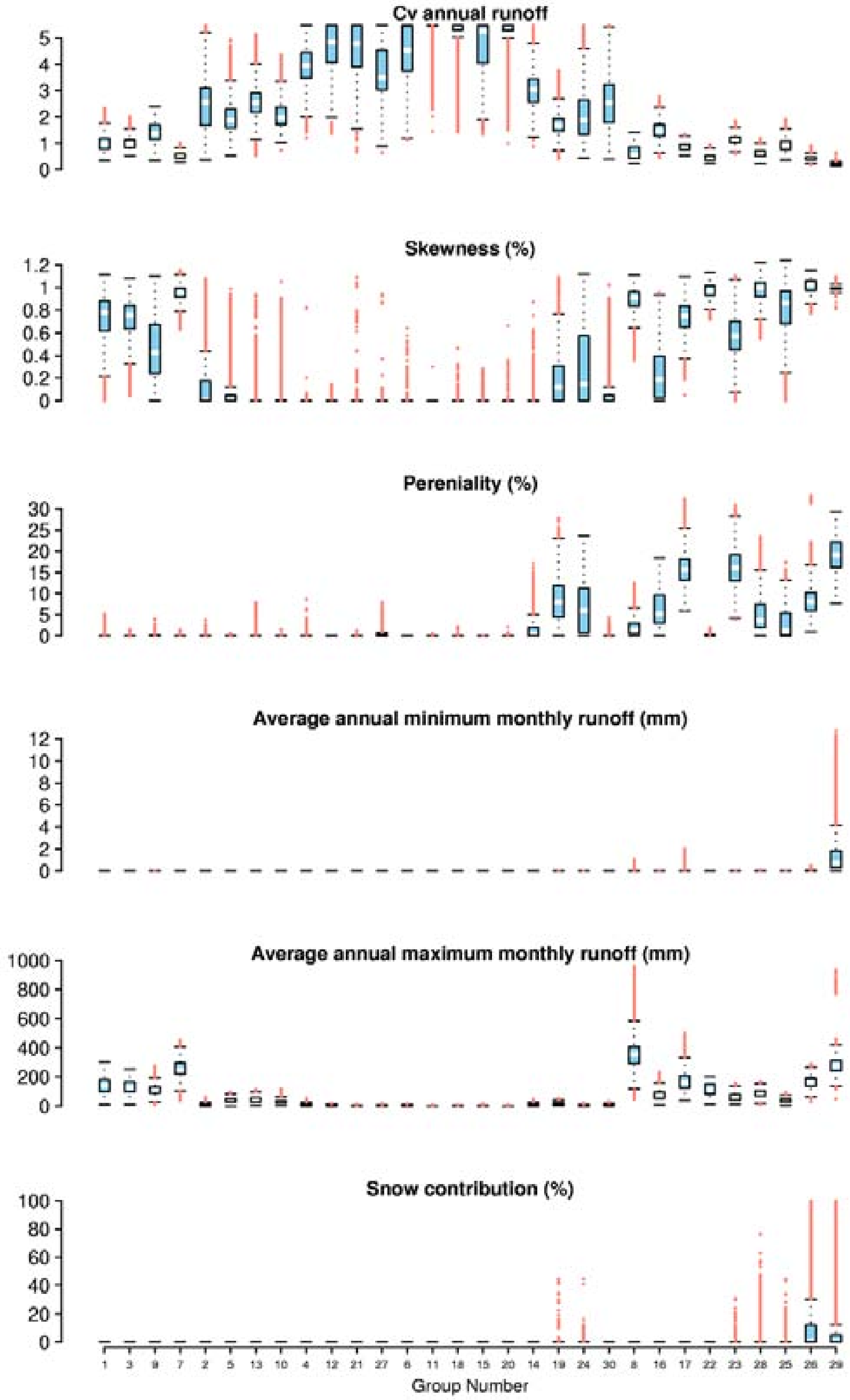


Figure A8.4. Distribution of values for catchment water balance attributes by ecohydrological environment group 2. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

