# DWLBC REPORT

# Best Practice Framework for the Monitoring and Evaluation of Water Dependant Ecosystems 2: Technical Resource

## 2007/13

Government of South Australia
Department of Water, Land and Biodiversity Conservation

# Best Practice Framework for the Monitoring and Evaluation of Water Dependant Ecosystems 2: Technical Resource


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# FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

**Rob Freeman**
**CHIEF EXECUTIVE**
**DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION**

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# EXECUTIVE SUMMARY


The Best Practice Framework for the Monitoring and Evaluation of Water Dependent Ecosystems is a comprehensive guide for developing robust monitoring programmes. The Framework comprises two parts: the Framework and the supporting Technical Resource. The Framework provides the information necessary to design and undertake a monitoring programme. The Technical Resource provides additional explanation and examples to support the concepts introduced by the Framework.

The components of the Framework are laid-out sequentially and comprise a series of four groups of tasks that enable an effective monitoring programme to be developed.

### Group 1 – Rationale and priorities

The first group of tasks provides the justification for developing a monitoring programme. The monitoring objectives are determined and placed into one or more categories. The objective category determines what sort of monitoring effort is required and how the monitoring programme develops. The physical and biological nature of your Water Dependent Ecosystem (WDE) and its risks and threats are also determined at this stage.

### Group 2 – Conceptual understanding

The next stage of the Framework is the development of conceptual diagrams and models. Conceptual diagrams and models may either be in the form of: a conceptual diagram, which is a pictorial representation at the landscape or ecosystem scale and includes the major ecosystem components and the influences on condition; a stressor model, which portrays the key stress response relationships affecting the system; and/or a state-and-transition model, which is for systems where there is a progression from one condition through various stages and back to the initial condition. The Framework introduces a standard approach to representing conceptual models.

### Group 3 – Monitoring programme

The monitoring programme is designed through a process of indicator selection, determining what to measure and establishing the frequency at which data is collected. The resources required to undertake the monitoring are then calculated.

### Group 4 – Implement and assess

The steps required to implement the monitoring programme are determined and guidelines on data collection and storage are provided along with information on effective data evaluation and assessment. A final review determines whether the monitoring results have met their desired objectives and the effectiveness of the selected indicators. The final step is to incorporate any new system understanding into the WDE conceptual models, maintaining the adaptive management cycle.

The Best Practice Framework is an evolving process requiring continuous development that incorporates the experience gained in its application across the State.

# INTRODUCTION

The Best Practice Framework for the Monitoring and Evaluation of Water Dependent Ecosystems comprises two parts: the Framework; and this supporting Technical Resource. The Framework provides the information necessary to design and implement a monitoring programme and is supported by this Technical Resource, which provides detailed information on the concepts presented by the Framework and helpful examples. Both documents have the same format so that information in the Technical Resource provides support to and corresponds with the same section in the Framework.

## *MONITORING AND EVALUATION*

### THE ROLE OF MONITORING

There are a number of points about the role of monitoring that are pertinent to the South Australian situation for WDEs (adapted from Fancy 2003):

1. A long-term, ecological-monitoring perspective:
    - Supports the provision of personnel and funding needed to track the condition of selected resources long-term, e.g., decadal sampling intervals in some cases (without a long-term view there is discontinuity and inconsistency).
    - Allows for the expectation of, and ability to plan for, turnover of personnel and technology; but requires more planning, documentation and protocols.
    - Demonstrates commitment and provides a structure that outlasts political whim.

2. Integration and coordination among regional agencies and local groups recognises that:
    - Monitoring is an integral part of natural resource stewardship.
    - Most regions were already doing work to assess conditions and address certain monitoring goals.
    - Monitoring is an important part of the scientific effort to track the condition of resources and provide data for management decision-making.
    - Collaboration between funded projects, agencies, research units and interest groups, etc. is efficient, and makes good sense.

3. Emphasis on information management:
    - Makes information more available and useful for management decision-making, research, and education.
    - Facilitates transformation of data into information and knowledge through analysis, synthesis and modelling.
    - In the long-term it builds a robust institutional knowledge base for inter-comparison of results and assessment of change.

4. Specific monitoring objectives:
    - Determine status and trends in selected indicators of the condition of WDEs to allow managers to make better-informed decisions.
    - Provide early warning of abnormal conditions of selected resources to help develop effective mitigation measures and reduce costs of management.

- ○ Provide data to better understand the dynamic nature and condition of WDEs and to provide reference points for comparisons with other altered ecosystems.
- ○ Provide data to meet certain legal mandates related to natural resource protection.
- ○ Provide a means of measuring progress towards performance goals. (You can't have performance management without monitoring).

## TYPES OF MONITORING

The types of monitoring that might be undertaken in any location, link with the monitoring drivers and indicators. There are two overall categories of monitoring applicable to WDEs, the first relates to the actual monitoring and function of the ecosystem and the second to management effectiveness or auditing.

### Function related monitoring

Thomas et al. (2001) identify three main categories of monitoring that relate to what monitoring tells us with respect to what is happening in the system:

- **Retrospective monitoring** — used to detect change in resource status or condition (sometimes referred to as effects-orientated monitoring, not to be confused with effectiveness monitoring).
- **Stressor-orientated monitoring** — when the cause-effect relationship is known.
- **Anticipatory monitoring** — when a hypothesised model of stressors, effects, and 'anticipatory indicators' is known.

**Retrospective (or effects-orientated) monitoring** seeks to find effects by detecting changes in status or condition of some organism, population, or community. It is retrospective in that it is based on detecting an effect after it has occurred. It does not assume any knowledge of cause-effect relationships. It involves monitoring such as measuring changes in the foliage condition of trees, size or trends in animal populations, or diversity of aquatic macroinvertebrates in streams, and it takes advantage of the fact that biological indicators integrate conditions over time.

Although retrospective monitoring does not require knowledge of cause-effect relationships, if both stressors and effects are monitored, then it may be desirable to investigate cause-effect relationships.

Retrospective monitoring may be inappropriate in cases where the cost of failing to detect an effect early is high, for example if the time lag for mitigation to be effective is long (NRC 1995). In such cases the predictive or stressor approach may be more appropriate (see below).

**Predictive or stressor-orientated monitoring** aims to detect the known or suspected cause of an undesirable effect before the effect has had a chance to occur or become serious (e.g. stress levels along a geologic fault, presence of carcinogens in animal tissue, canary in a coal-mine). It is predictive in that the cause-effect relationship is known, so if the cause can be detected early, the effect can be predicted before it occurs. Thomas et al. (2001) suggested that predictive monitoring was not commonly in use in US National Park ecosystems because knowledge of processes was still poor and cause-effect relationships had rarely been established.

**Anticipatory monitoring** does not require monitoring ecological condition or assessment of endpoints of interest. It attempts to detect effects as they are occurring, by measuring anticipatory indicators, rather than describing effects after they have occurred. Its success depends on the validity of the assumed cause-effect relationships among the stressor(s), their ecological effects, and the selected indicators of stress. This approach carries the risk of failing to detect the ecological effects of significant, but unanticipated stressors (Noon et al. 1999).

## Management orientated monitoring

While the types of monitoring distinguished above relate to monitoring system function and condition, the three categories below are orientated towards auditing management effectiveness. Plumb (2003) summarises Kershner's (1997) description of three types of natural resource monitoring for watershed management:

- **Implementation monitoring** should ask whether WDE management (as defined by objectives) is being implemented properly and is designed to continually evaluate whether stated WDE management objectives are designed appropriately. Kershner (1997) suggests that this type of monitoring would likely apply strongly to adaptive management programs, wherein WDE management decisions are based on incomplete knowledge, but where midcourse corrections can be implemented to adjust management outcomes.
- **Effectiveness monitoring** is sometimes referred to as trend monitoring and attempts to estimate change (variability) over time that is then translated into a quantifiable understanding of whether resource condition objectives are being met. This type of monitoring often requires some understanding of the physical, biological, and sometimes social factors that underpin ecosystem structure and function.
- **Validation monitoring** reflects a research motivation and is designed to generate explicit quantification of basic assumptions behind effectiveness monitoring. Thus, validation monitoring is a research tool for examining the fundamental understanding of ecosystem structure and function (Kershner 1997). Incorporation of both validation and effectiveness monitoring is a vital component of any park-based adaptive management programme.

## Monitoring and management cycles

Monitoring may be undertaken for a variety of purposes, which range from establishing baseline characteristics to assessing the cause of deterioration in condition, or the effectiveness of some management intervention. Management intervention necessitates monitoring and review of condition, the results of which may prompt an adjustment in the management regime. This is adaptive management. Certain types of monitoring may not obviously imply management, although the act of monitoring can provide information that could lead to management action.

The Framework follows a cyclic structure that allows for review of condition against objectives. The outcome of the review might be an adjustment in management regime or an adjustment in the type of condition indicators monitored. For example, the monitoring programme might not be providing the information required, or alternatively redundancy due to duplication or auto-correlation in data may facilitate a reduction in monitored parameters.

Numerous examples of adaptive management cycles can be found in the literature and their content and complexity varies greatly. Depending on where the emphasis lies, there will be more stages represented in the cycle to deal with specific aspects of the cycle.

Gross (2003) suggests that the starting point for any monitoring programme will inevitably be related to one or more of the following three statements (and others):

1. There is a problem with the system (perceived or actual).
2. There are known stresses that could impact on system integrity.
3. There is little known about the system, its drivers, components and processes.

Figure 1 provides a very simple cycle that might be followed in the early stages of investigating a system, i.e. prior to the inception of management interventions. If the initial question posed is answered by one of the three statements above then the cycle is commenced.

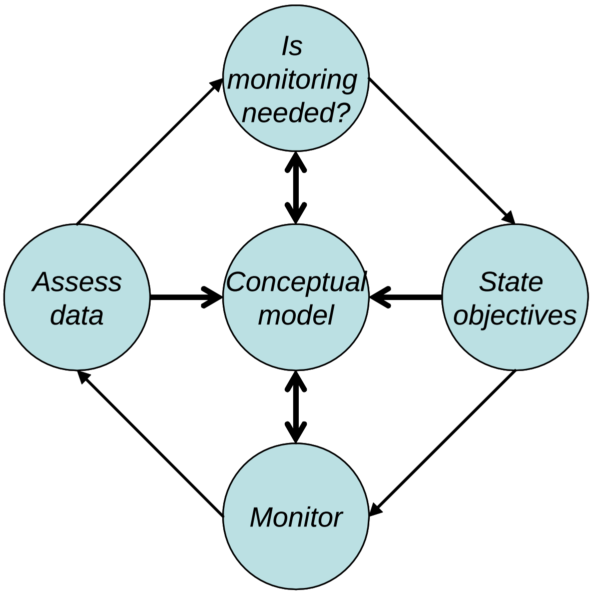


**Figure 1. Simplified "pre-management" monitoring cycle.**

Depending on which of the statements is applicable, monitoring and management objectives are set. At the centre of the cycle lies the conceptual model, this is used as a tool or map of knowledge and ideas about the how the system functions and what the stresses are. The objective (as with all modelling of natural systems) is that the model is updated and reviewed regularly and is informed by the data and informs the monitoring.

Assessment of the data may involve comparison with other sites, literature data, or data from the same site collected previously. Ideally, the availability of previous data and data for an adjacent or comparable site allows temporal variation to be filtered-out (Miner and Godwin undated). This is effectiveness monitoring.

If a problem exists and management intervention is chosen, then the monitoring cycle expands to a full adaptive management cycle (Fig. 2).

The full adaptive management cycle requires M&E objectives and management actions to be devised.

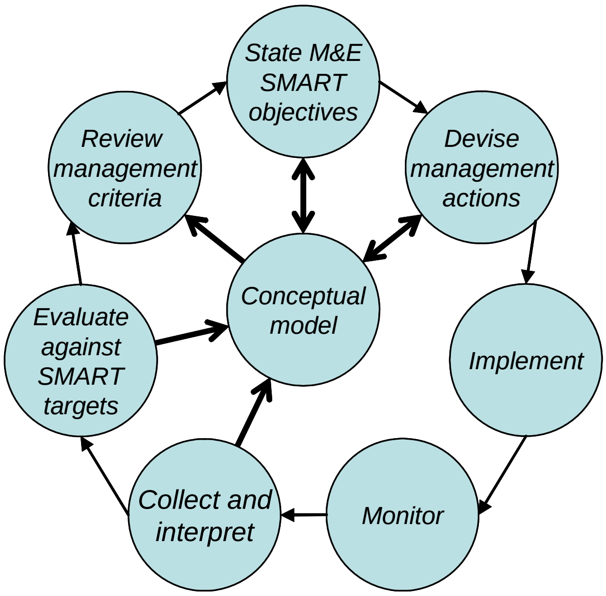


**Figure 2. Expanded adaptive management cycle.**

## More on adaptive management

The box below contains a literature review of adaptive management written by John Gross of the US National Parks Service and is presented here with his permission, with minor adaptations. The review provides a valuable and informative overview of the role of adaptive management and monitoring for ecosystems (original reference: Gross 2003).

Adaptive management refers to a structured process of "learning by doing", where management plans are explicitly designed to generate information that can be used to improve management in the future (Walters 1986, 1997). Deliberate manipulations of ecosystems are used to probe ecosystem responses in ways that yield new information about the system. New knowledge is incorporated into management decisions and this leads to a cycle of continuous improvement in policies and practices.

The term "adaptive management" is now widely used by natural resource managers and there are now many interpretations of its meaning. A liberal interpretation of adaptive management is management by trial-and-error. In this case, there is no formal program for manipulating the system in a manner that generates new knowledge, nor a defensible program for monitoring the results of management actions. Nyberg and Taylor (1995) proposed the following working definition for adaptive management:

> *"Adaptive management is a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form – **active adaptive management** – employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed. The key characteristics of adaptive management include:*
>
> - *Acknowledgement of uncertainty about what policy or practice is "best" for the particular management issue;*
> - *Thoughtful selection of the policies or practices to be applied;*
> - *Careful implementation of a plan of action designed to reveal the critical knowledge;*

- *Monitoring of key response indicators;*
- *Analysis of the outcome in consideration of the original objectives; and*
- *Incorporation of the results into future decisions."*

This definition clearly enunciates the structured set of activities that comprise an adaptive management program, especially the deliberate, experimental manipulation of the system.

Adaptive management begins with problem assessment and construction of dynamic models that represent alternative hypotheses of system functioning and that make predictions of alternative management policies (Holling 1978; Walters 1997). **In the formal sense, adaptive management involves much more than responding to anticipated effects of management actions, and it is more than a slight enhancement to monitoring programs. Adaptive management acknowledges complexity and uncertainty, and addresses uncertainty in processes, models, and measurements. When adaptive management is implemented correctly, it can replace learning by trial and error (an evolutionary process) with learning by careful tests (a process of directed selection) (Walters 1997).**

### The modes of adaptive management

Walters and Holling (1990) succinctly distinguish several adaptive management modes:

1. "**Evolutionary or "trial and error,"** in which early choices are essentially haphazard, while later choices are made from a subset that gives better results.
2. **Passive adaptive**, where historical data available at each step are used to construct a single best estimate, or model, for response and the decision is based on assuming this model is correct.
3. **Active adaptive**, where data available at each step are used to structure a range of alternative response models, and a policy choice is made that reflects some computed balance between expected short-term performance and long-term value of knowing which alternative model (if any) is correct."

### The role of monitoring within the adaptive management cycle

The monitoring program can contribute substantially to the goal of adopting adaptive management principles in WDE management. Walters (1997) noted that the modelling step is intended to serve three functions:

1. Clarify the problem and enhance communication among scientists, managers, and other stakeholders.
2. Screen policy options to eliminate options that will most likely fail because of inadequate scope or type of impact.
3. Identify key knowledge gaps that make model predictions suspect.

In many situations, the monitoring program can directly contribute to the first and third functions identified by Walters (1997). Furthermore, by generating models that clearly state hypotheses on how systems function, the monitoring program has the opportunity to contribute to the second goal.

# THE FRAMEWORK

## GROUP 1 – RATIONALE AND PRIORITIES

### TASK 1.1 – KEY QUESTIONS

| 1: Rationale and priorities | | | |
|---|---|---|---|
| **Answer key questions** | Review M&E objectives | WDE summary table: rank priorities | Identify and rank risks and threats |

#### Key Questions – a worked example

Working through Task 1.1 for a range of examples gives an idea of how this task may be approached. Three examples have been chosen: a resource condition milestone; a target from the State Natural Resources Management Plan (DWLBC 2006); and an ecological target from the Lower Lakes, Coorong and Murray Mouth Icon Site Asset Environmental Management Plan (MDBC 2006):

- *Milestone 2.4*: By 2010 all water resources will be managed within ecologically sustainable limits (excluding the River Murray[1]).
- *Resource condition target W2*: By 2020 all aquatic ecosystems have improved ecological health compared with 2006.
- *LLCMM ecological target*: Maintain the 1% flyway population level for Sharp-tailed Sandpiper, Curlew Sandpiper, Red-necked Stint, Sanderling, Common Greenshank and Banded Stilt.

The three examples are worked through and contrasted below (the following responses may not be those adopted in reality as this is purely an exercise).

#### Will monitoring and evaluation answer my questions?

*Milestone 2.4*: Whilst there is a deadline provided (2010) there is no reference to assessing change over time. This suggests that monitoring may not be suitable. The question requires that some assessment be made of ecologically sustainable limits and the resource be managed within them. Thus, it is possible that when and if measurable, such limits may be monitored to ensure compliance. It appears that whilst monitoring is possible, it may not be the best option.

*Resource condition target W2*: The case for designing a monitoring programme for this resource condition target is relatively straightforward, as a comparison in a parameter, ecological health, has to be made over time.

[1] The River Murray is subject to a separate resource condition target and is to be managed within sustainable limits by 2018.

*LLCMM ecological target*: This target involves the maintenance of a specific population level over time and is answerable by monitoring the population size over time.

## Is monitoring and evaluation really needed?

*Milestone 2.4*: There are a number of alternatives available, such as assessing the driving variables for aquatic systems (i.e. hydrology) and the limits to which they can be altered within sustainable limits (although not used to design a monitoring programme a conceptual model would prove useful in this process). Policy is then enacted to ensure that development is kept within these limits. An assessment of whether this is occurring may be via pre-existing data, such as water licenses.

*Resource condition target W2*: Rather than design a specific monitoring programme to assess all of the State's aquatic ecosystems, a form of inventory data collection could be adopted, whereby river health data collected across the state for other purposes is gathered and assessed via meta-analysis. Such an approach would provide an answer to this question, and likely at less cost than a full monitoring programme. However, such an approach, depending on the power of the meta-analysis would potentially be less accurate, given that the data were collected for other purposes.

*LLCMM ecological target*: There is no alternative to monitoring the population size of the bird species over time.

## What would happen if I didn't monitor?

*Milestone 2.4*: Even without monitoring, the target could still be assessed via other means (as listed above) and the policy implemented.

*Resource condition target W2*: Without specific monitoring the target could still be reported on by assessing data (most likely monitoring), gathered for other purposes. This option would be cheaper than designing a specific monitoring programme for this purpose, but due to the nature of the data, a larger change in ecological health may be required before it is able to be detected. Assessing the target in this way also relies on comparable data being available in 2010 for comparison.

*LLCMM ecological target*: The consequences of not monitoring would be that no data would be collected and the success or otherwise of the target could not be assessed.

## What are the core or key monitoring needs?

*Milestone 2.4*: An assessment of ecological sustainability would have to be undertaken. What this entails is not immediately obvious. A workable definition may be found in a policy document or strategy, or suitable indicators can be developed through the use of conceptual models. However, from the proceeding analysis, any monitoring (if undertaken at all) is likely to be a relatively minor part of this process.

*Resource condition target W2*: An assessment of ecological health would have to be undertaken. This may differ between the different types of WDEs across the state, but a suitable indicator must be chosen and is best selected by constructing conceptual models. This is a good time to consider the logistical and funding issues which will impact on the range of indicators that may be selected.

*LLCMM ecological target*: Bird abundance.

By going through this process it can be seen that whilst a monitoring programme can be developed for all three examples, monitoring is: not the best option for assessing Milestone 2.4; is feasible for Resource Condition Target W2 (although there is a viable alternative available); and is the only option for assessing the LLCMM Ecological Target.

## TASK 1.4 – IDENTIFYING NATURAL AND ANTHROPOGENIC STRESSORS

***1: Rationale and priorities***

| Answer key questions | Review M&E objectives | WDE summary table: rank priorities | **Identify and rank risks and threats** |
|---|---|---|---|

Stressors may be defined as: physical, chemical, or biological perturbations to a system that are either foreign to that system or natural to the system, but applied at an excessive (or deficient) level (Barrett et al. 1976). Stressors cause significant changes in the ecological components, patterns and processes in natural systems. Examples include: water abstraction or impoundment; turbidity; sodicity; increased salt concentration; faecal contamination; nutrient enrichment; pesticide use; trampling; poaching; land use change; and air pollution (Table 1).