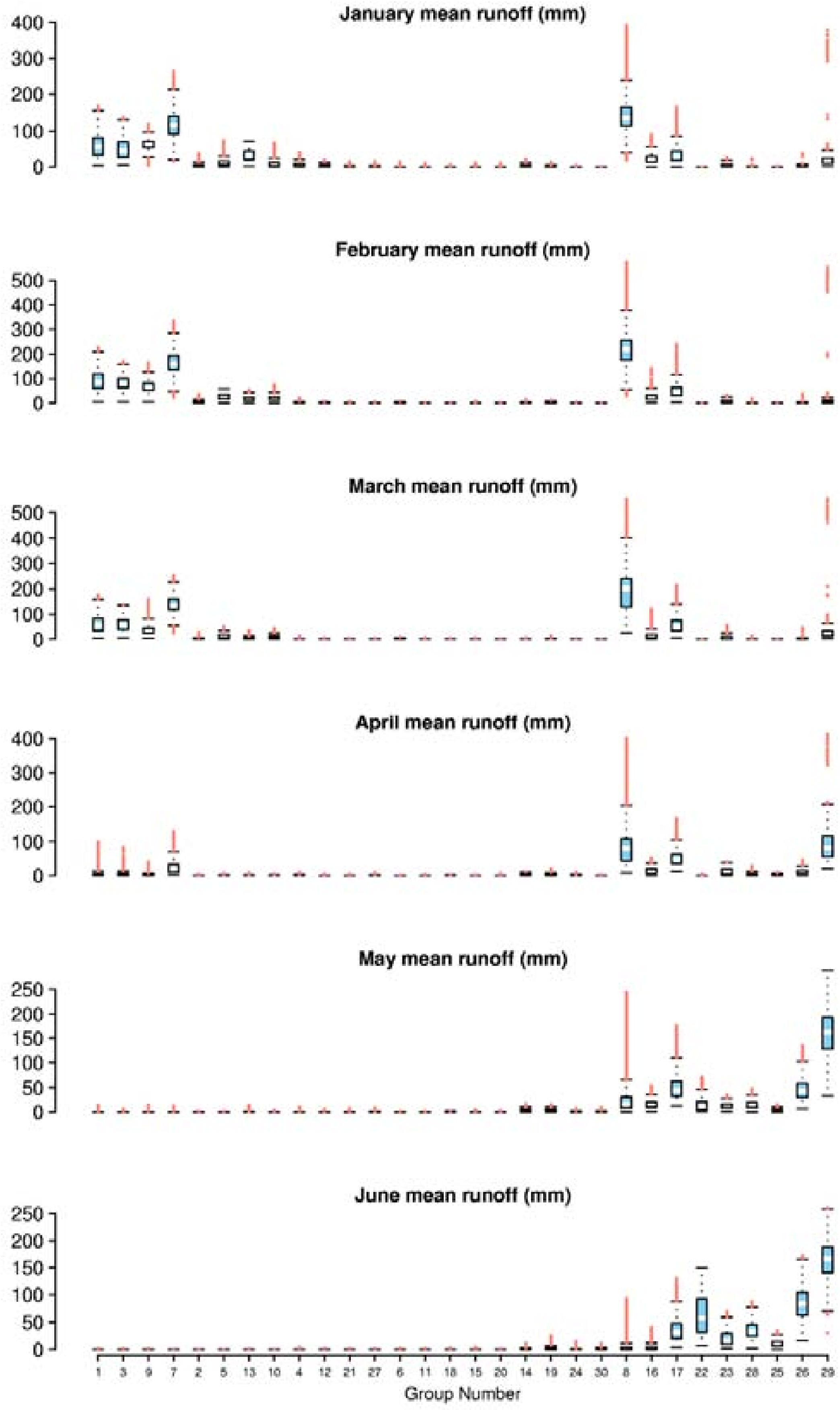


Figure A8.5. Distribution of monthly mean runoff values by ecohydrological environment group 1. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

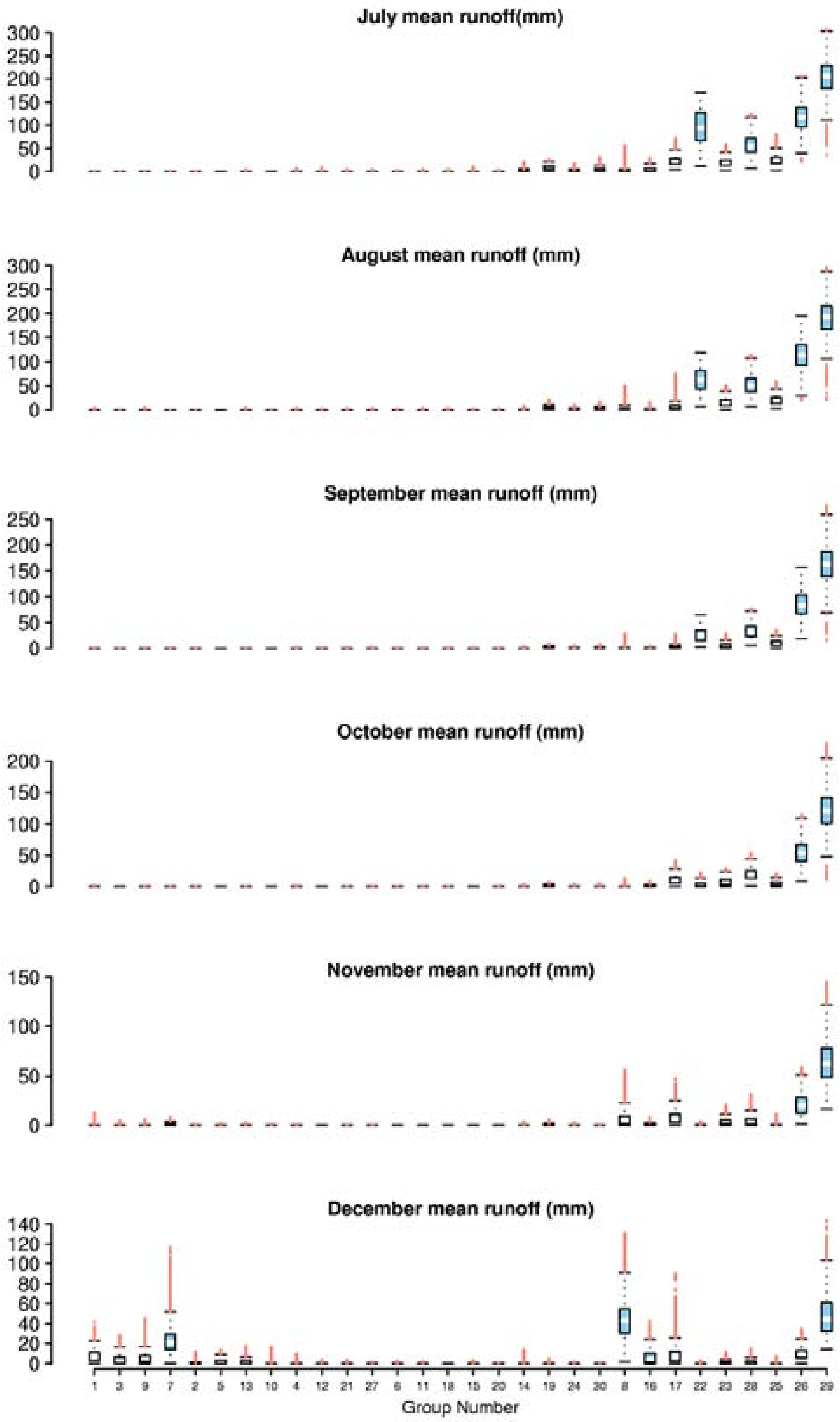


Figure A8.6. Distribution of monthly mean catchment runoff values by ecohydrological environment group 2. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