Stressors act at differing spatial and temporal scales and may impact on components of an ecosystem in differing ways, and to differing extents. For this reason, a structured approach to identifying stressors is desirable. Potential stressors are often driving variables in the conceptual model, so constructing a model helps to highlight these and, additionally, may assist in prioritising variables to monitor. If a driving variable is known to be behaving within its predictable range of behaviour, and is not a stressor, it might be acceptable to minimise observation of this value and concentrate efforts on known stressor variables.

### Overview of known stresses to WDEs in SA

Van Dam et al (1999) outline five main causes of adverse change in wetlands, namely:

- changes to the water regime
- water pollution
- physical modification
- exploitation of biological products
- introduction of exotic species.

These can impact on the ecological character of the ecosystem by impairing or causing an imbalance in biological, physical, or chemical components of the wetland ecosystem, or their interactions.

**Table 1. WDE threats (Source: Holmes and Papas 2005).**

| General threat | Specific threats |
|---|---|
| **Physical conversion or change of wetland for specific purposes** | • land filling<br>• drainage<br>• damming<br>• dredging<br>• mining<br>• sand/gravel extraction<br>• landforming<br>• cultivation<br>• clearing of native wetland vegetation<br>• adoption of new agricultural practises (farm forestry, raised-bed cropping) |
| **Water storage, regulation and extraction** | • construction and operation of reservoirs and storages<br>• river regulation<br>• release of cold water from dams<br>• diversion and extraction of surface water<br>• extraction of groundwater |
| **Control of floodwater or seawater** | • inappropriate shoreline 'erosion' control measures (seawalls, tirewalls)<br>• artificial opening of estuary mouths<br>• impairment of tidal movements<br>• impairment of water movement on floodplains and in natural drainage lines (by levees, natural drainage line obstruction or restriction) |
| **Poor land use practices in wetland catchment** | • clearing native vegetation (excess runoff and raised water tables)<br>• poor irrigation practices (excessive watering)<br>• excessive fertilizer use<br>• soil erosion |
| **Poor management of wastes and pollutants** | • inadequate sewage treatment<br>• poor stormwater management<br>• littering and dumping of rubbish<br>• industrial discharges<br>• oil/chemical spills<br>• disposal of irrigation tailwaters |
| **Introduction and poor control of exotic species** | • planting inappropriate species<br>• introduction of diseases<br>• spread of invasive species<br>• translocation of live aquatic organisms<br>• aquaculture |
| **Unsustainable utilisation of wetland products** | • grazing<br>• harvesting wildlife (hunting, fishing)<br>• aquaculture<br>• harvesting native vegetation (forestry) |
| **Fire** | |
| **Recreational use** | • water-based activities (fishing, boating)<br>• shore-based activities (camping, picnicking, walking) |
| **Urbanisation** | • increased catchment run-off<br>• straying domestic pets<br>• increased human activity |
| **Climate change** | • changed rainfall patterns<br>• changed temperature and wind regimes<br>• more frequent severe weather events |

Seaman (2003a,b,c,d), Lamontagne (2002), Holmes and Papas (2005) list numerous threats, risks and causes of WDE degradation. Land clearance, invasive plant species and access tracks were the most common causes of degradation in the four South Australian wetland inventory regions surveyed by Seaman (Table 2). Perkins et al. (2005) cites work by Carlisle, indicating that around 50% of wetland loss in the USA is due to urban and rural development. Lamontagne (2002) notes expected threats to GDEs in South Australia (Table 3), declining water tables and salinisation are listed as threats to all GDE types.

**Table 2. Numbers of wetlands in four NRM regions of South Australia, with specified causes of degradation (data from Seaman 2002a,b,c,d).**

| Threat/Risk | Kangaroo Island | Eyre Peninsula | Northern and Yorke | AMLR | Totals |
|---|---|---|---|---|---|
| Access tracks | 13 | 18 | 11 | 22 | 64 |
| Land clearance | 22 | 18 | 17 | 41 | 98 |
| Grazing damage | 14 | 6 | 2 | | 22 |
| Fence lines | 5 | 9 | 15 | | 29 |
| Mining impact | 1 | | | | 1 |
| Altered flows | 3 | 3 | 3 | | 9 |
| Invasive plants | | | | 70 | 70 |
| Pest vertebrates | | | | 33 | 33 |
| Drains | | 6 | | | 6 |
| Borrow pits/quarry | | 1 | | | 1 |
| Rubbish dumping | | 2 | 8 | | 10 |

**Table 3. Threats (x) to GDEs in South Australia (summarising Lamontagne 2002).**

| | Wetlands | Terrestrial vegetation | Baseflow systems | Karst/ stygofauna | Terrestrial fauna/ avifauna |
|---|---|---|---|---|---|
| Declining water table | x | x | x | x | x |
| Drainage for agriculture | x | | | | |
| Less frequent floods | x | | | | |
| Drowning (rising water tables) | | x | | | |
| Reduced recharge from alluvial aquifers | | | x | | |
| Pumping from perm. pools | | | x | | |
| Invasion by exotics | x | | | | |
| Salinisation | x | x | x | x | x |
| Anoxia | | | | x | |

Land clearance contributes to habitat fragmentation, loss of unique habitat, changes in the hydrological regime and causes salinisation. Invasive plant species are often difficult to remove once established. Declining water tables and generally reduced water availability may exceed the ability of certain species to survive between wet periods. Table 4 summarises the impacts of changes in hydrological regime on WDEs. Begg et al. (2001) provide a detailed narrative of these impacts in their assessment of risks to WDEs of the Daly Basin in the Northern Territory.

**Table 4. Features of the hydrology of WDEs and the ecological consequences of changes in their characteristics (Source: Boulton and Brock 1999).**

| Feature | Ecological consequences |
|---|---|
| Duration of zero flow | Affects water quality in remaining pools; longer periods may cause declines in some aquatic species richness; alters extent of isolation and drying of channel and floodplain wetlands; survival of resting eggs and seeds often declines over time; influences establishment of terrestrial floodplain vegetation; eradicates species intolerant of drying. |
| Amplitude of falling limb ('drawdown') | Extent of drawdown affects the degree of isolation of floodplain wetlands from main channel; influences fish recruitment with cascade effects on invertebrates and waterbirds; alters extent of inundation of littoral habitats; strands or inundates sessile and sedentary organisms; influences germination and growth of some floodplain vegetation. |
| Amplitude of rising limb | Related to initial river height and final size of flood; big floods enable extensive breeding/recruitment of most river and floodplain species; leads to inundation of large areas of floodplain; affects extent of nutrient release and hatching of resting stages; affects germination and growth of some floodplain vegetation. |
| Interval since last flood peak | Changes from natural patterns may affect recruitment of fishes and other biota with seasonal life cycles (flooding may be a spawning cue); drying and cracking may affect saturation and slump of river banks; may lead to sedimentation of river bed, promotes establishment of some floodplain vegetation; leads to drying of floodplain wetlands. |
| Duration of rising and falling limbs, and interval since last flood minimum | Influence the length of time that the floodplain is inundated and hence the time for recolonisation of floodplain wetlands; control fish, invertebrate and plant growth on the floodplain; regulate successional changes in biota; affect changes in water quality, dissolved oxygen and temperature. Cumulative effects and survival and growth since previous flood relate to interval since last flood minimum. |
| Slope of rising and falling limbs | Rates of change of the flood pulse influence types of species favoured by the flood (e.g. steep rising limbs may flush out biota typical of standing water habitats; steep falling limbs may strand slow-moving taxa); affect survival and recruitment of species; influence rates of flow and erosion deposition of sediments; alter rates of change in water quality. |

These kinds of threats have potentially irreversible impacts, especially in relation to habitat fragmentation and the loss of source areas for replenishment of susceptible species. Where impacts may be regional, for example if there was a large scale impact on water tables, there may be the potential for wide scale collapse of ecosystems. Where impacts are spatially localised the ability to recover a system with intervention may be greater.

## Management intervention to address risks and threats

The NRM M&E framework works on the principle of recovering impacted systems with appropriate intervention (Figs 3 and 4).

The management intervention approach of the NRM system lends itself to the "state-and-transition" conceptual modelling approach, where a system has passed a threshold from which no return is possible without human intervention. This type of model will be of significant utility within the NRM system (i.e. Task 2.4).

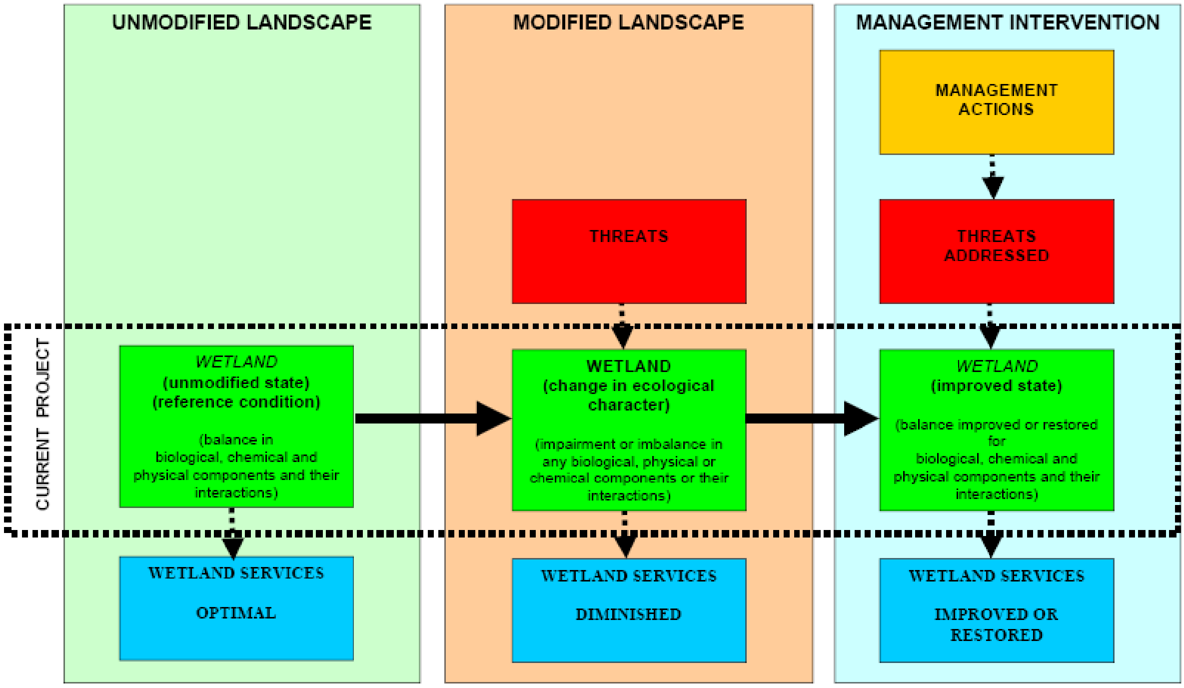


**Figure 3.** **Progression from: unmodified, modified, and management intervention of wetland systems (Holmes and Papas 2005).**

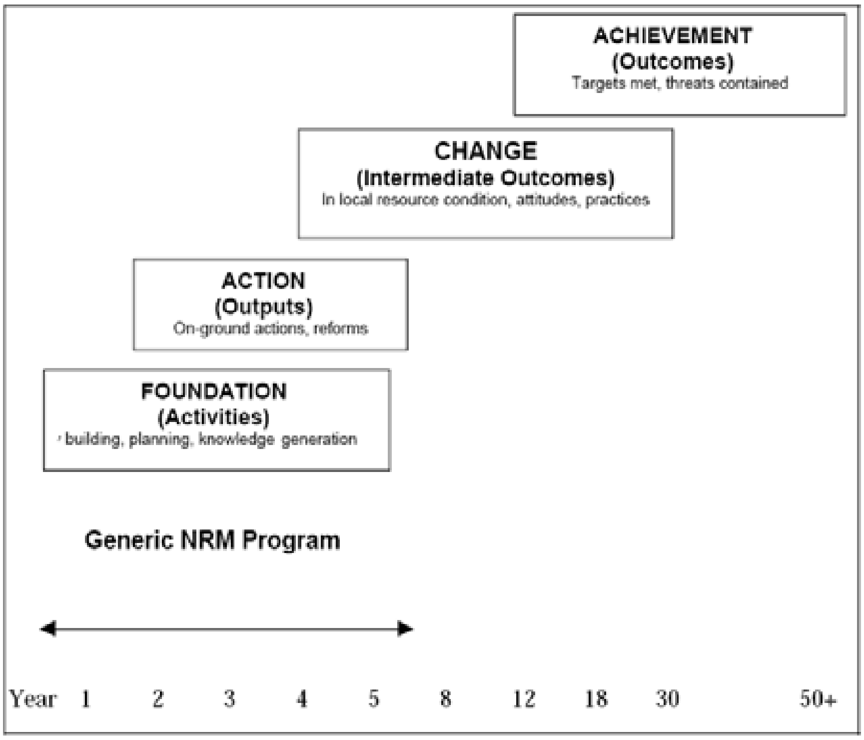


**Figure 4.** **NRM M&E framework timeframe, and objectives for improvement of natural resource conditions (NRM Ministerial Council 2003).**

One of the tools presented in this document to assist WDE practitioners is the Stommel diagram. The Stommel diagram can be used to plot system drivers, objectives and ecosystem processes demonstrating the overlap or relationships of temporal and spatial scales (i.e. Task 2.2).

## Ramsar risk assessment

Risk assessment has been adopted by Ramsar (Ramsar Convention Bureau 2000) as an integral component of the management planning process for wetlands (Begg et al. 2001; Seaman 2003a,b,c,d). The risk assessment conceptual framework assists in predicting and assessing change in ecological character of a wetland. Wetland inventory records the ecological character of a wetland and is an integral component of the risk assessment (Seaman 2003a,b,c,d). Ecological character is the sum of the biological, physical, and chemical components of the wetland ecosystem and their interactions that maintain the wetland and its products, functions, and attributes (Seaman 2003a,b,c,d). Seaman states that "*this information is also critical in order to develop monitoring programs*".

The wetland risk assessment framework provides a logical analysis pathway (identification of the problem → the effects → the extent → the opportunity for risk management and reduction) for identifying and assessing risks and recommendations for management and monitoring (van Dam et al 1999).

Begg et al. (2003) summarise the major steps in the Wetland Risk Assessment (WRA) process, adapted from Ramsar Convention Bureau (2000) and van Dam et al. (1999), for their Daly Basin study:

**Step 1 Identification of the problem:** This is the process of identifying the nature of the problem and developing a plan for the remainder of the risk assessment, based on this information. It defines the objectives and scope of, and provides the foundation for the risk assessment.

**Step 2 Identification of the effects:** This step evaluates the likely adverse change or impact on the wetland. Such data should preferably be derived from field studies, as these are often more appropriate for assessment of multiple impacts, such as those occurring in many wetlands. However, the value of literature reviews of existing information should not be underestimated.

**Step 3 Identification of the extent of the problem:** This step estimates the likely extent of the problem in the wetland of concern, by using information gathered about its characteristics and extent of occurrence elsewhere. For biological (e.g. invasive species) pressures it could include information on the current distribution or habitat preference, in order to estimate its potential distribution. For physical pressures it could include a map of the current situation and projected trends.

**Step 4 Identification of the risk:** This involves integration of the results from the assessment of the effects with those from the assessment of the extent of the problem, in order to estimate the likelihood and, ideally, magnitude of adverse ecological change within the study site. A GIS-based approach can be useful for characterising risks to wetlands, by overlaying relevant information onto a map of the region of interest in order to link effects to extent. In addition to estimating risks, such an approach also focuses future assessments and/or monitoring on identified problem areas. The uncertainty and information gaps associated with the assessment must always be described.

**Step 5 Risk management and reduction:** This is the final decision-making process and uses the information obtained from the assessment processes described above and, in conjunction with other relevant information (e.g. political, social, economic and engineering), attempts to minimise the risks without compromising other societal, community or environmental values. It is a multidisciplinary task, usually requiring coordination by the land managers and communication between stakeholders.

**Step 6 Monitoring:** This is the last step in the risk assessment process and should be undertaken to verify the effectiveness of the risk management decisions. It should incorporate reliable early warning techniques that can detect the failure or poor performance of risk management decisions prior to serious environmental harm occurring. The risk assessment will be of little value if effective monitoring is not undertaken.

### *Ramsar risk assessment in the Framework*

This risk assessment process follows similar steps to that of the Framework, without the conceptual modelling. Step 6 is “effectiveness monitoring”. The objectives of the Ramsar risk assessment framework are encapsulated within the Framework.

The purpose of the risk assessment within the Framework is to provide a simple presence/absence listing of all threatening influences in the vicinity or catchment of the WDE. This would take advantage of all and any appropriate existing material, local knowledge and includes a rapid field assessment of potential or known risks. By gathering together this information the WDE practitioner would be aware of the range of potential threats, which can then be prioritised and appropriate indicators built into the monitoring programme to assess attribute condition in relation to those threats.

# *GROUP 2 – CONCEPTUAL UNDERSTANDING*

***2: Conceptual understanding***

| Create conceptual diagram | Stommel diagram for temporal and spatial bounds | Wetting/drying and event response? | Build stressor and/or state-and-transition model |
|---|---|---|---|

## CONCEPTUAL MODELS

### The role of conceptual models

Conceptual models express ideas about components and processes deemed important in a system, document assumptions about how components and processes are related and help identify gaps in our knowledge. They are working hypotheses about system form and function (Manley et al. 2000).

"*Given the complexity of natural systems and the huge variety of factors that influence natural processes, there is an obvious need for conceptual models that help organize information and make sense of system components and interactions. Failures in the development of major ecosystem monitoring programs have repeatedly been attributed to the absence of sound conceptual models that articulate key system components and their interactions (NRC 1995; Busch and Trexler 2003).*"

A conceptual model should facilitate transparency of thought process and assumptions around the functioning of the WDE of interest. The following roles of conceptual models for ecosystem understanding are adapted from Gross (2003), Thomas et al. (2001), and Brown et al. (2006):

- Identification and description of ecosystems.
- Identification of the bounds and scope of the system of interest.
- Show the range and limits of potential management interventions.
- Representation of ecosystem components and drivers.
- Identification of key system stressors, natural or anthropogenic.
- Formalising current understanding of system processes and dynamics.
- Articulating key interactions of ecosystem components.
- Identifying linkages of processes across scientific disciplinary boundaries.
- Assisting in the selection of indicators (vital signs).

In addition, from a broader communication perspective, they should:

- Enable communication between WDE workers, scientists, planners, managers and the public (transparency of thought process and assumptions).
- Provide an illustration of current conditions to future audiences.

Plumb (2003) provides a longer-term context for the role of conceptual models in monitoring and evaluation, suggesting that they:

- Facilitate understanding of the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic (vital) ecological parameters. (This understanding can then be translated into deliberate and transparent long-term monitoring protocols, capable of adequately detecting important departures from the natural range of variability).

In addition, conceptual models should:

- Facilitate understanding of the range of anthropogenic-induced ecosystem variability that overlays the range of natural variability. (This in turn can be translated into deliberate and transparent adaptive management alternatives for WDE managers, in order to attempt mitigation).

Such longer-term objectives for the models are reliant on quantitative information derived from consistent long-term monitoring. Since quantification is the process by which science tries to build a conceptual basis for understanding the complexities of reality, our quantification will always be imperfect (Plumb 2003), but not necessarily inadequate. However, the need for long-term monitoring within an adaptive management framework, within which system understanding is continually reviewed and updated, is a necessity for enabling appropriate stewardship of WDEs in an uncertain and changing climate.

Despite the role of conceptual models in facilitating understanding, they don’t replace the need to identify the most significant natural resources, and may not prioritise among issues of concern (Thomas et al. 2001), which points to the need for trained and skilled interpretive staff.

## Types of conceptual model

There are a variety of approaches to representing conceptual models of ecosystems. Most monitoring programmes use a combination of means for presenting conceptual models. These can take many forms and include combinations of narrative, tables, matrices of factors, or box-and-arrow diagrams, pictorial diagrams and more (Gross 2003). Combining several forms in the same figure can be very effective. It is anticipated that for the Framework stressor models, conceptual diagrams and state-and-transition models will be the main approach used for most systems. Table 5 gives an indication of the types of model that might be appropriate to communicate certain types of information about a system. Table 6 lists the types of model and the applications to which they are best suited. Examples of conceptual models from a variety of studies are provided at the end of this section.

**Table 5. Information to be communicated and type of model to be used (source: Gross 2005).**

| What you want to communicate | Model to use |
|---|---|
| General system traits | Generalised model – picture or box and arrow |
| System dynamics | State-and-transition, control model, picture diagram |
| Links and feedbacks | Control diagram, picture diagram |
| Driver - vital sign links | Driver - stressor diagram |

**Table 6. Types of conceptual model and their suited application (source: Gross 2005).**

| Type of model | Suited to: |
|---|---|
| State-and-Transition | Some aquatic systems. Arid and semi-arid systems. Situations with phase shifts |
| Control model | Show causal loops, process, mechanistic description |
| Driver-Stressor model | Show clear linkages, but few feedbacks |
| Conceptual diagram | Varies |

### *Narratives*

Narrative conceptual models are generally: a written articulation of an ecosystem expressed as formal or informal hypotheses in a few sentences; formulae; or combinations of both (Plumb 2003). Narratives generally accompany diagrammatic models in order to describe the diagram, explain the functional relationships, and cite sources of information and data on which models are based (Gross 2003).