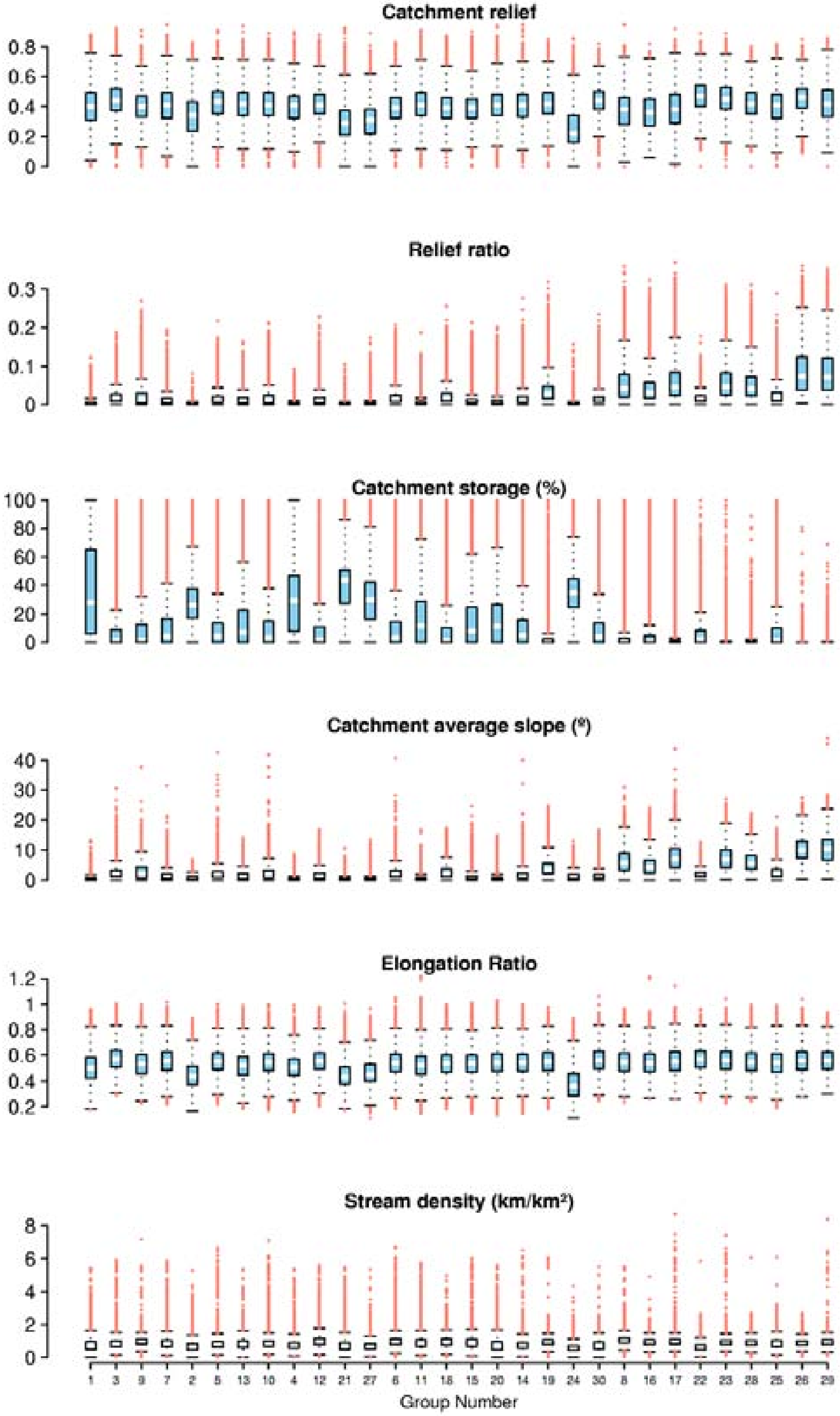


Figure A8.8. Distribution of values for catchment and valley morphology attributes by ecohydrological environment group 1. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

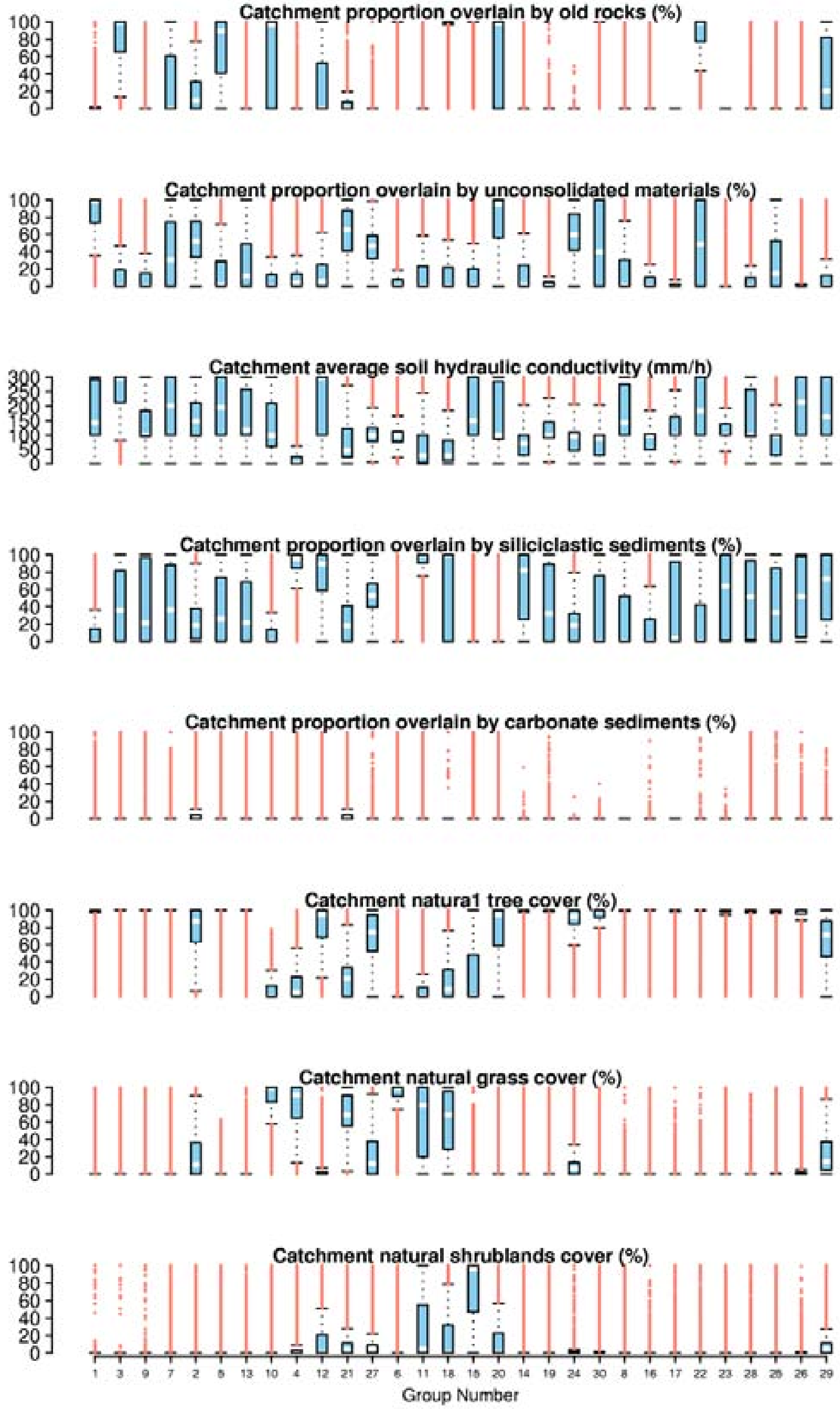


Figure A8.9. Distribution of values for catchment substrate and vegetation cover attributes by ecohydrological environment group. Groups are arranged in dendrogram order (Figure 8.9**Error! Reference source not found.**).

Appendix 9

Future development of ecohydrological classifications and limitations of the current classification approach

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Summary

We identified several limits to existing information and identified areas of research or further development that would strengthen the project's outcomes and provide greater aid to managers and researchers. These were:

1. Future development of the River Analysis Package (RAP) and Catchment Modelling Kits to provide:

    - clear guidance on metric calculation
    - incorporation of maps developed during the project
    - incorporation of gauge summaries
    - incorporation of predictive capacity i.e. for gauged and ungauged streams.

2. Incorporation of light and temperature regimes into ecohydrologic classification to provide spatial information on variation in aquatic productivity.

3. Refinement of regional classifications. Specifically, the continental-scale hydrologic classification was constrained by its broad spatial scale of investigation to adequately account for variation at finer scales in some regions. Regional classifications nested within the continental-scale classification may provide better resolution. Note that the on-line provision of hydrological metrics for the 830 gauges used in this project will allow (when available) other researchers to undertake classification for areas of particular interest.

4. Extension of the classification scheme to include regulated rivers and streams would provide a powerful tool to assess how regulation modifies flow regimes and to gauge whether commonalities in impacts occur, thus providing a template for future studies on the impacts of river regulation.

5. Future development of the environmental classification. This could include:

    - use of other classification techniques incorporating uncertainty and fuzzy boundaries
    - better development of the catchment water balance models e.g. introduction of a slow flow component
    - better ability to spatially model variations in lithology and incorporate groundwater inputs into the catchment water model. This is currently limited by the coarse grain of available spatial data.

9.1 Introduction

As might be expected from an innovative and exploratory project of this scale, there are several extensions that could be further developed. We list these below and stress that the list is not exhaustive.

9.2 Potential future contributions to RAP and the Catchment Modelling Toolkits

The River Analysis Package (RAP) developed by Dr Nick Marsh with initial funding from the CRC for Catchment Hydrology, and subsequent development under funding from the eWater CRC, was an essential tool in the completion of Land & Water Australia Project GRU36. Additional hydrological metrics previously not available within RAP were added to this package (see Table 9.1) and have strengthened its analytical capacity (see Final Report).

The current extension and incorporation of RAP into a catchment modelling toolkit offers potential for the outcomes of GRU36 to become widely available and provide guidance in several areas of hydrological analysis.

Further extension and development of the package utilising the outcomes of GRU36 are envisaged but beyond the scope of the current project. However, we view their development as potentially highly valuable for managers, scientists and environmental flow practitioners. Two developments include:

1. Preliminary investigation of the influence of differing periods of record on precision and accuracy of estimate hydrological records was a substantial part of the GRU36 project. Similarly, investigation of the influence of record overlap on comparing different gauging stations was a key preliminary step in the classification process. These investigations collectively provide very useful methodological guidance to be contained within the RAP help system. We would envisage a single page template within RAP for each metric summarising the likely error in metric calculation for a range of record lengths. This will not be completed within the life of the current project (i.e. development of the catchment modelling tools) but extend into future editions of RAP. Extension of this material into RAP requires additional funding.

2. Maps developed during the GRU36 project could be incorporated into new versions of RAP. It is envisaged that several maps could be incorporated, each supported by accompanying data tables. First, a clickable map showing the location of gauges throughout the country would provide a useful means for researchers to identify the availability of gauged data for streams of interest. Second, a map showing gauge locations and classification group membership would provide a useful knowledge base to support eflow investigations. Additionally, the capacity for a researcher to enter (input) a gauge number and output classification group membership for that gauge (or nearby gauges) would be useful. Similarly, the capacity for a researcher to input spatial coordinates and output the classification group membership derived from the classification based on remotely sensed variables would provide a useful tool for researchers in ungauged catchments. We would envisage that this product would also alert the user to online content that allows summary values of each metric for any location (gauge), plus that of the classification average and landscape

related variable (i.e. catchment area, elevation, slope, catchment characteristics, annual and monthly temperature series, etc.). This would be an extremely useful tool for assessing hydrological responses to regulation when combined with the outputs of the classification. To progress this development would require approval and funding from eWater CRC.