### *Tabular conceptual models*

Tabular conceptual models often present ecosystem components in a row/column structure and can vary in complexity according to the number of rows and columns (Plumb 2003) (Table 7). Their utility lies in the ability to summarise large quantities of information (stressors, drivers and responses) and interactions between components (Gross 2003). Tabular models, however, convey little about how the system works, especially when the spatial scale is significant.

**Table 7. A tabular conceptual model (adapted from Williams et al. 1997).**

| Five classes of factor that organise ecological systems and provide a framework for assessing biological integrity | | |
|---|---|---|
| | **Physico-chemical conditions** | |
| Temperature | Nutrients | Oxygen |
| pH | Salinity | Contaminants |
| Insolation | Precipitation/runoff | |
| | **Trophic base (the food supply)** | |
| Energy source | Standing stock (biomass) | Energy transfer efficiency |
| Productivity | Nutritional content of food | Complexity of trophic web (connencted food chains) |
| Food particle size | Spatial distribution of food | |
| | **Habitat Structure** | |
| Spatial complexity | Vegetation height | Water depth |
| Cover and refugia | Vegetation form | Current velocity |
| Topography/bathymetry | Basin and channel form | |
| Soil/sediment composition | Streambed substrate (e.g. clay, gravel, bedrock) | |
| | **Temporal variation** | |
| Seasonal | Fire | Weather |
| Annual | Amplitude | Flow regime |
| Climate change | Predictability | |

| Five classes of factor that organise ecological systems and provide a framework for assessing biological integrity | | |
|---|---|---|
| | **Biotic interactions** | |
| Competition | Herbivory (consumption of living plants) | Coevolution |
| Parasitism | Mutualism (mutually beneficial relations between organisms) | |
| Predation | | |

### *Schematic conceptual models or diagrams (Task 2.1)*

Schematic conceptual models or diagrams are usually necessary to communicate linkages between system components (Gross 2003). The variety of diagrammatic models is seemingly unending (Plumb 2003) and can be categorised into picture models, box-arrow models, matrix models, X-Y axis pictures etc. The conceptual diagram approach of Dennison and Carruthers combines pictures with arrows and narrative to give a very visual and rapid impression of ecosystem arrangement and functioning (e.g. Fig. 5). Dennison, who developed his conceptual diagram tools while based in Australia, now operates from the University of Maryland in the United States and his library of symbols and diagrammatic material is available at http://www.ian.umces.edu/symbols/. His conceptual diagrams have formed the basis of the Geoscience Australia models of Australian coastal and estuarine systems (Ryan et al. 2003), the EHMP (Ecosystem Health Monitoring Programme) of South East Queensland (see Appendix 5), and the US NPS (National Parks Service) (e.g. Perkins et al. 2005) programmes.

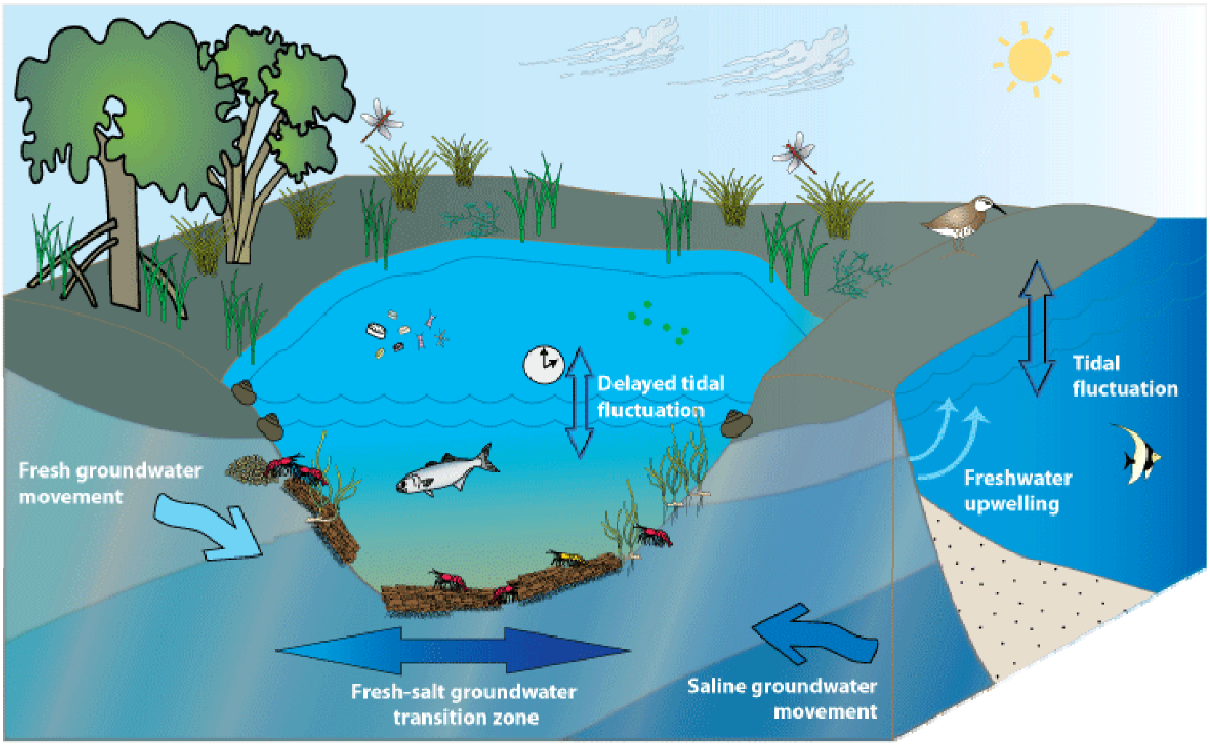


**Figure 5. A pictorial conceptual diagram showing major components and water movement in a costal pool connected to the sea (source: Stephens & Daniel 2006).**

Dennison and Carruthers have the following advice when creating conceptual diagrams:

- Define the overall message (e.g. what story or stories to tell).
- Identify the audience (e.g. scientific peers, general audience).

- List the key structural and functional aspects.
- Identify major processes (e.g. biogeochemical pathways, food web).
- Define biota/habitats (e.g. forest types, wetlands).
- Experiment with ways to depict system (2D vs. 3D; mirror images; nested).
- Start drawing (white boards are useful).

In addition, Dennison and Carruthers (no date) offer the ten commandments of drawing conceptual diagrams, which are intended to maintain the accessibility and effectiveness of the models (Table 8).

The actual “type” of model used may depend on the M&E objectives.

**Table 8. Dennison’s ten commandments.**

| | Dennison's ten commandments for the creation of conceptual diagrams |
|---|---|
| 1 | Thou shalt honor thy audience |
| 2 | Thou shalt simplify |
| 3 | Thou shalt-not use garish colors or apply colors inconsistently |
| 4 | Thou shalt-not produce a diagram without a complete legend |
| 5 | Thou shalt-not covet a single style |
| 6 | Thou shalt-not be constrained by geometry |
| 7 | Thou shalt-not use arrows indiscriminately |
| 8 | Thou shalt-not be afraid of making new symbols |
| 9 | Thou shalt-not publish diagrams without significant editing |
| 10 | Thou shalt-not confine use of diagrams to scientific peers |

### *Stressor models (Task 2.4)*

Stressor models are designed to represent relationships between stressors, ecosystem components, responses and indicators. The intention of these models is to articulate sources of stress and ecosystem response to those stresses (Figs 6–10). They are often based on control models, but only include a limited subset of system components that are pertinent to the M&E objectives.

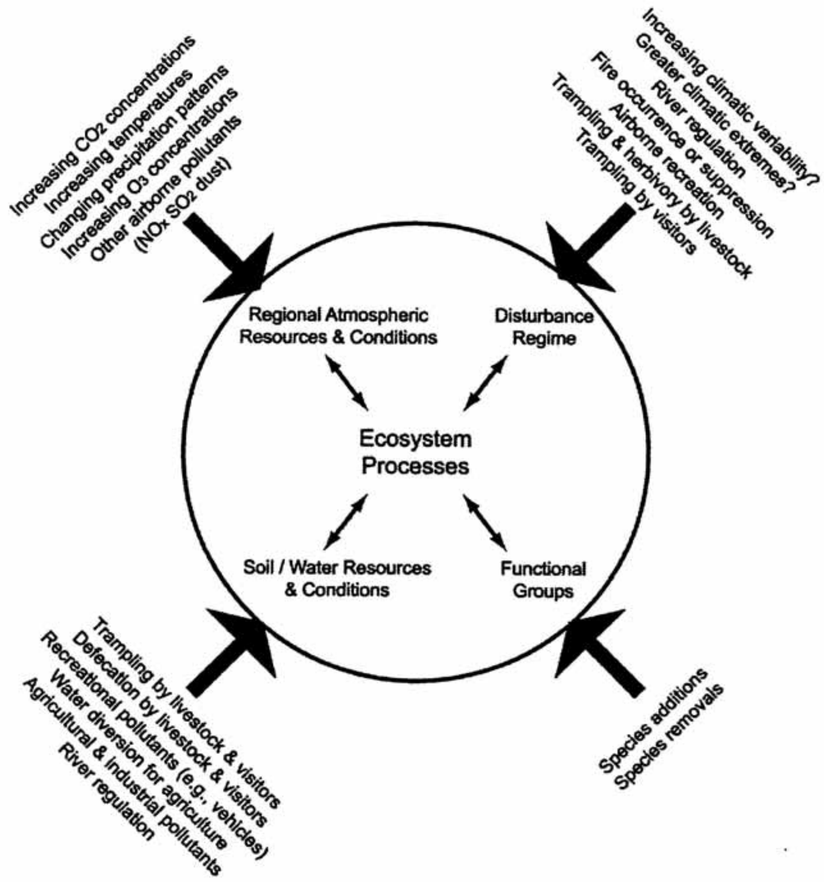


**Figure 6. An adaptation of the Jenny-Chapin model for the Northern Colorado Plateau Inventory and Monitoring Programme showing the array of stressors in relation to their first order effects (source: Evenden et al. 2002).**

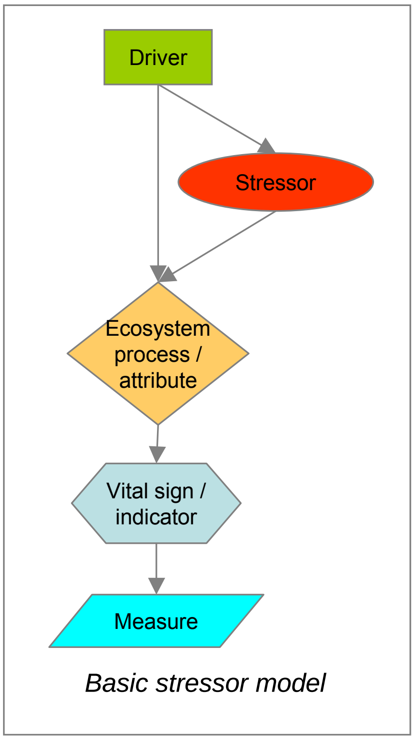


**Figure 7. A legend of symbols and basic structure for use in conceptual models for distinguishing between the roles of model components.**

The role of stressor models in the design of monitoring and evaluation programmes is to provide clear communication of linkages between stresses and system responses that are directly relevant to the monitoring programme, and do not include any extraneous information (Gross 2003). These models may be relatively simple and focus on a specific sub-system or demonstrate an array of system attributes. A hierarchical structure may provide a framework to incorporate a number of very specific stressor sub-models. Issues of scale are important to consider and different processes or system dynamics may be prevalent at different temporal and spatial scales. For the purposes of communicating to managers, policy makers and the public, several diagrams with increasing detail can be valuable to communicate a basic idea and then elaborate on the causative processes.

Fancy (2003) describes the components and symbols of a hierarchical conceptual model (Fig. 7). There are various terms used for the model components, in this document we attempt to adhere to the set of terms presented below, the alternative terms are included in the square brackets. From top to bottom, the components are:

- Rectangles = Drivers [disturbances] – these exert a major forcing influence on natural systems and are associated with large-scale processes.
- Ovals = Stressor [consequences] – these cause significant change in ecological components, patterns and relationships. Barrett et al. (1976) give this definition: "*Stress is defined here as a perturbation (stressor) applied to a system (a) which is foreign to that system or (b) which is natural to that system but applied at an excessive [or deficient] level.*"
- Diamonds = Ecosystem attribute [process, ecological effect, response] – are the responses to the drivers and stressors.
- Hexagons = Indicators [vital signs] – any "information rich" feature of an ecosystem that may be independent or integrative and may be measured or estimated and provide insight into the condition of the ecosystem.
- Parallelograms = Measurements – measures of the attribute or indicator.

Further definitions of model components are provided on pages 39 and 40 of this document.

Figures 8–10 present three stressor models in different ways: Figure 8 gives an uncluttered flow-through representation without direct linkages; Figure 9 presents all of the influences and components of the system without linkages, but provides details of indicators and measures; and Figure 10 presents the linkages of the components. The model provides the broad driver-stressor-response causality and then lists the indicators and measures for each component. Figures 8 and 9 are useful for presenting the overall collection of WDE components and measures to be presented at the policy or public level, whereas Figure 10 provides linkages and is perhaps more useful for day to day operational presentation – perhaps as a wall chart.

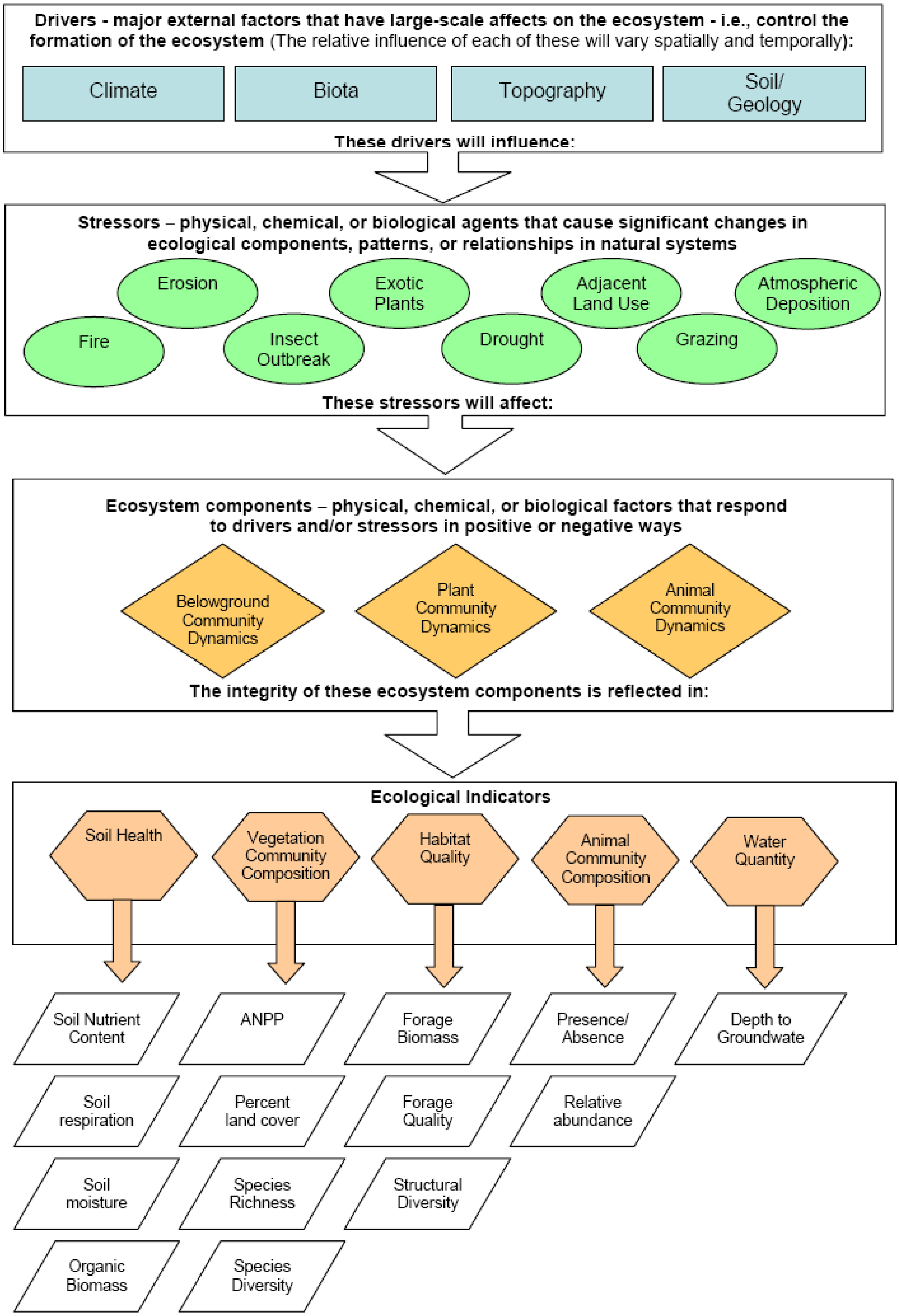


**Figure 8. A stressor model with drivers, stressors, ecosystem attributes, indicators and measures (Piñon-Juniper Forest Ecosystem Model) (source: Perkins et al. 2005).**

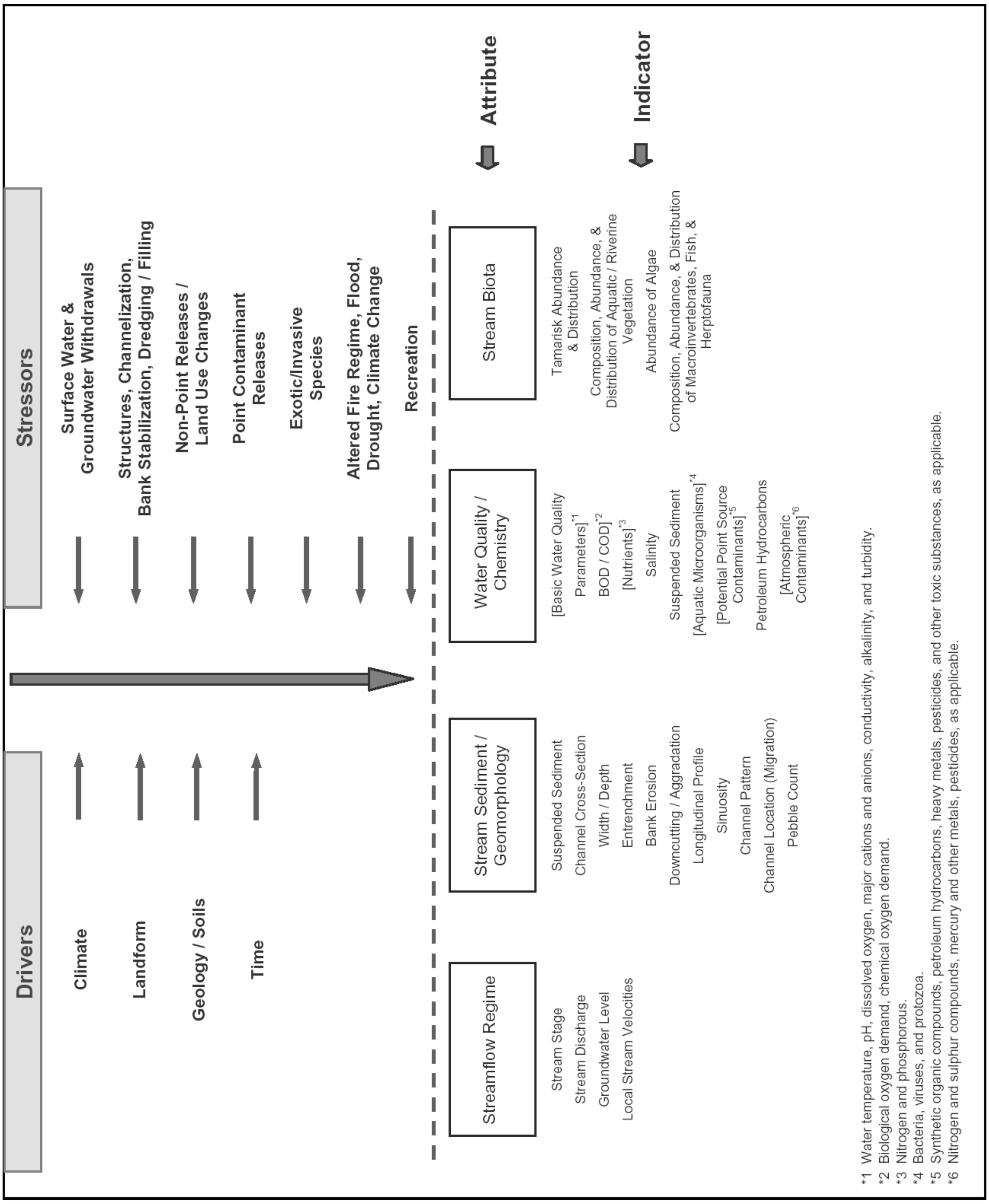


**Figure 9. An alternative way of expressing stressor model structure with drivers, stressors, attributes (ecosystem components), and indicators (including measures) (source: Braumiller 2005).**

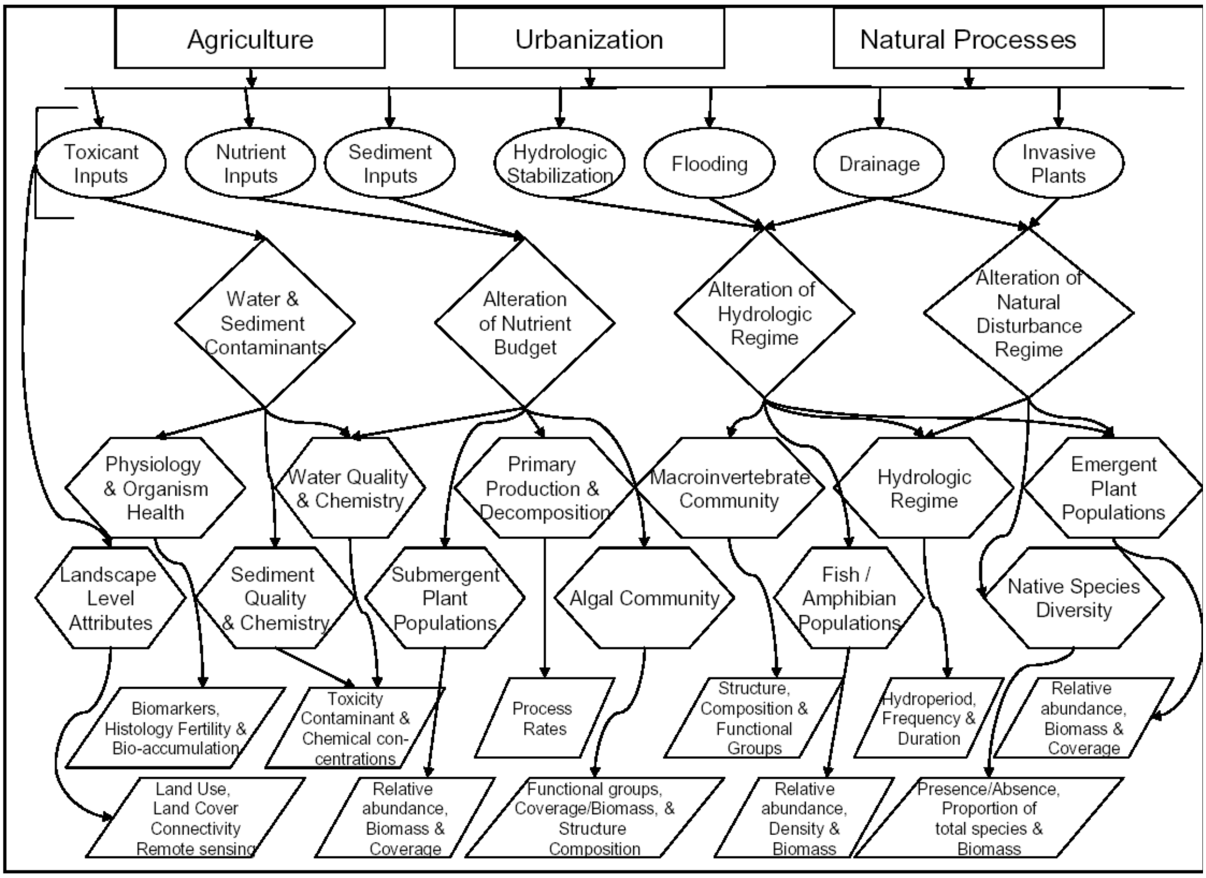


**Figure 10. Stressor model for a freshwater marsh (US) (source: Perkins et al. 2005).**

### *Wetting/drying model for WDEs (Task 2.3)*

Carlisle, in Perkins et al. (2005) provides an example of a wetting/drying model for seasonal wetlands (Fig. 11). This model provides a template that can be adapted to represent South Australian conditions. The model is entered at the appropriate point and presents the vegetational succession through wetting and drying cycles. In addition to vegetation this type of simple model can be adapted to represent freshwater fauna, or even water quality conditions.

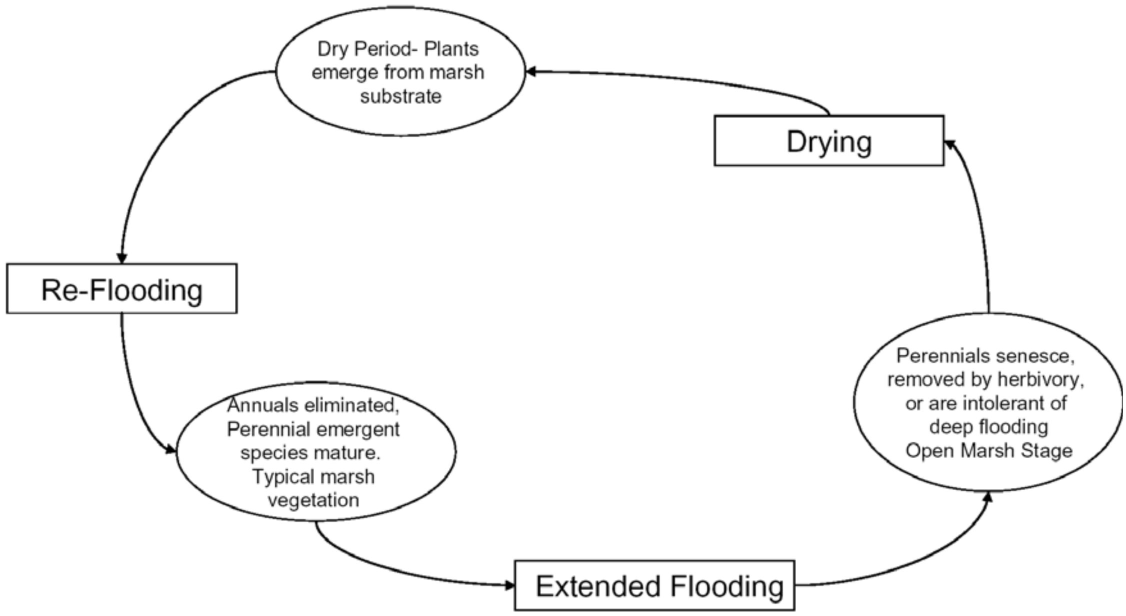


**Figure 11. The seasonal, or event-based wetting and drying cycle of a wetland (source: Carlisle, in Perkins et al. 2005).**

## *Control models*

Control models represent the actual controls, feedback and interactions that determine system dynamics, and present a more complete and accurate picture of system components. These models are intended for understanding ecosystem functioning. The example below (Fig. 12) is intended to represent faecal indicator dynamics in fluvial systems (see Wilkinson, 2001). This is a simplified model that focuses on the timescales that can range from hours to months, and are associated with the dominating processes and mechanisms influencing faecal indicator numbers. This model is revisited when considering phases of system behaviour, which are particularly relevant to South Australian systems that undergo major cycles of wetting and drying.

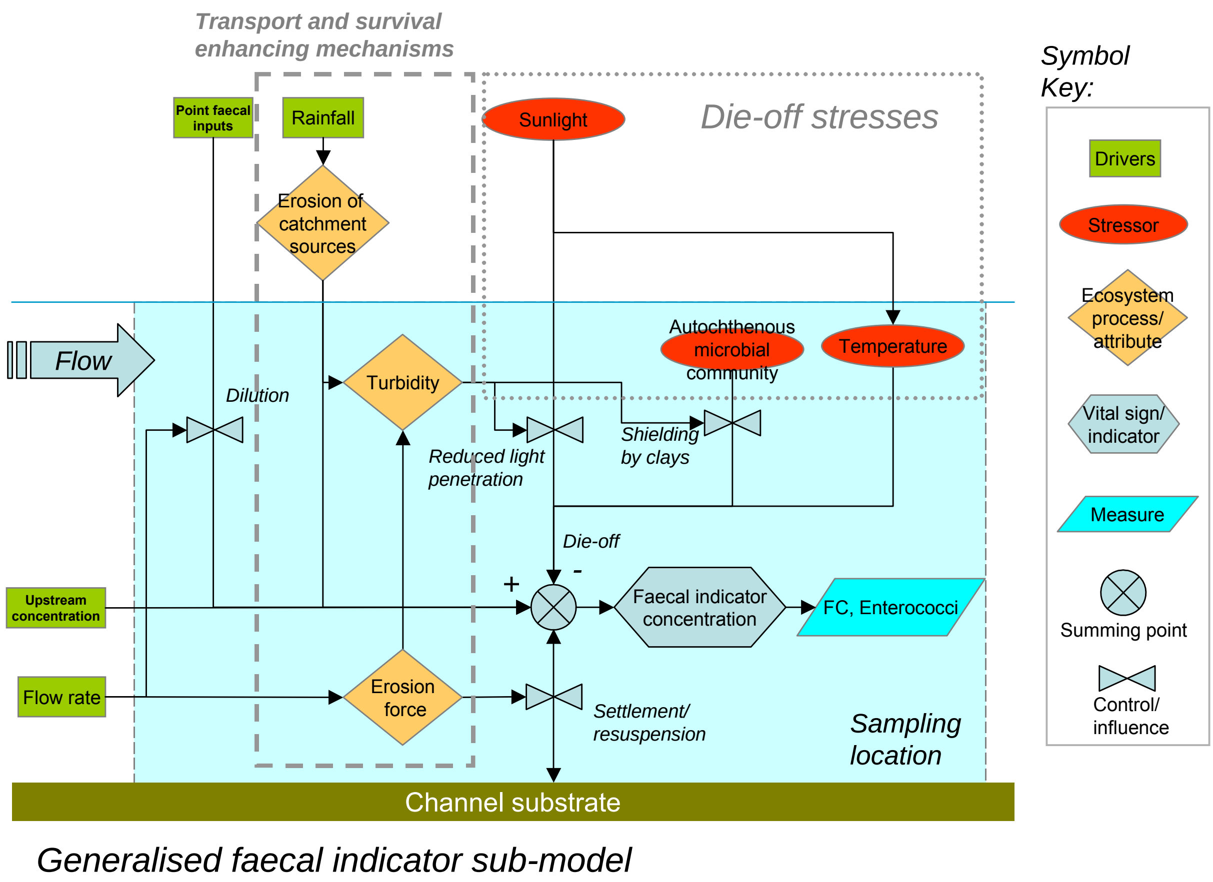


**Figure 12. Control model for faecal indicator bacterial concentration, using symbology for stressor models.**

## *Event response control model (Task 2.3)*

Figure 13 provides a simple example of end states for the stream/creek faecal contamination sub-model, while Figure 12 shows the generalised model with the dominant processes. In general however, only certain processes will be dominant at any time. In this sense, the system has different phases of operation and undergoes a transition between the two phases represented in Figure 13, and in this case it is a reversible transition. Figure 12 represents the transition phase between the two end states when both sets of processes operate to some degree. During dry weather the die-off and settlement mechanisms dominate and the rate of transport downstream is at its minimum (Fig. 13a). During a rainfall induced flow event rapid transport occurs through the reach, settled organisms are disturbed and entrained into the flow, and the turbidity (and flow velocity) renders die-off processes irrelevant because they operate at such a slow rate under these conditions (Fig. 13b). In Figure 12, especially after the flow peak has passed, a slow (relative to the rise in the hydrograph) transition from fluvial domination to die-off and settlement occurs. Figure 14 combines the phases into a simple state-and-transition representation (see flowing).

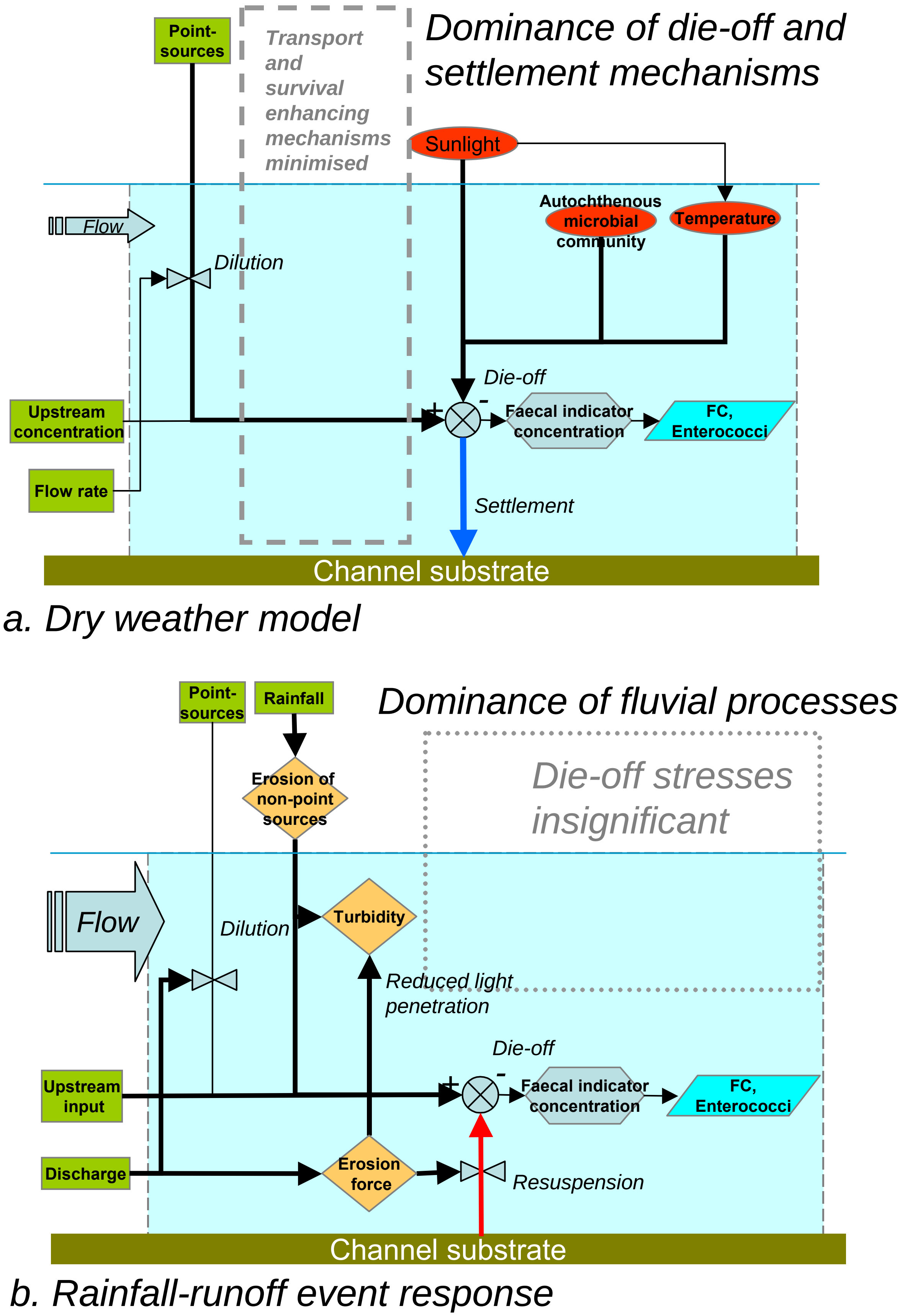


**Figure 13. Alternative states of the faecal contaminant sub-model; a. dry-weather flow; b. rainfall-runoff event response.**

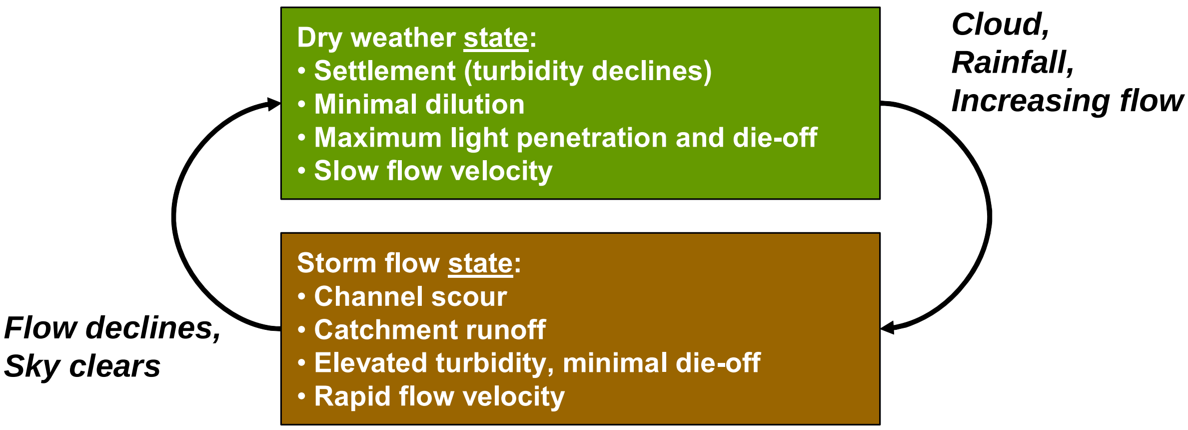


**Figure 14. Simple state-and-transition model of the faecal contaminant sub-model.**

### *True state-and-transition models (Task 2.4)*

State-and-transition models are modelling tools used to represent threshold-type processes in natural systems. The models have a utility for representing systems that might make a transition from one steady condition or state to another different state, in response to a stress (either natural or anthropogenic), the transition may be effectively irreversible or may be reversible either naturally (i.e. without intervention) when the stress is removed, or the transition state may only be reversed by management intervention (Evenden et al. 2002) (Fig. 15). The succession and climax concept was the forerunner to state-and-transition modelling (e.g. Clements 1916; Tansley 1935) and describes the situation where an ecosystem develops (say following a glaciation) to reach climax condition, disturbances then drive the ecosystem backwards to an earlier state and the climax state is once again attained when the stress is removed (a long time scale example might be vegetation recovery following clearfelling). The key difference with state-and-transition models is the recognition that the transition may be permanent. In disturbed and fragmented systems, such as commonly occur in modern times, the likelihood of irreversible transitions is heightened, this is because the discontinuity of source habitat may mean that a species of plant or animal may not be able to recolonise the system once the stress is removed. The summary by Evenden et al. (2002) specifically focuses on arid-land ecosystem health and sustainability, which is dependant on the ability to capture and retain water and nutrients (Whitford 2002).

Stringham et al. (2003) provides some definitions specific to the state-and-transition model context:

**State**: A recognisable, resistant and resilient complex of ecological components.

**Threshold**: A boundary in space and time between possible states, or along irreversible transitions. A threshold is crossed when the capacity to resist and recover in a primary process is exceeded.

**Transition**: Trajectories of change that are precipitated by natural events, and/or management actions, which degrade the integrity of one or more of the state's primary ecological processes.

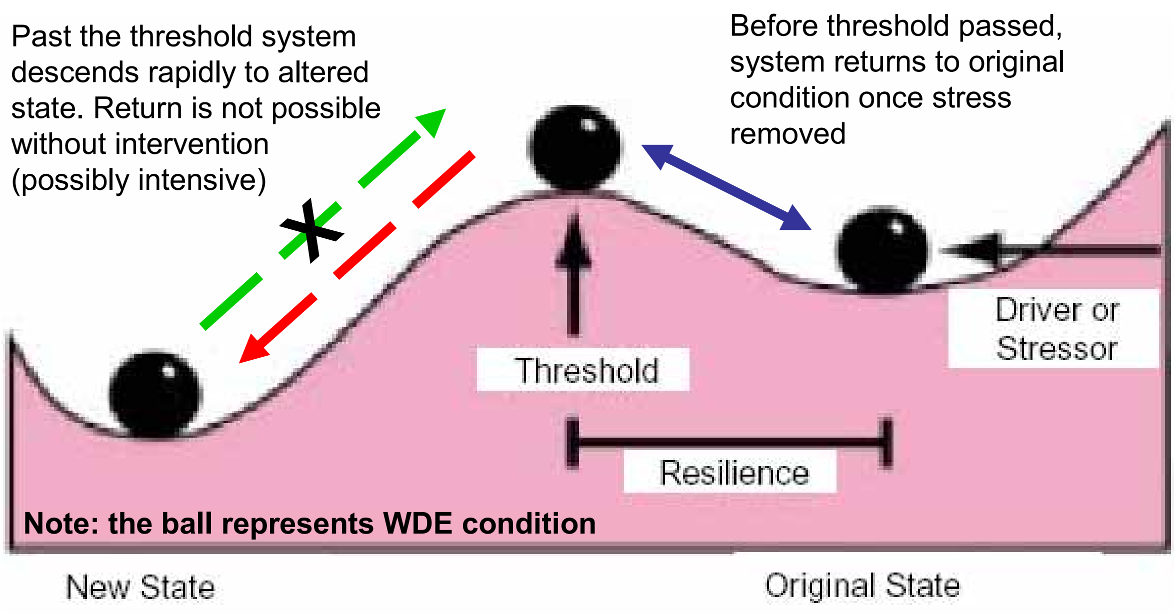


**Figure 15. Ball and cup schematic representation of state-and-transition (adapted from Cherwin and Perkins 2005).**

Evenden et al. (2002) points out the difficulty of linking indicators for end-point conditions in state-and-transition models. Indicators generally pertain to the condition of a particular state. The transition to a new or altered state is like having a different system to deal with, in which an indicator for the previous state may no longer be appropriate. For this reason there is a need for a control or mechanistic model of the existing state and the known or anticipated state after transition, from which potential suitable indicators can be selected.