9.3 Extension of the classification schemes to include variables potentially related to aquatic productivity.

The coincidence of flow and temperature is an important factor in determining instream production (Winemiller *et al.* 2004). Incorporation of temperature within an otherwise hydrologically-based classification has been attempted previously (Monk *et al.* 2007). Although temperature and solar radiation within the photosynthetically active band of wavelengths (PAR) are frequently closely related, interception of PAR by cloud cover may decouple this relationship. Therefore aquatic production is a function of flow, temperature **and** PAR. We developed different classification schemes within GRU36 that could, in future, be extended to include temperature and PAR to allow an assessment of the spatial variation in aquatic production across the continent. One approach could involve coupling the flow accumulation curves that proved useful in defining seasonal flow signatures for each of the classification groups (see Appendix 5) with accumulation curves for temperature (analogous to degree day accumulation curves) and PAR (analogous to a photon flux accumulation curve). An alternative approach may be based on the use of remotely sensed data overlaid with the classification group distribution and the remotely sensed classification to derive distinct classes of potential aquatic production. Note that this concept is poorly developed at present but could be refined in future.

9.4 Refinement of regional classifications

It was apparent from material presented in Appendix 6 that a continent-wide classification scheme did not adequately convey the extent of hydrological variation that may exist at small scales such as within individual river basins. It is acknowledged that when Principal Component scores are examined in tandem with the continental classification, fine-scale variation can be decomposed to allow a more refined appreciation of spatial variation. At project's end, both the classification scores and PCA scores for each gauge will be available online and researchers will therefore have the capacity to undertake this examination.

Nonetheless, we consider that reclassification of gauges limited to particular regions may have utility. For example, a classification limited to tropical regions only may determine that a greater variability in flow regime signatures is present than is accounted for by the continental classification. At issue here is the extent to which large-scale classifications are constrained by the requirement to deal with a wide and divergent array of potential signatures. Such investigations are beyond the scope of the current study but may prove fruitful in the future.

9.5 Comparison with modified flow regimes

Modified regimes (i.e. downstream of impoundments or points of supplementation) were not included in the classification exercise given our focus on 'natural regimes'. Inclusion of such data in the future would however be useful for determining the types of impacts such structures have, for determining whether such impacts share common characteristics etc. and for determining the extent to which impacts shift flow regimes away from that expected given location or catchment characteristics. Such investigations are beyond the scope of the current study but may prove fruitful in the future.

9.6 Further development of the environmental classification

We employed the ALOB non-hierarchical clustering procedure to generate the hydroecological environment classification based on its successful application to many other environmental domain analyses and its ability to handle the very large data matrix that we generated (i.e. 1.2 million stream reaches x 48 attributes). The inter-group association matrix it produces also enables exploration of the relationship between groups and their higher level clustering. However, it does not explicitly incorporate data uncertainty into the algorithm though this might be approximated by appropriate variable weightings. More seriously, it produces hard boundaries between classes that may not reflect gradual change. Probabilistic methods such as that used to generate the flow regime classes overcome the problem of indeterminate boundaries and might be assessed for future revisions of the hydroecological environment classification.

Catchment averages were also used to characterise the catchment climate and similarly, may not adequately represent the heterogeneous climatic conditions of a large catchment. This might be improved by weighting the average according to the potential contribution of an area to stream flow (e.g. as indicated by the monthly runoff estimates). An even better solution would be to model directly the physical processes that shape the character and behaviour of the stream hydrology although in many cases this is likely to be precluded by the coarse scale of national mapping of essential data layers.

The catchment water balance model attempted to do this. Clearly, it greatly simplifies the processes of converting rainfall into runoff. This avoided the need for calibration for individual catchments and complex parameterisation with concomitant demands on data thus enabling continental-scale application. It was computed from monthly rainfall totals rather than actual rainfall events and does not account for transmission losses in streamflow routing. Contributions to streamflow from surface (overland and interflow) and groundwater are not partitioned though work is now underway to introduce a slow flow component into the water balance model (M. Hutchinson, pers. comm. 31/1/08). The results will also be sensitive to the coarse resolution (~1 km) of the soils data that sets the size of the soil water storage capacity and the way the accumulated runoff is apportioned in anabranching systems.

Undoubtedly, these limitations and uncertainties weaken the ability of the classifying attributes to capture the critical landscape controls on stream hydrology and hence the effectiveness of the hydroecological environment classification. Some of these issues might be addressed in future revisions of the classification; many could be the focus of new research.

9. 7 References

Colwell, R.K. (1974). Predictability, constancy and contingency of periodic phenomena. *Ecology* 55: 1148–1153.

Monk, W.A., Wood, P.J., Hannah, D.M. and Wilson, D.A. (2007). Selection of river flow indices for the assessment of hydroecological change. *River Research and Applications* 23: 113–122.

Olden, J.D. and Poff, N.L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19:101–121.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10: 1163–1174.

Sokal, R.R. and Rohlf, F.J. (1995). *Biometry: the principles and practice of statistics in biological research*. 3rd edition. W. H. Freeman and Co.: New York

Winemiller, K.O. (2004). Floodplain river food webs: generalisations and implications for fisheries management. Pp. 285-309. In Welcomme, R. and Petr, T. (eds), *Proceedings of the Second international Symposium on the Management of Large rivers for Fisheries. Vol II.* FAO and the Mekong River Commission, Bangkok.

Table 9.1 (overleaf). Flow metrics used in the classification presented in Appendix 5 and now available in the River Analysis Package (RAP). Variable codes were derived from Olden and Poff (2003) and the present study. Time period refers to the temporal scale at which the variable is measured – D = daily, M = monthly & A = annual. Source refers to original publication in which metric is discussed: IHA = Richter *et al.* (1996), O&P = Olden and Poff (2003) and the present study. Standardisation of each metric to enable comparison across gauges independent of magnitude was achieved by dividing by catchment area (CA) or median daily flow (MDF).