Examples of a state-and-transition process relevant to WDEs include the invasion by, or introduction of, an exotic species that is in some way driving native species to extinction or marginalisation, thus permanently altering the structure and composition of the ecosystem. Another example would be the elevation of nutrient runoff driven by a land use change that results in the loss of susceptible invertebrate species. A state-and-transition model should be used to communicate transition states and would be used with more comprehensive control models to detail the processes and functions of the system in either state. This allows the practitioner to represent, for example, “State 1” that has these key components and operates in this way, versus “State 2”, which has these differing key components and operates in this way.

Scale issues are critical when considering state-and-transition models, especially spatial scales (issues of scale are addressed in the next section). Dramatic changes in ecosystem structure and composition may be present at the small scale, but at the larger scale little or no change may be apparent (Briske et al. 2003; Ryerson and Parmenter 2001). A more detailed discussion of state-and-transition models by Evenden et al (2002) is provided in Appendix 5.

Figure 16 is a fire-grazing state-and-transition model for a grassland ecosystem. While this model is not a WDE, it helps to illustrate the purpose and application of the state-and-transition representation, and may be applicable to wetlands where invasion by exotic plant species is an issue, or alternatively in systems where exotic fish species have displaced native species. The diagram shows three scenarios based on the degree of grazing and fire, or lack of fire. The model shows the transitions to new states associated with each impact and also demonstrates the irreversible nature of each transition. The long arrows returning to the initial undisturbed state are labelled with the management actions necessary to return the system to that condition. It is interesting to note that time itself is one of the factors shown in the model. Much habitat restoration requires time, patience and repetitive management actions to achieve a final recovery.

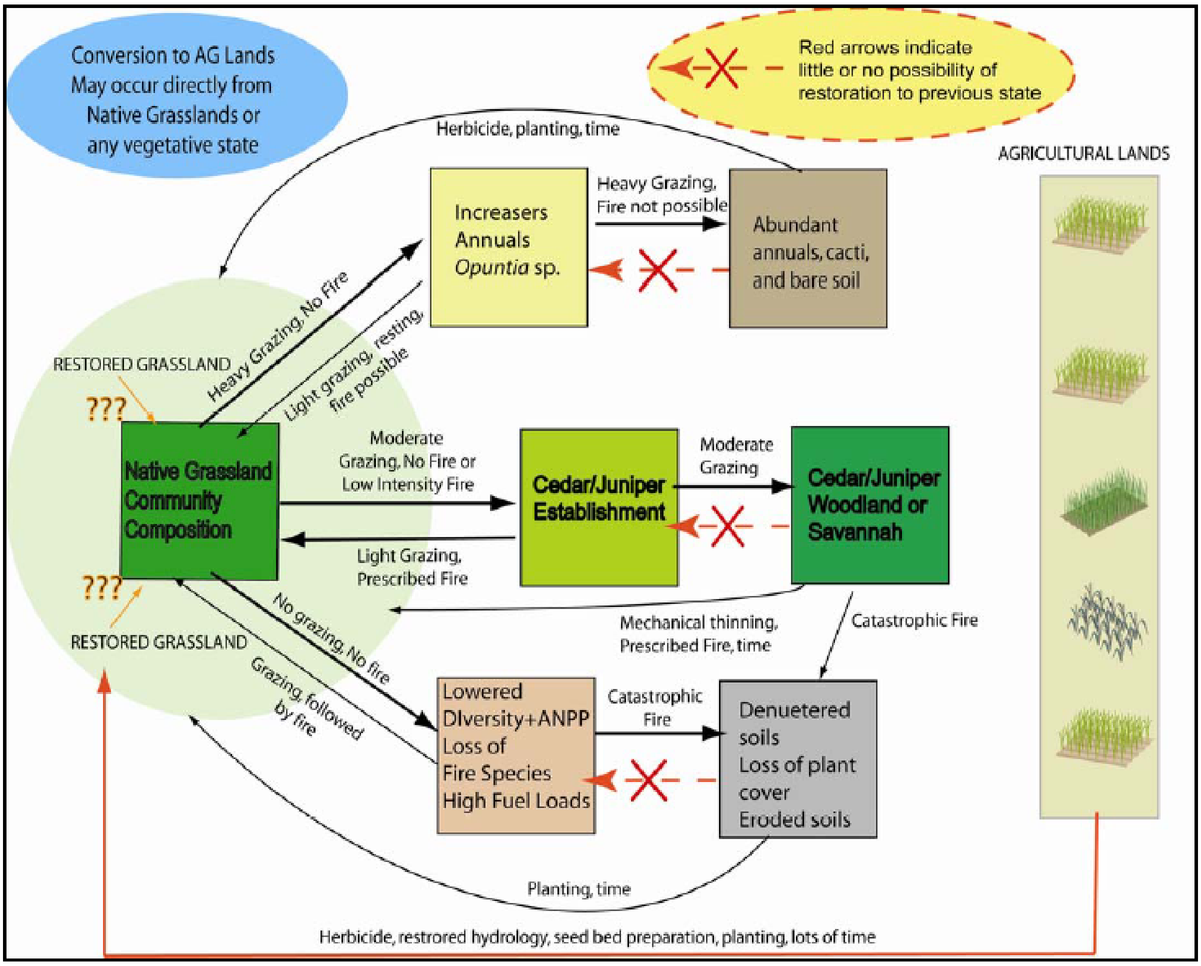


**Figure 16. Fire-grazing state-and-transition model (source: Tinker and Hild 2005).**

## *Representing issues of scale (Task 2.4)*

The first step of creating a conceptual model can be hampered by the challenge of encapsulating the complexity within the system and the spatial and temporal scales to be considered. If an over-arching theoretical framework can be identified, then the system can be decomposed into a series of less complex parts (Gross 2003). Table 9 lists a range of model scales and the information they can be expected to communicate.

**Table 9. Model scales and what they communicate (source: Gross 2005).**

| Model scale | What it communicates |
|---|---|
| General environmental model | Stage-setting; global and regional scale drivers and responses |
| Landscape-scale diagrams | Environmental gradients; broader scale drivers; linkages between systems (disturbances, land use) |
| Ecosystem | Dynamics; broad to fine scale factors |
| Species, site, or habitat | Detailed mechanisms and feedback, stressors to indicators |

This process is facilitated by Hierarchy Theory, which provides a strong theoretical basis for constructing a set of models that hold together in a coherent way (O'Neill et al. 1986; Allen & Hoekstra 1992). In Hierarchy Theory it is postulated that most complex ecosystems have both vertical and horizontal structure (e.g. Fig. 10) and that the system can be broken-down into a number of less complex parts. The vertical levels are characterised by different temporal and (usually) spatial scales (e.g. Fig. 8). The higher levels provide a context and constrain, or control, the lower levels, and the mechanisms and processes that explain observed patterns are contained in the lower levels (Gross 2003).

The Stommel diagram (developed by Stommel 1963) is a valuable tool for characterising the scales of complex ecosystem components in space and time, and has been applied in a wide range of ecosystem fields. These diagrams provide, at a glance, an impression of the time and space continuum (as seen by x and y axes, respectively) and the associated range of process dynamics and how these relate to one-another. For example, thunderstorms may be spatially extensive but are a short-term phenomenon, microbial processes are rapid and small-scale, lake mixing may be both long-term temporally and spatially extensive in a major system, and vegetation succession may take hundreds of years and cover a small to large range of area. The diagrams are not intended to provide any mechanistic linkages of system functions. Perry and Ommer (2003) apply the Stommel approach to fisheries and use the technique to map physical and biological processes, fishing operations and societal considerations (Fig. 17). Gunderson et al. (1995) use the approach to map a range of ecosystem drivers and processes.

Figure 18 presents time and space scale factors associated with an ecosystem response to a change in water quality. Here, unlike Figure 8, instead of looking at the individual processes or ecosystem components and where their spatial and temporal dynamics lie, the whole system is considered and the temporal progression at differing organisational levels is presented. This kind of diagram is useful because it can support arguments regarding the impact of transient water quality stresses and permanent changes in water quality. For example, a brief spike in water quality may have a short-term impact that does not alter the basic species composition of the system, whereas a long-term change in quality might be expected to ultimately result in changes in community structure and susceptible species are either lost or return to the system. In Figure 19 the flow-on effects of contaminant stress on ecosystem biotic components are presented, the diagram demonstrates the direction of effects represented in Figure 18, moving from the cellular level (bio-chemical effects), to increased physiological responses in terms of repair and maintenance, which impacts on the ability to grow and reproduce.

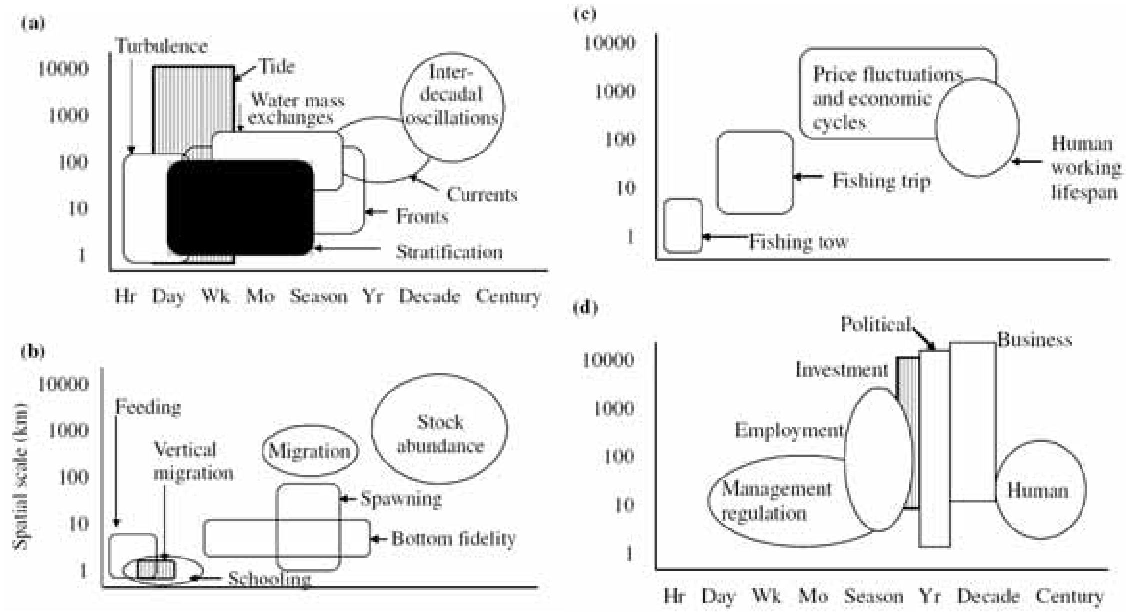


**Figure 17. Stommel diagrams representing a) physical, and b) biological processes, c) fishing operations, and d) societal considerations (source: Perry and Ommer 2003).**

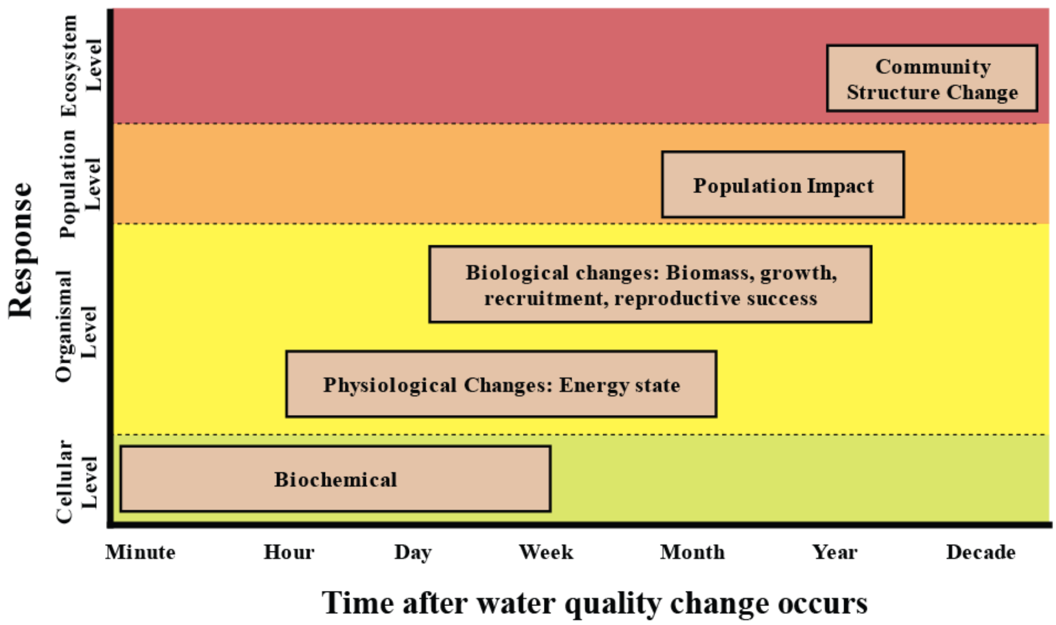


**Figure 18. Temporal and organisational scale impacts of water quality stressor impacts (source: Gross 2005).**

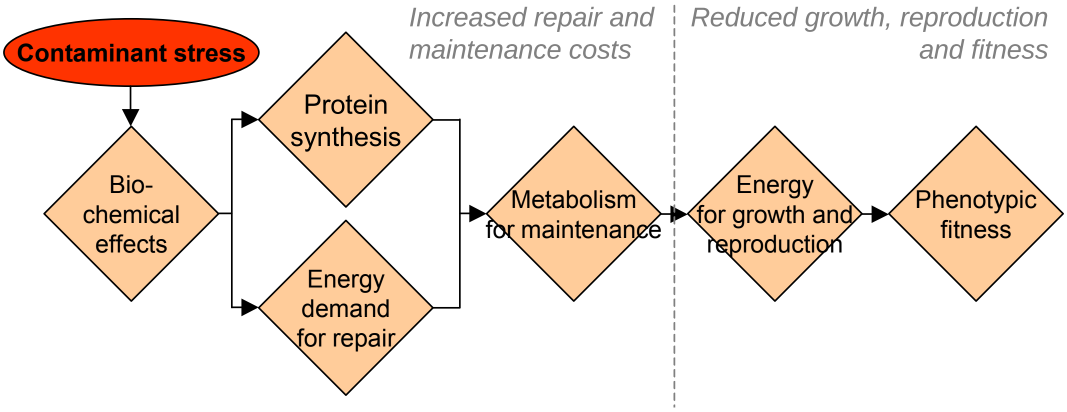


**Figure 19. Stressor impacts on ecosystem biotic components (adapted from material presented by Gross 2003).**

Once a model starts to enter the detail associated with organism functioning it is approaching the kind of detail that might be encountered in a control model, where the individual mechanisms, processes and feedbacks are represented.

## Constructing the conceptual model

To be effective, conceptual models must contain sufficient detail to represent processes that relate directly to attributes that might be included in a monitoring programme. Gross (2003) quotes Margoluis and Salafsky (1998) who, as he puts it, “elegantly summarise the goal of these models”;

> “*A good Conceptual Model does not attempt to explain all possible relationships or contain all possible factors that influence the target condition but instead tries to simplify reality by containing only the information most relevant to the model builder. One of the difficulties in building models is to include enough information to explain what influences the target condition without containing so much information that the most critical factors or relationships are hidden. Too much information can conceal important aspects of the model, while too little information in the model leads to oversimplification which in turn leads to a higher likelihood that the portrayal is not accurate.*"

Constructing a realistic set of conceptual models is an important starting point for designing effective monitoring programmes and for evaluating effective management strategies (Gross 2003). Monitoring programmes founded on solid conceptual models are more likely to identify key processes and indicators, and thereby contribute significantly to WDE management. The model should always be viewed as a work in progress and be subject to regular validation as part of the adaptive management cycle.

Inadequately understood, or controversial system/model components are invariably identified during the process of constructing a model. It can be insightful to investigate alternative approaches to represent a system, as this can help articulate important, and often mutually exclusive, hypotheses about drivers, stressors, or interactions that are key to understanding system function (Gross 2003).

In constructing a conceptual model, the need to keep it simple is a common catch-cry of practitioners. All-encompassing models will be too complicated for most people to follow, and a useful guide is to limit the content to that which will fit on one page (Gross 2003).

Plumb (2003) highlights the importance of identifying the intended outcomes of using the conceptual model and then employing basic guiding principles of relevance, reliability and censorship to devise a model or series of models that efficiently achieves the objective:

- *Relevance*: Conceptual abstraction must be relevant to audience and scale.
  - *Audience*: Is the purpose of the conceptual model is to inform, influence or both?
  - *Scale*: What spatial and temporal scales are of interest and relevant to the outcomes (a crucial point)?
- *Reliability*: Conceptual abstraction must be underpinned with reliable knowledge.
- *Censorship*: Conceptual abstraction must avoid over-simplification or over-sophistication.

The following set of tasks in constructing a conceptual model has been used by the US National Park Service (Gross 2003). These tasks form the basis of a systematic programme that leads to a set of conceptual models. This list offers an initial approach for the Framework, and the tasks can be adjusted or amended as experience grows within the State:

1. Clearly state the goals of the conceptual models.
2. Identify bounds of the system of interest.
3. Identify key model components, sub-systems and interactions.
4. Develop control models of key systems and sub-systems.
5. Identify natural and anthropogenic stressors.
6. Describe relationships of stressors, ecological factors and responses.
7. Articulate key questions or alternative approaches.
8. Identify an inclusive list of indicators (i.e. prioritise indicators).
9. Review, revise and refine models.

Tasks 3 and 4, and/or 5 and 6 will need to be answered at least partially simultaneously, and the order of the tasks may be determined by the starting point, i.e. based on what is already known it may not be necessary to complete each step in the list.

### *Stating the goals of the conceptual models.*

The relative importance of conceptual model goals will change over time and with the audience. Gross (2003) lists the following primary goals:

- Synthesize understanding of ecosystem dynamics.
- Provide a firm conceptual foundation for selecting vital signs indicators.
- Identify and illustrate relationships between vital signs indicators and key system processes and variables.
- Provide a clear means of illustrating major sub-systems, system components and their interactions.
- Facilitate communication on system dynamics and the vital signs monitoring programme among practitioners, managers, technical and non-technical audiences.

Other goals that Gross (2003) suggests include:

- Identify areas where knowledge is inadequate and further research is needed.
- Describe and illustrate alternative hypotheses about key processes or system dynamics.
- Provide management staff with models of sensitive habitat types to support management decisions.
- Develop models to support management of species of concern (an exotic taxon, threatened and endangered species, keystone species, etc.).

Given the possibility of having numerous goals for conceptual models, a way of gaining focus in developing your model might be to consider immediate and long-term goals separately (Gross 2003).

### *Identifying the bounds of your system and key sub-systems*

A key output of this step is an initial assessment of system bounds. These are essential to constrain the model domain (Gross 2003):

- Establish a common vision of the spatial and temporal bounds, and relevant system components.
- Go top-down: Start with the “big-picture” and work down as required.
- What are the major sub-systems and processes to be represented?
- Are there dominant ecological processes that require separate sub-models?
- What is the physical space that encompasses all of the key processes, and what are the time-scales that must be considered?

For example, in relation to this last point, fringing GDE wetlands along the margins of the GAB are a part of the GAB. However, when looking at an individual spring, the supply of water from the GAB system is an external driver and outside the scope of the model. The local wetland boundaries represent the spatial bounds of the individual system, but the temporal characteristics of water movement from within the GAB strongly determine the time scale of the wetland water dependence.

In a much broader sense, Gross (2003) highlights the impact of very large-scale factors (global influences), these are also clearly drivers beyond the bounds of the ecosystem and would be treated as model inputs, and at shorter time-scales could be treated as constants for the purposes of simplification.

### *Developing the control model of key systems and sub-systems*

This is a key task requiring a consideration of a wide range of ecosystem processes, temporal and spatial scales, and disciplines.

> “*An important function of the control model is to provide explicit, mechanistic links between system components and processes. It is difficult to justify a choice of indicator or evaluate the quality of data without an explicit understanding of the mechanisms that link indicators to the trait of interest*” (Gross 2003).

Approaches to developing a control model may vary: some workers may prefer a top-down approach which provides a very aggregated model, encompassing the whole system, and then investigate sub-systems; others may prefer to work from a known sub-system structure and work upwards to an overview. The time-scale associated with the M&E objective, as well as the spatial scale relevant to the system, will also be important considerations when deciding on an approach. For example, if your objective is to monitor the impact of runoff from agricultural land on an endemic species in a nearby wetland, the focus may be less on long-term global drivers, but more on daily or even hourly variation, and it may be necessary to consider event-based functioning as well as the general impact of say, elevated nutrient levels and turbidity. Consequently, the bounds of your aggregated “umbrella” control model would be associated with processes operating over periods of weeks or months, and you would have a sub-system model that dealt with event based processes resulting from oxygen lag, pH depression, extreme turbidity etc.

Alternatively, if studying a major system where the M&E objective was to determine the impact of increased salinity on riparian vegetation, the time and spatial scales for the aggregated model are clearly much larger. In this case, time would be measured in months and the driving variables would be associated with weather and climate (rainfall, evaporation, temperature and solar radiation), or river condition (flow, level, conductivity etc.). The sub-system models may then account for the daily or weekly variations in physiological response of the target vegetation to the drivers/stressors, and there may be threshold conditions that result in sudden impacts that are irreversible in the short-term. In this case a state-and-transition model is appropriate. So although, in general, the net (longer-term) condition of your system might be represented by the aggregated variation in drivers/stressors, there may be critical short-term mechanisms that cause sudden detrimental results.

### Advice on constructing your model

Gross (2005) has many useful points to make regarding constructing conceptual models:

- First of all: **avoid reinventing the wheel**; review the literature (is the system already represented out there?).
- Evaluate your model needs.
  - What is the main purpose for the model?
  - What aspects of the vital sign are important?
  - What important system dynamics do you want to accommodate?
  - Are there key linkages between objectives that you want to articulate?
- Select the model structure for the purpose. Avoid a ‘one size fits all’ philosophy.
- Construct needs-specific models rather than monolithic structures.
- Is there a clear connection between the models and vital signs? If not, are the models or vital signs inadequate?
- Hierarchically structured sets of models have advantages:
  - the holistic model provides regional/global context
  - there is a systematic means to add detail as needed
  - linkages within the model are obvious
- Expect differences of opinion on driving variables, ecosystem functioning, feedbacks and responses.
- Expect to identify knowledge gaps. Expect the unexpected!
- Avoid being too attached to a particular view of how the system functions.
- This is an adaptive process; the model is a working hypothesis, reassess and rework as needed.

- Craft is important. Rushing the final step is like letting a child finish fine furniture.
- Simplicity is a virtue, and a serious challenge.
- Remember that models are a tool to facilitate communication.

### *Building mechanistically correct models:*

Some definitions of model components (based on Grant et al. 1997; Gross 2003 and others):

- **State variable** — elements of accumulation of resources/energy/materials within a system (e.g. nitrogen concentration, algal biomass, numbers of invertebrates). If it is an internal condition of the ecosystem, it has a value; it could be a population size, a mass of chemical or biomass, a volume of water, or a quantity of energy. State variables change over time according to the balance of factors that result in their increase or decrease in size.
- **Auxiliary variable** — arising from model calculations and represent explicit (and usually internal) model functions.
- **Driver (a driving variable)** — external factors that influence a system condition (e.g. solar radiation). They are not affected by the rest of the system. They are expressed as a variable and by increasing or decreasing they influence the movement of materials, energy or numbers to/from the system. Hence, drivers may result in inputs or outputs.
- **Rate of transfer (includes; inputs/outputs/losses/sinks/feedback)** — movements (or material transfers) of numbers, mass, volume or quantity of energy that raise or lower the value of the "state variable". They are a rate because they represent the movement (or change) over time. These are the sinks and feedbacks within the system, between ecosystem components, the inputs from driving variables and the losses to links within or outside of the system.
- **Constant** — do not vary (under the assumptions of the conceptual model) and are a conversion factor associated with a transfer between variables of differing nature (e.g. sunlight to biomass).
- **Stressor** — Barrett et al. (1976) offer the following definition of stress: "*Stress is defined here as a perturbation (stressor) applied to a system (a) which is foreign to that system or (b) which is natural to that system but applied at an excessive [or deficient] level.*" Therefore a stressor is the disturbance that causes the stress that affects ecological components, patterns and relationships, and may act directly or indirectly (e.g. elevated temperature can cause stress directly, or the indirect consequential reduction in dissolved oxygen also causes stress).
- **Input** — a flow (i.e. rate), or movement of numbers, materials or energy. Inputs may be driven by drivers.
- **Output** — a flow (rate), movement outside the boundaries of the system.
- **Loss** — flow of material, energy or numbers are lost (they effectively disappear, e.g. death)
- **Sink** — is a store or accumulation within a system to which material, energy or numbers are removed (the removal may be temporary or conditional, e.g. energy stored in roots, or sediment settled from a stream; the energy or material may return and become active within the system under certain conditions).
- **Feedback** — is a transfer of numbers, material or energy arising from a state variable that contributes directly or indirectly to (itself) the state-variable. For example, in a **positive feedback** in climate science, increased $CO_2$ concentration raises temperature

which leads to melting of permafrost. Melting of permafrost releases stored $CO_2$ and methane which further increases heat retention, accelerating melting. A **negative feedback** mechanism in a predator-prey system (with a New Zealand context), tree seeding leads to explosion in rodent numbers, which in-turn increases mustelid numbers, which reduce rodent numbers, which supports fewer mustelids.

## Steps for building a control model

- **Identify**
  - Ecosystem components and processes.
  - State variables (population size, N, C, etc).
  - Major system drivers and inputs (this is the top tier of the hierarchy).
  - Outputs, sinks and losses.
- **Organise**
  - Separate external drivers, sources and sinks from internal variables.
  - Place the drivers at the top of the page and work down.
  - Identify the system "stressors".
  - Consider flows of information, energy/material.
  - Generate sub-models for each ecosystem component and process.
- **Connect**
  - Link drivers to stressors and to each sub-model.
  - Cross-link sub-models (if required – when considering multiple sub-model interactions).
  - Consider known responses to stressors and link from sub-models.
  - Identify response indicators (vital signs) and link to the appropriate sub-model (specifically for control models).
  - Connect the state variables ("rates" link variables).
  - Feedbacks are from state variables to rates, not rates to rates.
  - Think about functional form of relationships.
- **Summarise**
  - Write a brief summary, narrative, of the system function, write narratives for each of the sub-models (this will provide a logical check on whether the model makes sense).

## Reviewing the conceptual model

### *Model review questions*

The following questions (adapted from Gross 2003) provide a cross-check for reviewing model utility:

- Have the WDE components of concern been identified?
- Have the conceptual models effectively helped organise, summarise and communicate complex information (on the WDE)?
- Are the conceptual models sufficiently detailed to assist in selecting, justifying and interpreting potential ecosystem health indicators?
- Are the tables and figures, and the supporting narrative, clear, complete and understandable?

- Is relevant literature cited; do citations provide valid, credible and sufficient scientific justification for the models?
- Is the treatment and presentation of conceptual models systematic and integrative such that interactions within and linkages among ecosystem components are described?

A further set of questions, that are helpful in assessing whether conceptual models are adequate and link appropriately with monitoring objectives and stressors (adapted from Thomas et al. 2001 and others), are provided below:

- For this monitoring objective, is the primary interest in; biotic resource condition (retrospective monitoring), changes in stressor levels, or are both types of information needed?
- Is it necessary to distinguish the effects of particular stressors, or is the focus on the resource response to multiple stressors?
- Does the conceptual model suggest anticipatory indicators that may help to predict effects before they occur?
- Does the conceptual model help identify environmental information necessary to differentiate natural variability from stressor effects?
- Does the conceptual model suggest fundamental structural aspects of the ecosystem that may be useful in meeting several monitoring objectives?
- Does the conceptual model illustrate the potential influence of management interventions?

## Examples of conceptual models

A wide range of additional conceptual model examples are provided below. These can be used as a guide or template for ideas when developing models for South Australian WDEs. For the Coorong models, example sub-models have been modified using the symbology presented in the Framework (Fig. 7). This demonstrates the utility of using a system of symbols in facilitating model clarity.

### *Tide-dominated estuary: nutrient dynamics (conceptual diagram and narrative)*

Ryan et al. (2003) present a series of conceptual diagrams for Australian coastal and estuarine systems. The example presented below is for nutrient dynamics in a tide-dominated estuary (Fig. 20). A detailed and well referenced narrative is provided for each numbered feature.

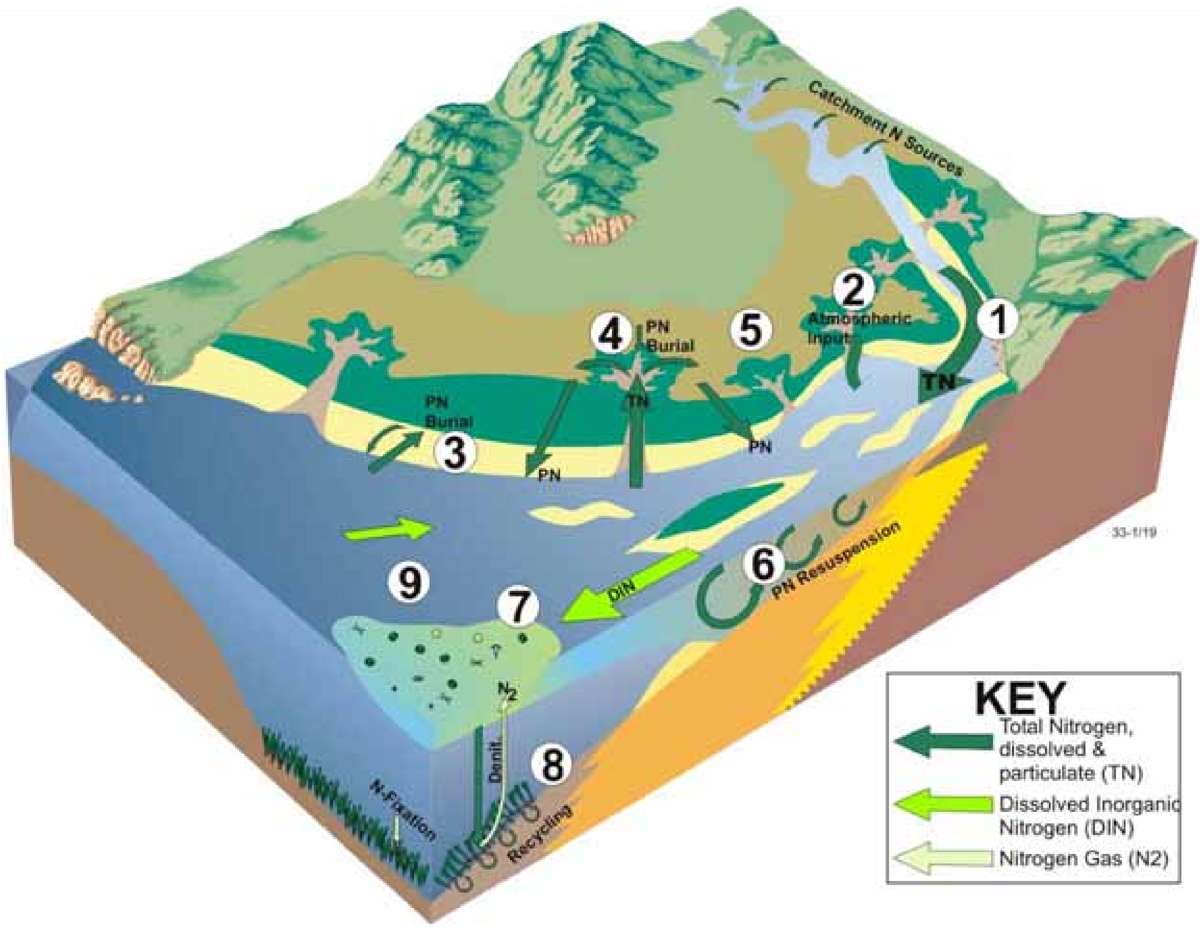


**Figure 20. Nutrient dynamics of a tide-dominated estuarine system in Australia (Ryan et al. 2003).**

Narrative:

1. Nitrogen (both particulate and dissolved, or total nitrogen (TN)) enters the estuarine system from point and non-point sources within the catchment. River flow and nutrient input varies regionally, depending on local catchment and climatic conditions. However, the input of catchment-derived nutrients into estuaries and deltas is typically high (Harris 2001).
2. Input of particulate N (PN) from atmospheric sources such as smoke and ash is significant in some tide-dominated estuaries.
3. Large tidal movements on the flanks of the estuary transport particulate nitrogen (PN) and dissolved inorganic nitrogen (DIN) onto the intertidal flats (Alongi et al. 1999), where some of the dissolved inorganic nitrogen (DIN) is converted to particulate nitrogen (PN) through the activity of benthic micro-algae and other sediment-dwelling organisms.
4. Mangrove sediment is a net sink for dissolved inorganic nitrogen (DIN), and particulate nitrogen (PN) (Alongi 1996). Nutrient uptake is driven by high rates of plant productivity and microbial activity. N-fixation (incorporation of atmospheric N2 to form nitrogenous organic compounds) is active in the root-zone and contributes to the dissolved inorganic nitrogen (DIN) pool (Kristensen et al. 1998). Some N is liberated to the atmosphere as N2 gas through denitrification (Rivera-Monroy & Twilley 1996; Trott et al. 2000). Particulate nitrogen (PN) is typically processed by sediment-dwelling biota such as crabs, or is exported to the coastal waters in the form of leaf litter and fine particulate

matter (Ayukai et al. 1998). This material is redistributed during ebb tides and may be exported from the estuary.

5. Small amounts of particulate nitrogen (PN) are buried in saltflats during king tides. Most particulate nitrogen (PN) is exported back into the estuarine system during the ebb tide (Ridd et al. 1988).
6. Particulate nitrogen (PN) and dissolved inorganic nitrogen (DIN) exist within the water column. However, due to turbidity and low light penetration, phytoplankton productivity is limited (Cloern 1987; Monbet 1992). Circulation and re-suspension of particulate nitrogen (PN) occurs in this zone. Particulate nitrogen (PN) is probably reworked during the resuspension process, and dissolved inorganic nitrogen (DIN) can be released into the water column through the process of remineralisation.
7. A proportion of the dissolved inorganic nitrogen (DIN) reaches the less turbid zone at the mouth of the estuary. The nitrogen exported into the ocean is typically assimilated by marine phytoplankton, and converted into particulate nitrogen (PN).
8. Seagrasses, which colonise the tidal sand banks near the mouth of the estuary, may also process nitrogen that has been exported from within the estuary. Denitrification may also occur here (Moriarty & O'Donohue 1993; Pollard et al. 1991).
9. Typically, moderate quantities of nitrogen are exported to the marine environment, due to the large exchange of seawater and lack of a constricted entrance. Export is more significant during extreme flood events, when large quantities of total nitrogen (TN) and other organic material are moved offshore.

### Conceptual model showing sphere of potential management influence

Figure 21 is another conceptual model with a coastal theme. It is presented because it shows, and attempts to demonstrate, the reach of the potential management influence of (in this case) the US National Parks Service. An indication of what can be directly or indirectly managed is a valuable piece of information as it provides a reality check to what might be done, and assists in setting SMART management objectives that provide realistic and achievable goals, rather than wasting effort in fruitless areas. While this may be obvious, it is a further cross-check in terms of what can be done.

In Figure 21, the green shaded areas are within the sphere of influence of the US National Parks Service, either through direct action, or indirectly by influencing other authorities and decision makers outside of NPS jurisdictional boundaries (Brown et al. 2006). Areas in grey are outside of the NPS managerial ability to influence. Prominent agents of change are represented by rectangles. Major components of the ecosystem are represented by circles and vital signs by light blue rectangles. The stressors (agents of change) are linked to the entire ecosystem by the large pink arrows. The stressors or resources/attributes that are managed by NPS lie within the darkest green area (Brown et al. 2006).

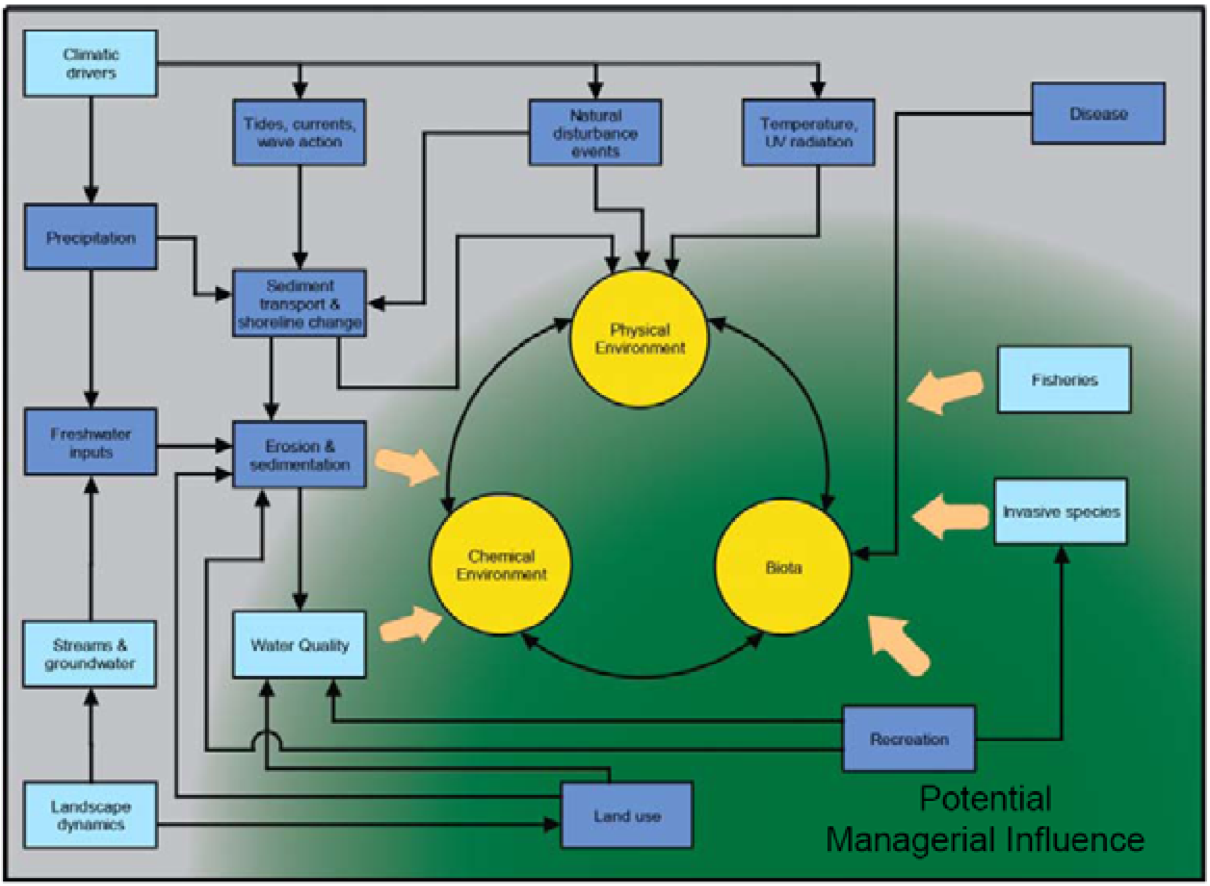


**Figure 21. Conceptual model of ecosystem dynamics in near-shore marine ecosystems of PACN parks highlighting areas under the NPS sphere of managerial influence (Source: Brown et al. 2006).**

## The Coorong and Lower Lakes models

A selection of the conceptual models developed for the Coorong and Lower Lakes Management Plan (MDBC 2005) are presented below.

Figure 22 is the overview model for the functioning of the Coorong system. It provides an overview of the main features, components and driving variables associated with various sub-models (e.g. Figs 23–26). This is an example of a case where the authors might have appreciated more time to create an accessible model that effectively communicated the system functioning. The diagram presents a collection of similar boxes that are not arranged in a logical structure, and multitude of arrows that point backwards and forwards. With the guidelines and examples in this report it is possible to see how this model might be presented more effectively by using the symbology (Fig. 7), the hierarchical flow-down structure and, in this case, where two states are represented (i.e. “mouth-open” and “mouth-closed”) a state-and-transition model might be of value.

The Coorong overarching model focuses on drivers and major sub-systems; for example, the system is driven by wind and tides (and freshwater input) and influenced by management of dredging and barrage control, which contribute to the variability in movements of water in and out of the system. The sub-systems for *Ruppia*, fish spawning, mudflats and waders, and invertebrates are too complicated to incorporate in the diagram of the overarching model.