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
Magnitude of flow events							
Average flow conditions							
	MA1	ML day^{-1}	D	Mean daily flows	Mean daily flow	O&P2003	CA
	MA2	ML day^{-1}	D	Median daily flows	Median daily flow	O&P2003	CA
	MA3	dimensionless	D	Variability in daily flows	Coefficient of variation in daily flows	O&P2003	
	MKMA1	dimensionless	D	Skewness in daily flows	g1 skewness - Sohkal & Rolf	This study	
	MA12	ML day^{-1}	M	Mean Jan discharge	Mean Jan discharge	IHA & O&P2003	MDF
	MA13	ML day^{-1}	M	Mean Feb discharge	Mean Feb discharge	IHA & O&P2003	MDF
	MA14	ML day^{-1}	M	Mean Mar discharge	Mean Mar discharge	IHA & O&P2003	MDF
	MA15	ML day^{-1}	M	Mean Apr discharge	Mean Apr discharge	IHA & O&P2003	MDF
	MA16	ML day^{-1}	M	Mean May discharge	Mean May discharge	IHA & O&P2003	MDF
	MA17	ML day^{-1}	M	Mean Jun discharge	Mean Jun discharge	IHA & O&P2003	MDF
	MA18	ML day^{-1}	M	Mean Jul discharge	Mean Jul discharge	IHA & O&P2003	MDF
	MA19	ML day^{-1}	M	Mean Aug discharge	Mean Aug discharge	IHA & O&P2003	MDF
	MA20	ML day^{-1}	M	Mean Sep discharge	Mean Sep discharge	IHA & O&P2003	MDF
	MA21	ML day^{-1}	M	Mean Oct discharge	Mean Oct discharge	IHA & O&P2003	MDF
	MA22	ML day^{-1}	M	Mean Nov discharge	Mean Nov discharge	IHA & O&P2003	MDF
	MA23	ML day^{-1}	M	Mean Dec discharge	Mean Dec discharge	IHA & O&P2003	MDF
	MA24	dimensionless	M	CV Jan discharge	CV Jan discharge	IHA & O&P2003	
	MA25	dimensionless	M	CV Feb discharge	CV Feb discharge	IHA & O&P2003	
	MA26	dimensionless	M	CV Mar discharge	CV Mar discharge	IHA & O&P2003	
	MA27	dimensionless	M	CV Apr discharge	CV Apr discharge	IHA & O&P2003	
	MA28	dimensionless	M	CV May discharge	CV May discharge	IHA & O&P2003	
	MA29	dimensionless	M	CV Jun discharge	CV Jun discharge	IHA & O&P2003	
	MA30	dimensionless	M	CV Jul discharge	CV Jul discharge	IHA & O&P2003	
	MA31	dimensionless	M	CV Aug discharge	CV Aug discharge	IHA & O&P2003	

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
	MA32	dimensionless	M	CV Sep discharge	CV Sep discharge	IHA & O&P2003	
	MA33	dimensionless	M	CV Oct discharge	CV Oct discharge	IHA & O&P2003	
	MA34	dimensionless	M	CV Nov discharge	CV Nov discharge	IHA & O&P2003	
	MA35	dimensionless	M	CV Dec discharge	CV Dec discharge	IHA & O&P2003	
	MA41	ML day^{-1} Km^{2}	A	Mean annual runoff	Mean annual flow divided by catchment area	O&P2003	CA
	MKMA3	dimensionless	A	Variability in annual flows	Coefficient of variation in annual flows	This study	
	MKMA4	dimensionless	A	Skewness in annual flows	g1 skewness - Sohkal & Rolf	This study	
	MKMA6	ML day^{-1}	A	Median annual flow	median annual flow divided by catchment area	This study	CA
Low flow conditions							
	ML16	dimensionless	A	Median of annual minimum flows	Median of the lowest annual daily flow divided by the **mean** annual daily flow averaged across all years	O&P2003	
	ML17	dimensionless	A	Baseflow index	Ratio of base flow to total flow, averaged across all years, where baseflow is calculated using 3 way digital filter as described in (Grayson *et al.* 1996)	IHA & O&P2003	
	ML18	dimensionless	A	Variability in Baseflow Index	Coefficient of variation in ML17	IHA & O&P2003	
	MKML1	dimensionless	A	Low flow discharge 75%ile	Mean of the 75th percentile from the flow duration curve divided by mean daily flow across all years	This study	MDF
	MKML2			Low flow discharge 90%ile	Mean of the 90th percentile from the flow duration curve divided by mean daily flow across all years	This study	MDF

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
	MKML3			Low flow discharge 99%ile	Mean of the 99th percentile from the flow duration curve divided by mean daily flow across all years	This study	MDF
	ML22	ML day^{-1} Km^2	A	Specific mean annual minimum flows	Mean annual minimum flows divided by catchment area	O&P2003	CA
High flow conditions							
	MH14	dimensionless	A	Median of annual maximum flows	Median of the highest annual daily flow divided by the **mean** annual daily flow averaged across all years	O&P2003	
	MH15	dimensionless	A	High flow discharge 1%ile	Mean of the 1st percentile from the flow duration curve divided by mean daily flow across all years	O&P2003	MDF
	MH16	dimensionless	A	High flow discharge 10%ile	Mean of the 10th percentile from the flow duration curve divided by mean daily flow across all years	O&P2003	MDF
	MH17	dimensionless	A	High flow discharge 25%ile	Mean of the **25th** percentile from the flow duration curve divided by mean daily flow across all years	O&P2003	MDF
	MH20	ML day^{-1} Km^2	A	Specific mean annual maximum flows	Mean annual maximum flows divided by catchment area	O&P2003	CA
	MH21	days	A	High flow volume 1xMDF	Mean of the high flow volume (calculated as the area between the hydrograph and the upper threshold during the high flow event) divided by MDF. The upper threshold is defined as 1	O&P2003	MDF