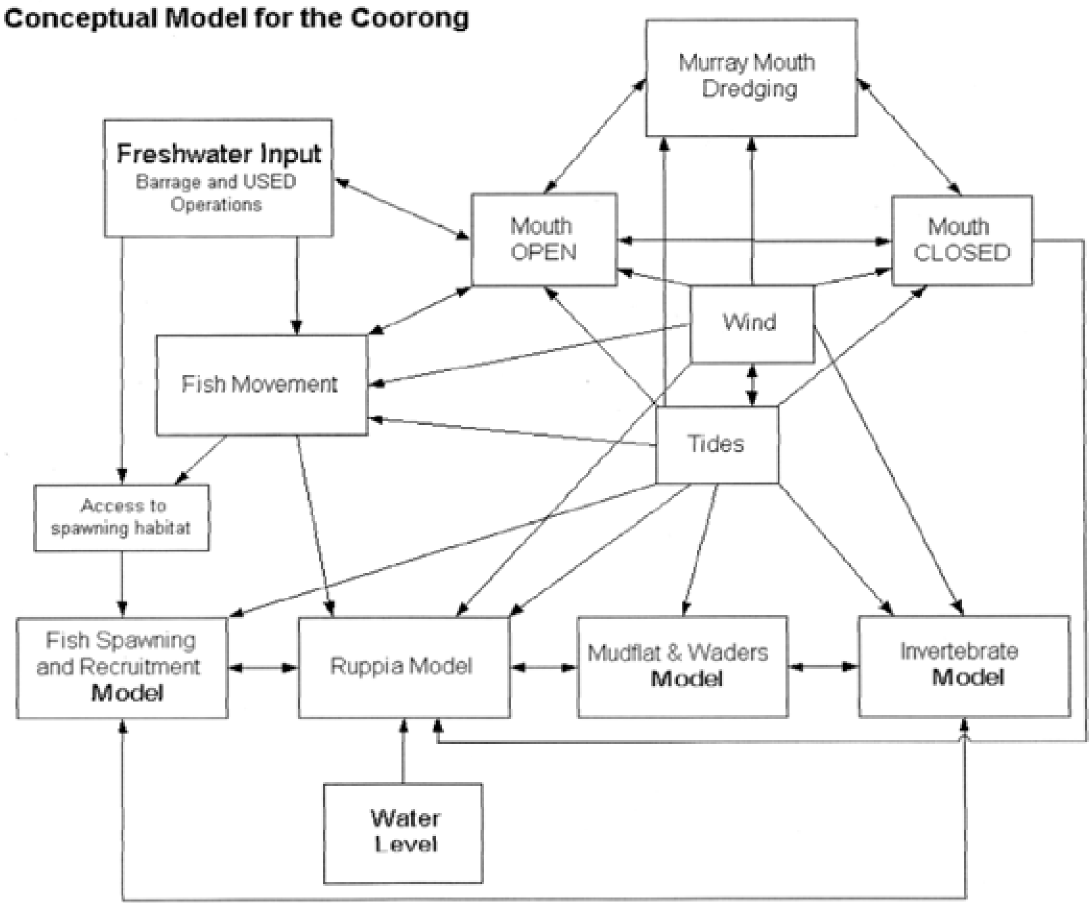


**Figure 22. Overview conceptual model for the Coorong (source: MDBC 2005).**

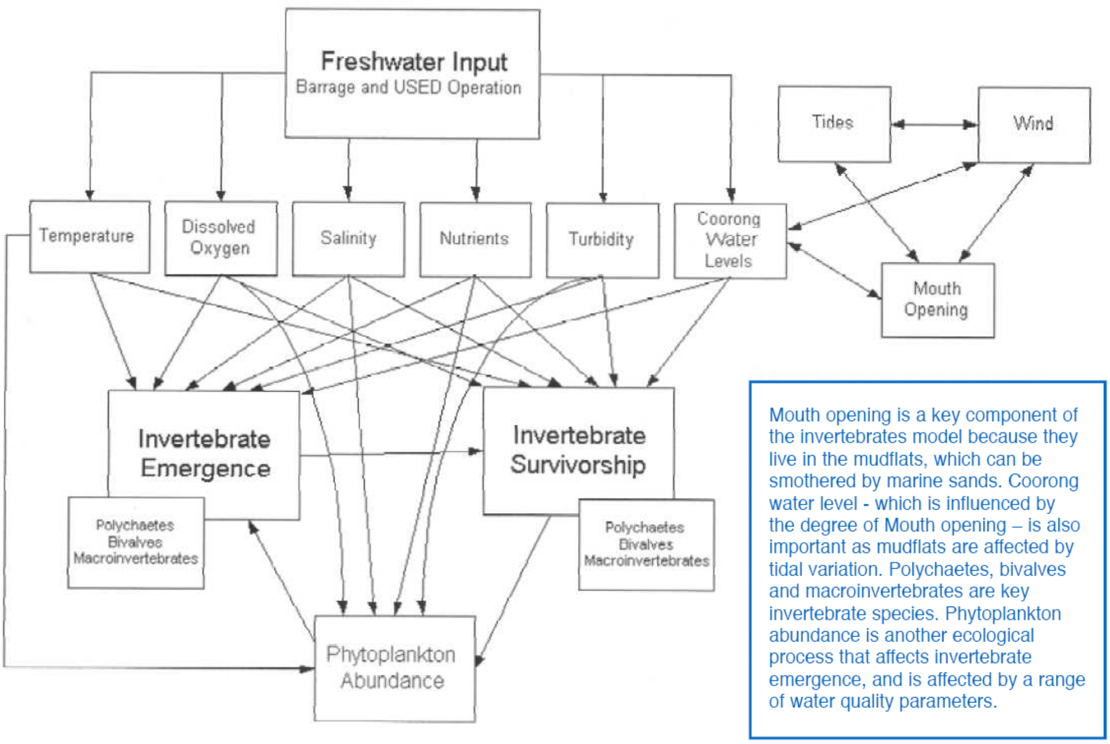


**Figure 23. Invertebrate sub-model for the Coorong (source: MDBC 2005).**

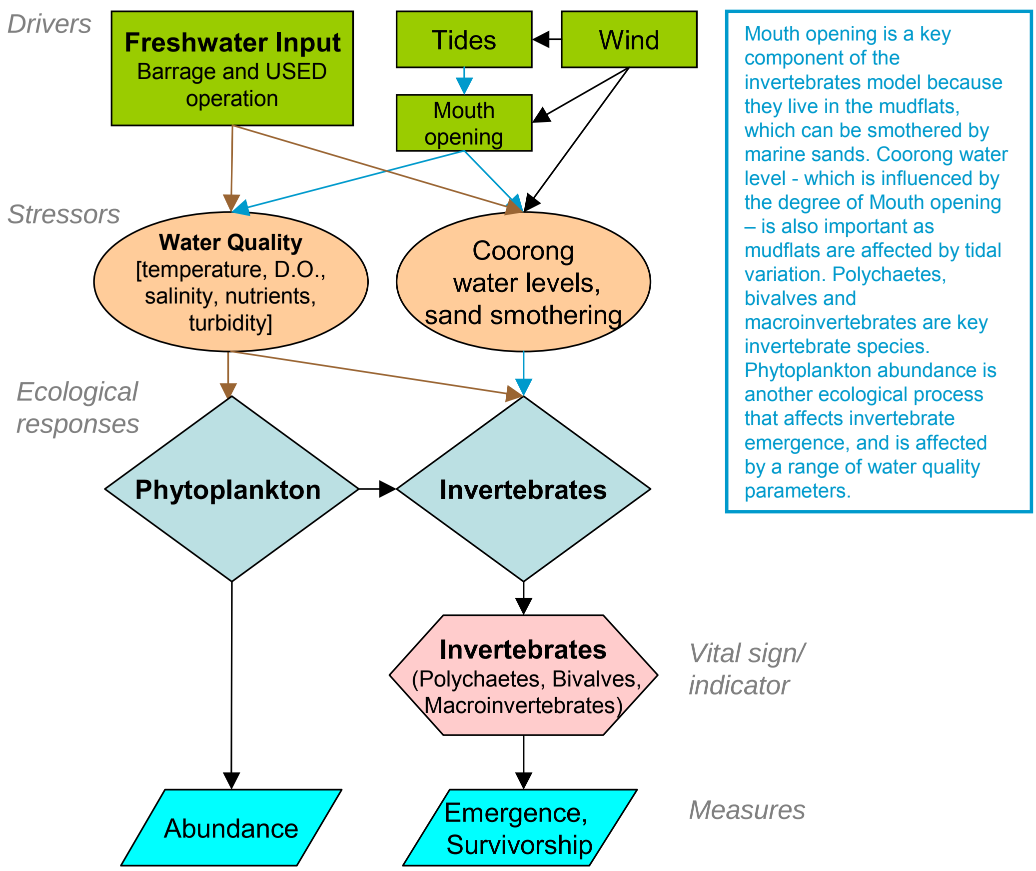


**Figure 24. Invertebrate sub-model for the Coorong using symbology and hierarchical structure as per Figure 7 (adapted from MDBC 2005).**

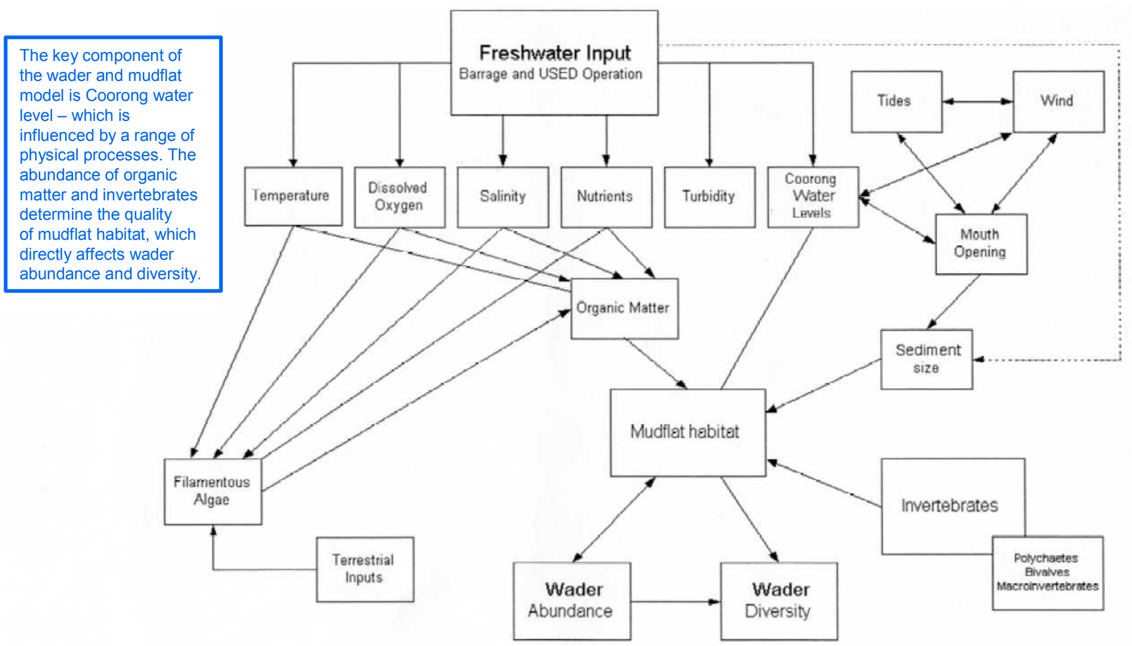


**Figure 25. Wader and mudflat sub-model for the Coorong (source: MDBC 2005).**

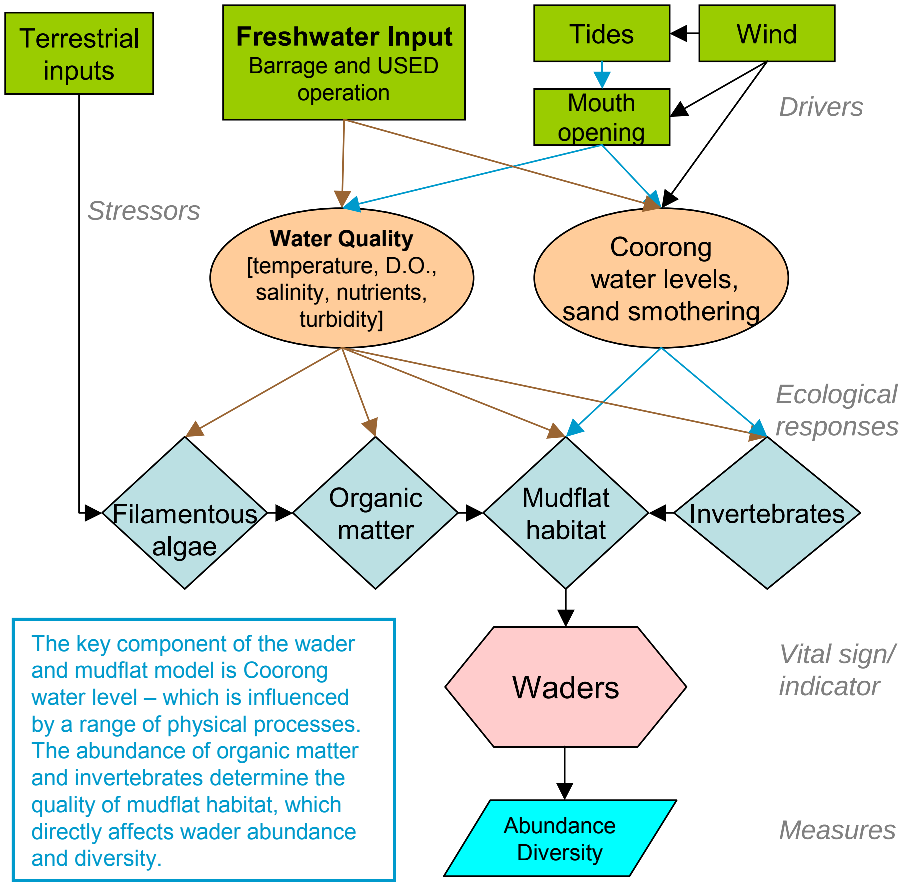


**Figure 26. Wader and mudflat sub-model for the Coorong system using symbology and hierarchical structure as per Figure 7 (adapted from MDBC 2005).**

These original sub-models (Figs 23–25) do not use the system of boxes presented above (Fig. 7), although the nature of each component can be discerned from the text within, the diagrams have to be studied carefully to pick-up what is intended. By rearranging, simplifying (i.e. lumping related factors together, such as the water quality parameters), adopting the hierarchical structure, and symbology, it is possible to eliminate many boxes and arrows, and using colour to produce a more immediate and accessible representation of the systems (Figs 24–26). The use of coloured arrows makes it easier to see where arrows are coming from and going to, in this case brown arrows for river water entering the system, and blue arrows for seawater.

## US National Parks Service models

The conceptual diagrams and conceptual models devised for the US Southern Plains Inventory and Monitoring Network (SOPN) provide useful examples of workshopped conceptual models that may be helpful in guiding South Australian practitioners when preparing conceptual models as a tool and basis for devising and updating monitoring and evaluation programmes for WDEs. Additional sub-models are also presented that focus on habitat loss and fragmentation.

Figure 10 provides an overview of the general conceptual model developed for US Southern Plains wetlands as reported in Perkins et al. (2005). Figures 27–30 present a general stream or creek overview conceptual model and sub-models. These flow diagram type models use three types of boxes to indicate drivers (rectangular), state variables or ecosystem components (octagonal) and stressors represented by ovals. At the top of the overarching model (Fig. 27) are regional, climatic and atmospheric drivers directly driving watershed, riparian and in-stream characteristics, of habitat and aquatic biota. The stressors (labelled here as disturbance regimes) impact the water quality as well as the other external factors. Figures 28–29 present examples of sub-models associated with the overview model presented in Figure 27. These sub-models (not all presented here) deal with the impacts of various specific drivers and stressors such as fire, drought, in-stream vehicle driving and adverse land management activities. The arrows used in these models indicate the direction of causality. Increases are denoted by a thick up-arrow and decreases by a thick down-arrow. This provides a rapid visual indication to the model viewer and aids understanding. These sub-models tend to concentrate on changes in flow and sediment load and the impact of algal populations, invertebrate communities and fish.

Figure 30 approaches the stream system from a different perspective. This sub-model provides a representation of the relationships between the physical and biological components of the system. This sub-model represents the various system components and the arrow linkages between the components demonstrate the flows of materials or energy, and what one component of the system provides to the others. For example, the riparian wetlands provide resources and habitat to macroinvertebrates. The water quality influences macroinvertebrates as a consequence of temperature, oxygen and toxins. Solar radiation provides energy that produces organic matter, which in turn delivers energy to macro-invertebrates, etc.

In addition to the generalised flow-diagram type models presented by the US National Parks Service, the pictorial model or conceptual diagram approach developed by Bill Dennison has also been adopted (see also Task 2.1), Figure 31 provides an example. This visual pictorial type of conceptual diagram is the same as those used in the South Eastern Queensland EHMP, introduced in Wilkinson et al. (2006). A general landscape schematic is developed, upon which pictograms of each ecosystem component; drivers, stressors and ecological responses are superimposed. The general direction of causality is indicated by linking arrows. A comprehensive key presents each model component and a concise narrative on the process/function relevance, or importance of that component. These are top level simplistic diagrams that both communicate system structure and give an accessible overview of the system. In terms of the subjects of the content, these diagrams are not of direct relevance to the South Australian situation however, it can be seen that with adjustments to the pictograms they are readily adaptable. The models are self-contained and self-explanatory and a brief examination of each one is recommended.

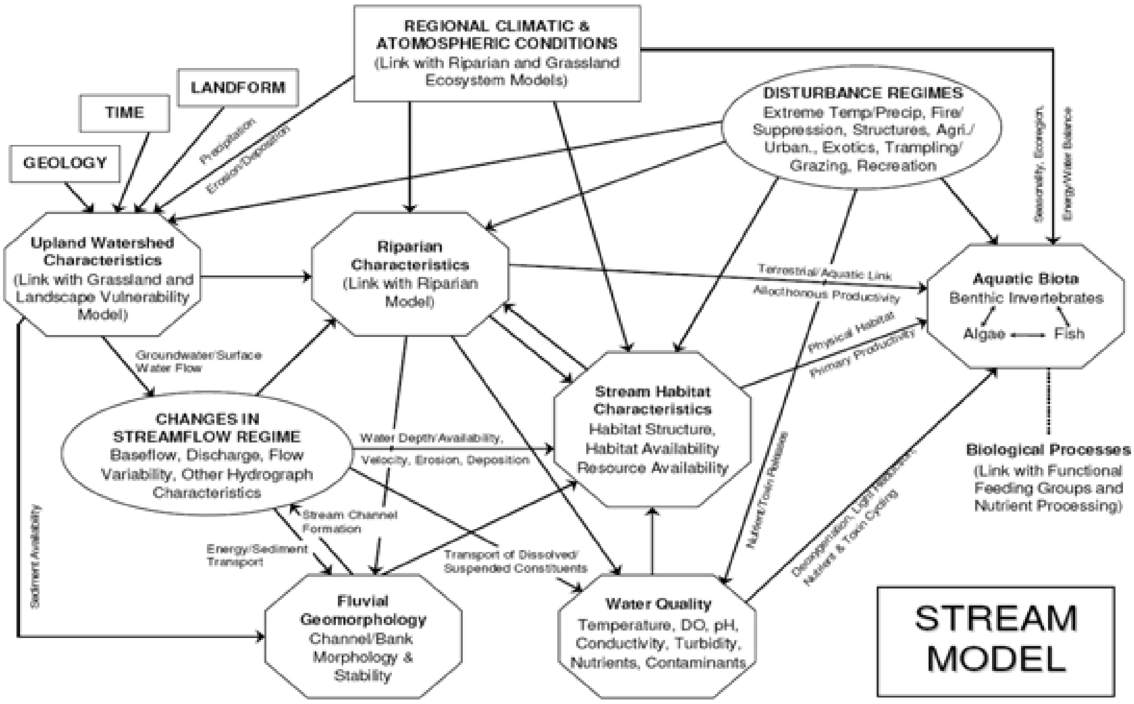


**Figure 27. General stream conceptual model of the SOPN study (source: Perkins et al. 2005).**

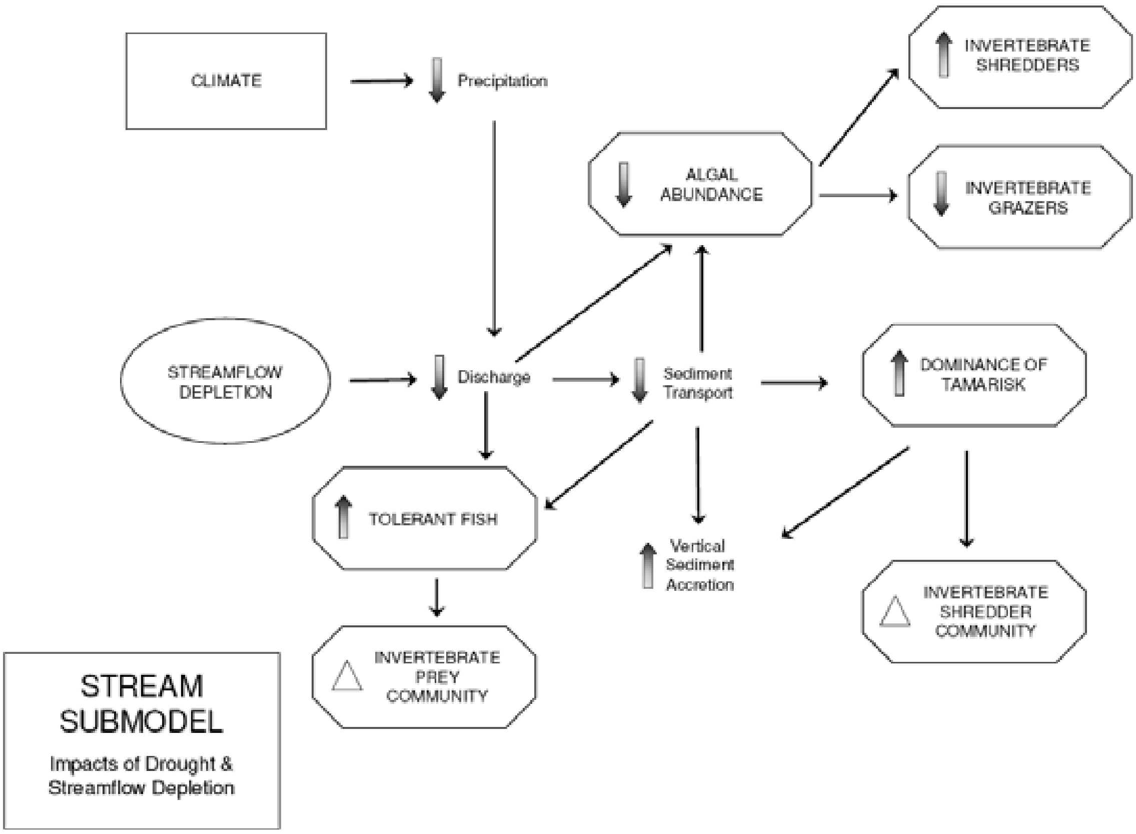


**Figure 28. Stream sub-model focussing on impacts of drought and stream-flow depletion (Note: up-arrows denote increase; down-arrows denote decrease; and the symbol Δ means change-in) (source: Perkins et al. 2005).**