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
					times MDF		
	MH22	days	A	High flow volume 3xMDF	Mean of the high flow volume (calculated as the area between the hydrograph and the upper threshold during the high flow event) divided by MDF. The upper threshold is defined as 3 times MDF.	O&P2003	MDF
	MH23	days	A	High flow volume 7xMDF	Mean of the high flow volume (calculated as the area between the hydrograph and the upper threshold during the high flow event) divided by MDF. The upper threshold is defined as **7** times MDF.	O&P2003	MDF
	MKMH1	ML day^{-1}	A	Magnitude 1-year ARI	Magnitude of flood events with Average Recurrence Intervals of 1.67 (partial series)	This study	MDF
	MKMH2	ML day^{-1}	A	Magnitude 2-year ARI	Magnitude of flood events with Average Recurrence Intervals of 2 (partial series)	This study	MDF
	MKMH3	ML day^{-1}	A	Magnitude 5-year ARI	Magnitude of flood events with Average Recurrence Intervals of 5 (partial series)	This study	MDF
	MKMH4	ML day^{-1}	A	Magnitude 10-year ARI	Magnitude of flood events with Average Recurrence Intervals of 10 (annual series)	This study	MDF
	MKMH5	ML day^{-1}	A	Magnitude 15-year ARI	Magnitude of flood events with Average Recurrence Intervals of 15 (annual series)	This study	MDF

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
	MKMH6	ML day^{-1}	A	Magnitude 20-year ARI	Magnitude of flood events with Average Recurrence Intervals of 20 (annual series)	This study	MDF
	MKMH7	dimensionless	D	Skewness in maximum annual flows 2	g1 skewness - Sokal & Rolf, 1995.	This study	
Frequency of flow events *Low flow conditions*							
	FL1	year^{-1}	A	Low flood pulse count (<75%ile)	Number of annual occurrences during which the magnitude of flow remains below a lower threshold. Hydrologic pulses are defined as those periods within a year in which the flow drops below the **75th** percentile (low pulse) of all daily values for the time period	IHA & O&P2003	
	MKFL1	year^{-1}	A	Low flood pulse count (<90%ile)	Number of annual occurrences during which the magnitude of flow remains below a lower threshold. Hydrologic pulses are defined as those periods within a year in which the flow drops below the **90th** percentile (low pulse) of all daily values for the time period	This study	
	MKFL2	year^{-1}	A	Low flood pulse count (<99%ile)	Number of annual occurrences during which the magnitude of flow remains below a lower threshold. Hydrologic pulses are defined as those periods within	This study	

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
					a year in which the flow drops below the **99th** percentile (low pulse) of all daily values for the time period		
	FL2	dimensionless	A	Variability in low flood pulse count (75%ile)	Coefficient of variation in FL1 (75%ile)	IHA & O&P2003	
	MKFL3	dimensionless	A	Variability in low flood pulse count (90%ile)	Coefficient of variation in MKFL1 (90%ile)	This study	
	MKFL4	dimensionless	A	Variability in low flood pulse count (99%ile)	Coefficient of variation in MKFL2 (99%ile)	This study	
High flow conditions							
	FH1	year^{-1}	A	High flood pulse count 1 (25%ile)	See FL1, where the high pulse is defined as the **25**th percentile	IHA & O&P2003	
	MKFH1	year^{-1}	A	High flood pulse count1 (10%ile)	See FL1, where the high pulse is defined as the **10th** percentile	This study	
	MKFH2	year^{-1}	A	High flood pulse count1 (1%ile)	See FL1, where the high pulse is defined as the **1st** percentile	This study	
	FH2	dimensionless	A	Variability in high flood pulse count (25%ile)	Coefficient of variation in FH1 (25%ile)	IHA & O&P2003	
	MKFH3	dimensionless	A	Variability in high flood pulse count (10%ile)	Coefficient of variation in MKFH1 (10%ile)	This study	
	MKFH4	dimensionless	A	Variability in high flood pulse count (1%ile)	Coefficient of variation in MKFH2 (1%ile)	This study	
	FH3	year^{-1}	A	High flood pulse count 3xMDF	See FH1, where the upper threshold is defined as 3 times median daily flow, and the value is represented as an average instead of a tabulated count	O&P2003	

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
	FH4	year^{-1}	A	High flood pulse count 7xMDF	See FH1, where the upper threshold is defined as 7 times median daily flow, and the value is represented as an average instead of a tabulated count	O&P2003	
Duration of flow events *Low flow conditions*							
	DL1	ML day^{-1}	D, M, A	Annual minima of 1-day means of daily discharge	Magnitude of minimum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DL2	ML day^{-1}	D, M, A	Annual minima of 3-day means of daily discharge	Magnitude of minimum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DL3	ML day^{-1}	D, M, A	Annual minima of 7-day means of daily discharge	Magnitude of minimum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DL4	ML day^{-1}	D, M, A	Annual minima of 30-day means of daily discharge	Magnitude of minimum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DL5	ML day^{-1}	D, M, A	Annual minima of 90-day means of daily discharge	Magnitude of minimum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DL6	dimensionless	D, M, A	Variability in annual minima of 1-day means of daily discharge	Coefficient of variation in DL1	IHA & O&P2003	
	DL7	dimensionless	D, M, A	Variability in annual minima of 3-day means of daily discharge	Coefficient of variation in DL2	IHA & O&P2003	
	DL8	dimensionless	D, M, A	Variability in annual minima of 7-day means of	Coefficient of variation in DL3	IHA & O&P2003	

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
				daily discharge			
	DL9	dimensionless	D, M, A	Variability in annual minima of 30-day means of daily discharge	Coefficient of variation in DL4	IHA & O&P2003	
	DL10	dimensionless	D, M, A	Variability in annual minima of 90-day means of daily discharge	Coefficient of variation in DL5	IHA & O&P2003	
	DL16	days	A	Low flow pulse duration (75th %ile)	Mean duration of FL1 (Low flow pulse 75%ile)	IHA & O&P2003	
	MKDL1	days	A	Low flow pulse duration (90%ile)	Mean duration of Low flow pulse <90%ile)	This study	
	MKDL2	days	A	Low flow pulse duration (99%ile)	Mean duration of Low flow pulse <99%ile)	This study	
	DL17	dimensionless	A	Variability in low flow pulse duration (75th %ile)	Coefficient of variation in DL16 (75%ile)	IHA & O&P2003	
	MKDL3			Variability in low flow pulse duration (90th %ile)	Coefficient of variation in MKDL1 (90%ile)	This study	
	MKDL4			Variability in low flow pulse duration (99 %ile)	Coefficient of variation in MKDL2 (99%ile)	This study	
	DL18	year^{-1}	A	Number of zero-flow days	Mean annual number of days having zero daily flow	IHA & O&P2003	
	DL19	dimensionless	A	Variability in number of zero-flow days	Coefficient of variation in DL18	IHA & O&P2003	
High flow conditions							
	DH1	ML day^{-1}	D, M, A	Annual maxima of 1-day means of daily discharge	Magnitude of maximum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DH2	ML day^{-1}	D, M, A	Annual maxima of 3-day means of daily discharge	Magnitude of maximum annual flow of various duration, ranging	IHA & O&P2003	MDF

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
					from daily to seasonal		
	DH3	ML day^{-1}	D, M, A	Annual maxima of 7-day means of daily discharge	Magnitude of maximum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DH4	ML day^{-1}	D, M, A	Annual maxima of 30-day means of daily discharge	Magnitude of maximum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DH5	ML day^{-1}	D, M, A	Annual maxima of 90-day means of daily discharge	Magnitude of maximum annual flow of various duration, ranging from daily to seasonal	IHA & O&P2003	MDF
	DH6	dimensionless	D, M, A	Variability in annual maxima of 1-day means of daily discharge	Coefficient of variation in DH1	IHA & O&P2003	
	DH7	dimensionless	D, M, A	Variability in annual maxima of 3-day means of daily discharge	Coefficient of variation in DH2	IHA & O&P2003	
	DH8	dimensionless	D, M, A	Variability in annual maxima of 7-day means of daily discharge	Coefficient of variation in DH3	IHA & O&P2003	
	DH9	dimensionless	D, M, A	Variability in annual maxima of 30-day means of daily discharge	Coefficient of variation in DH4	IHA & O&P2003	
	DH10	dimensionless	D, M, A	Variability in annual maxima of 90-day means of daily discharge	Coefficient of variation in DH5	IHA & O&P2003	
	DH15	days	A	High flow pulse duration (25%ile)	Mean duration of FH1 (25%ile)	IHA & O&P2003	
	MKDH1	days	A	High flow pulse duration (10%ile)	Mean duration of FH1 (10%ile)	This study	
	MKDH2	days	A	High flow pulse duration (1%ile)	Mean duration of FH1 (1%ile)	This study	

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
	DH16	dimensionless	A	Variability in high flow pulse duration (25%ile)	Coefficient of variation in DH15	IHA & O&P2003	
	MKDH3			Variability in high flow pulse duration (10%ile)	Coefficient of variation in MKDH1		
	MKDH4			Variability in high flow pulse duration (1%ile)	Coefficient of variation in MKDH2		
Timing of flow events *Average flow conditions*							
	TA1	dimensionless	D	Constancy (C) of mean daily flow (month)	Constancy (C) of mean daily flow (month)	O&P2003, Colwell (1974)	
	MKTA1	dimensionless	D	Seasonality (M/P) of mean daily flow (month)	Seasonality (M/P) of mean daily flow (month)	Colwell (1974),this study	
	TA2	dimensionless	D	Predictability (P = C+M) of mean daily flow (month)	Predictability (P = C+M) of mean daily flow (month). Composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity)	O&P2003	
	MKTA2	dimensionless		Perreniality	% contribution to mean annual discharge by the six driest months of the year	This study	
Low flow conditions							
	TL1	dimensionless	D	Julian date of annual minimum	The mean Julian date of the 1-day annual minimum flow over all years	IHA & O&P2003	
	TL2	dimensionless	D	Variability in Julian date of annual minimum	Coefficient of variation in TL1	IHA & O&P2003	

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
	MKTL1	dimensionless	D	Seasonality (M/P) of minimum instantaneous flow (month)	Seasonality (M/P) of minimum instantaneous flow (month). See Colwell (1974)	This study	
	MKTL2	dimensionless	D	Predictability (P = C+M) of minimum instantaneous flow (month)	Predictability (P = C+M) of minimum instantaneous flow (month). Composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity)	This study	
High flow conditions							
	TH1	dimensionless	D	Julian date of annual maximum	The mean Julian date of the 1-day annual maximum flow over all years	IHA & O&P2003	
	TH2	dimensionless	D	Variability in Julian date of annual maximum	Coefficient of variation in TH1	IHA & O&P2003	
	MKTH1	dimensionless	D	Seasonality (M/P) of maximum instantaneous flow (month)	Seasonality (M/P) of maximum instantaneous flow (month). See Colwell (1974)	This study	
	MKTH2	dimensionless	D	Predictability (P = C+M) of maximum instantaneous flow (month)	Predictability (P = C+M) of maximum instantaneous flow (month). Composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity)	This study	
Rate of change in flow events *Average flow*							

Flow component	Metric code	Unit of measurement	Time scale	Hydrologic index	Definition	Source	Standardised
conditions							
	RA1	ML day^{-1} day^{-1}	D	Rise rate	Mean rate of positive changes in flow from one day to the next	IHA & O&P2003	MDF
	RA2	dimensionless	D	Variability in rise rate	Coefficient of variation in RA1	IHA & O&P2003	
	RA3	ML day^{-1} day^{-1}	D	Fall rate	Mean rate of negative changes in flow from one day to the next	IHA & O&P2003	MDF
	RA4	dimensionless	D	Variability in fall rate	Coefficient of variation in RA3	IHA & O&P2003	
	RA8	year^{-1}	D	Number of reversals	Number of negative and positive changes in water conditions from one day to the next	IHA & O&P2003	
	RA9	dimensionless	D	Variability in reversals	Coefficient of variation in RA8	IHA & O&P2003	