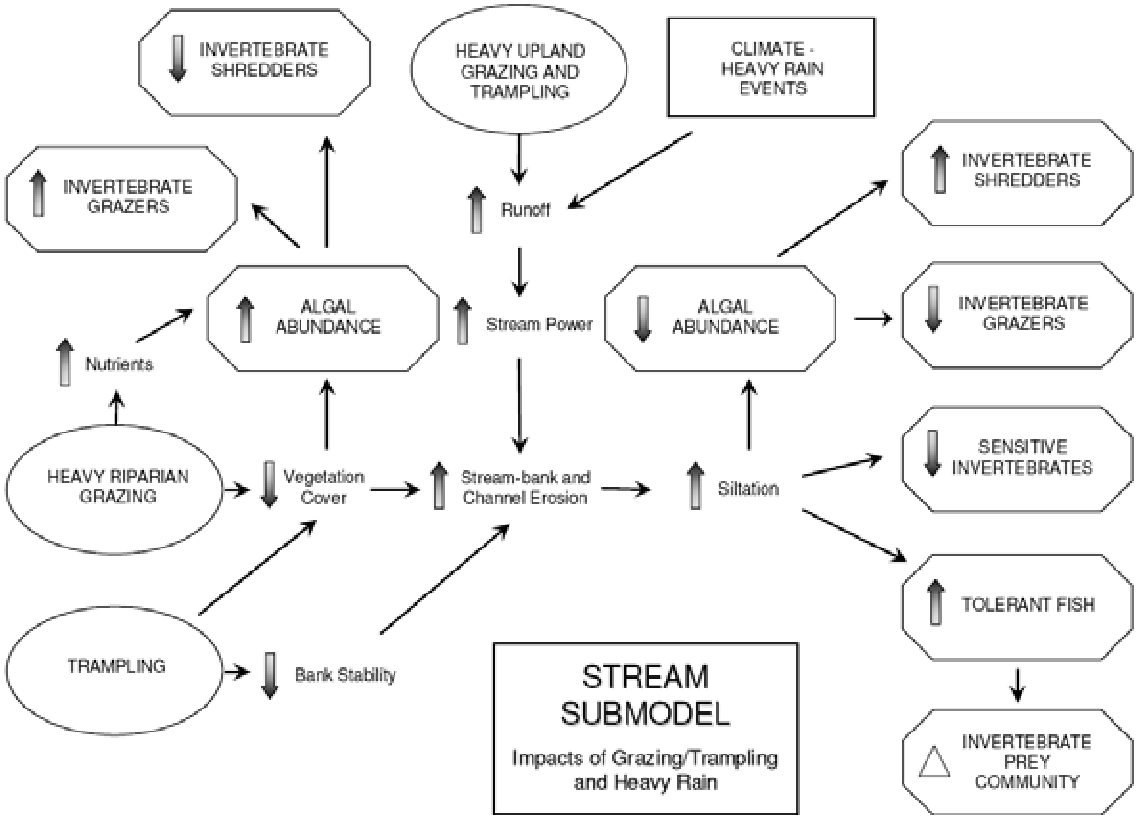


**Figure 29. Stream sub-model focussing on the impact of grazing, trampling and heavy rain (Note: up-arrows denote increase; down-arrows denote decrease; and the symbol Δ means change-in) (source: Perkins et al. 2005).**

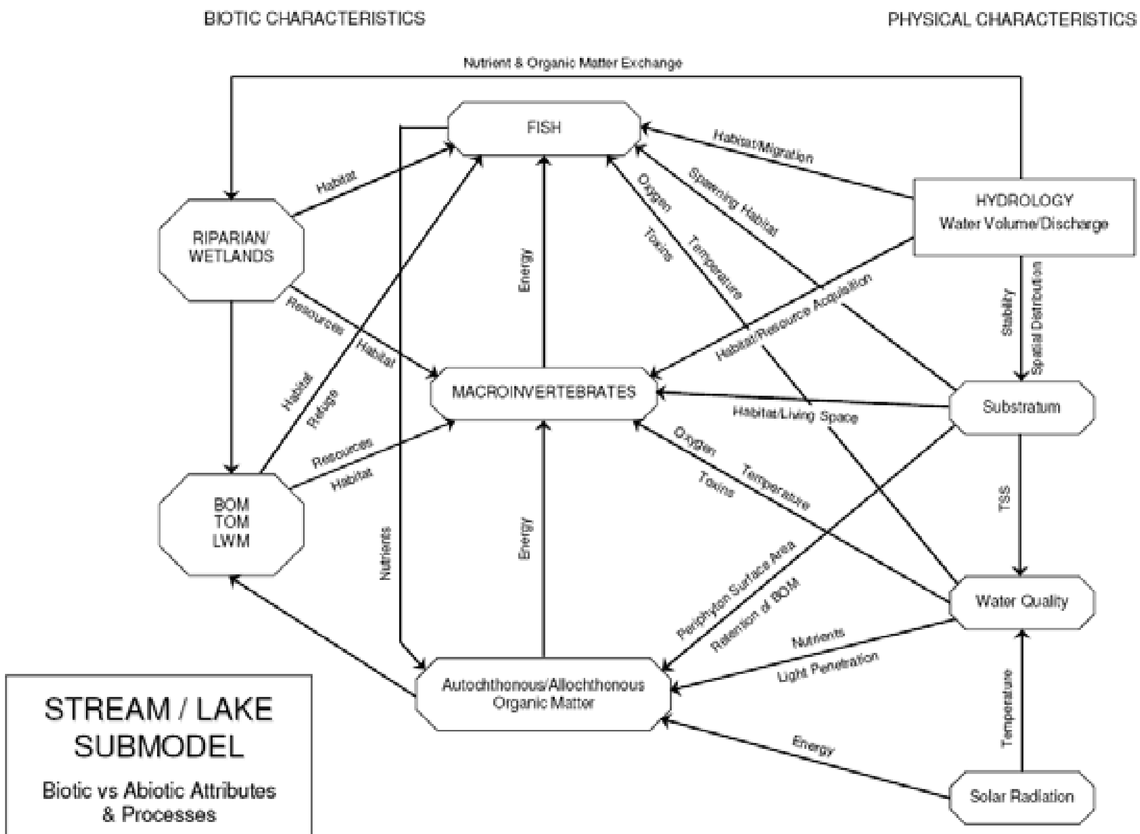


**Figure 30. Stream/lake sub-model representing the relationships between physical and biological components of the system (source: Perkins et al. 2005).**

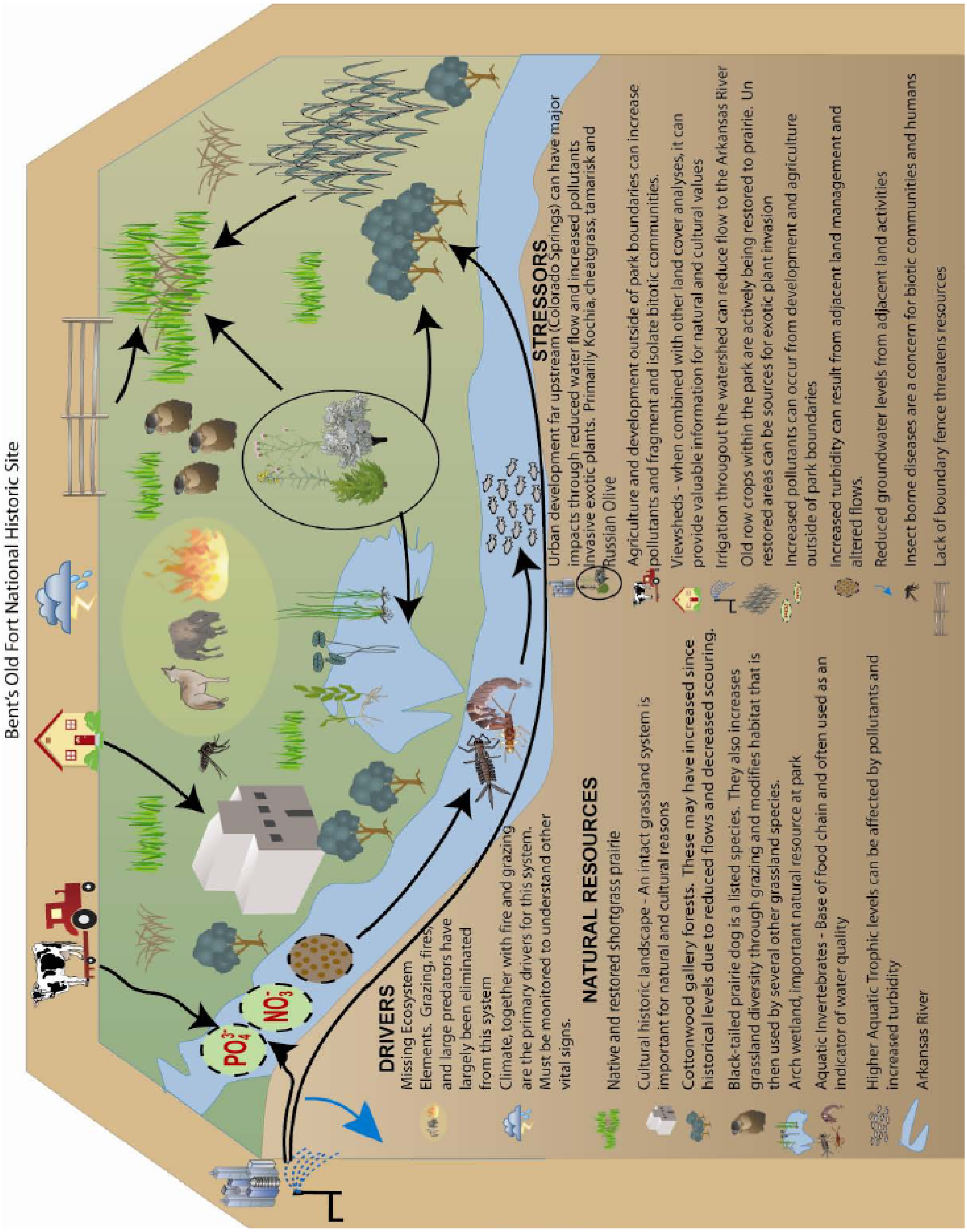


**Figure 31. Riverine conceptual diagram with wetland, showing whole of ecosystem processes; biotic and abiotic, and including key with narrative on drivers, natural resources and stressors (source: Perkins et al. 2005).**

## Conceptual models for habitat fragmentation and loss of unique habitat

Figures 32 and 33 provide example models for habitat fragmentation and loss of unique habitat. These models have been included as they have general relevance to conservation, and act as a guide and reminder of fragmentation impacts and loss of unique habitat, such as may occur around WDEs due to developmental pressures. Whilst the focus is on US rangeland applications, these models are readily adaptable to South Australian conditions. The end point of each model is increased susceptibility of target species to extinction. Zero extinction is an objective of the *State Strategic Plan*.

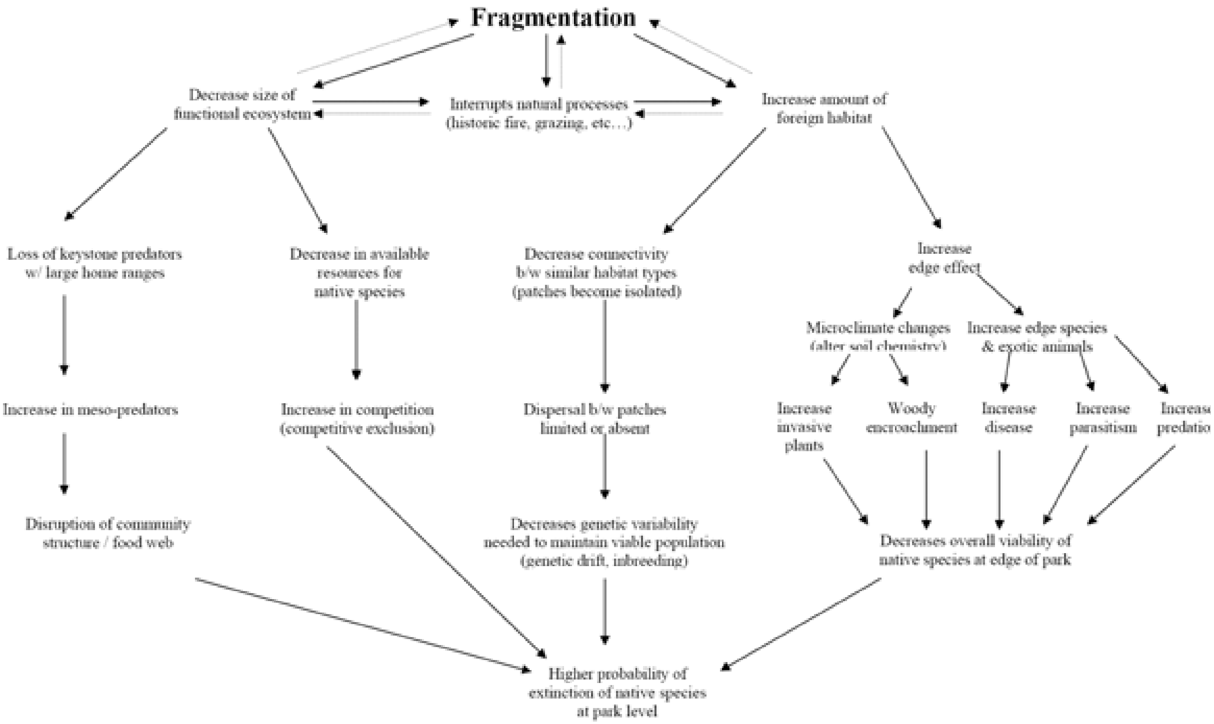


**Figure 32. Habitat fragmentation sub-model from the US NPS Southern Plains region (source: Perkins et al. 2005).**

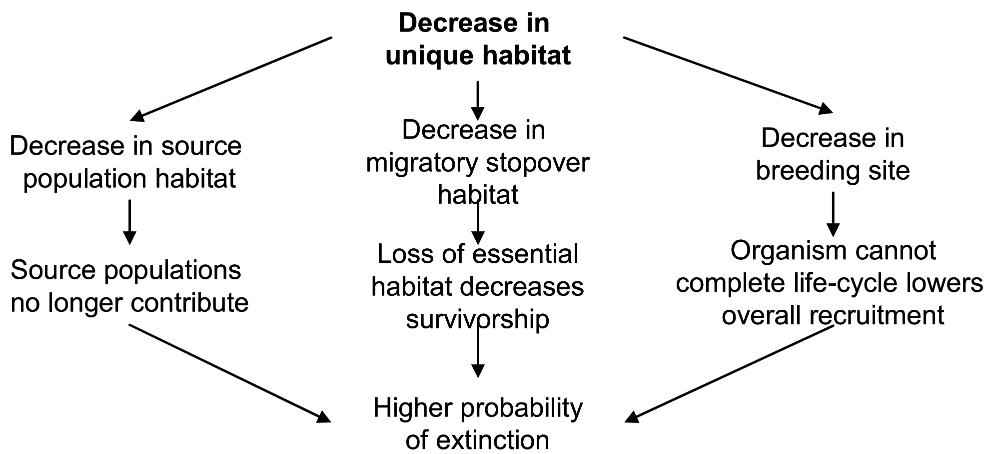


**Figure 33. Loss of unique habitat model adapted from the US NPS Southern Plains study (source: Perkins et al. 2005).**

# *GROUP 3 – MONITORING PROGRAMME*

## TASK 3.2 – CHOICE OF INDICATORS

***3: Monitoring programme***

| Review monitoring | **Review/select indicators** | Choose measures and frequencies | Consider resources |
|---|---|---|---|

### Indicators

All monitoring programmes need appropriate means of assessing condition of the system of interest. In order to assess condition it is necessary to quantify or provide a measure of that condition. Prior to measuring condition it is necessary to know what information is required and why it is needed, then determine the characteristic or component of a system that is indicative of the aspect of condition that needs to be quantified.

The answers to these questions may already be known or it may be that a new monitoring programme is being established. These are a subset of the initial questions that need to be asked at the very outset of the process of devising a monitoring programme and it is worth revisiting these questions to ensure that indicators chosen are appropriate to the project or programme requirements.

- What is the purpose of the monitoring (why)?
- What information is needed to meet the purpose?
- What is the target component or aspect of the system?
- What characteristic or aspect of that component can be measured to provide the necessary information?

No single indicator can capture and reflect the inherent complexity of WDEs and the use of suites of indicators as described by Karr et al. (1986), Karr (1987), Fausch et al. (1990) may be necessary (see also Downes et al. 2002 – Chapter 10). The extent and breadth of indicator coverage will be dependent on monitoring objectives.

The terms measure, vital sign and indicator need to be distinguished. In general, indicator and vital sign are associated with the condition of an ecosystem or some aspect of an ecosystem:

**Vital-sign** is used specifically to imply an indication of ecosystem health. A vital sign is more likely to be an end-point or a consequence, or consequent condition of a system resulting from the set of circumstances that determine or influence that condition. The circumstances are drivers, stressors and processes that are represented by the indicating vital sign.

Fairweather and Napier (1998) use the term indicator in a quite different sense. This is associated with “State of the Environment Reporting” (SOER) for inland waters in Australia, i.e. a federal and international programme of SOER. Three categories of indicator are used, condition (C), pressure (P), and response (R). A condition indicator indicates the status of a given system or system component. A pressure indicator provides an indication of negative impacts or consequences of stresses, it indicates that the system has experienced stress and has deteriorated (it is not a measure of a given stress). A response indicator provides evidence of management initiatives or interventions undertaken to mitigate adverse conditions or offset stress (it is not a measure of a responding variable within the system).

Given that usage of terms does vary, a clear definition or bound for these terms is required for devising a monitoring scheme.

**Indicator** is used here in a broad sense and is applicable to various aspects of a system, rather than just an outcome, so that driving conditions, stresses and system responses or outcomes have indicators. Thus an indicator becomes a characteristic of any aspect of a given system.

**Measure** is distinct from an indicator, since it is the means of quantifying a given indicator (or vital sign) such that it can be assessed and evaluated against some appropriate knowledge base.

With these definitions it is then possible to specify indicators for any part of a system and the measures needed to quantify and evaluate the status of the system or that part of the system.

### *Indicator characteristics*

Before instigating a new monitoring programme or when reviewing an existing programme it makes sense to understand the role of different measures of ecosystem condition in the proposed or existing programme. Different types of indicator have differing roles and can be used to provide information at different points within the structure of the system of interest.

Plumb (2003) summarised ecological indicator characteristics as described by Dale and Beyeler (2001). Maddox et al. (1999) also presented categories of indicators which fit into the range listed below:

- Stress-sensitive indicators display **high sensitivity to** particular, and perhaps subtle, **stressors**, thereby serving as an early warning signal of reduced system integrity (Karr 1991).
- Minimal variability indicators have a **small range of variability** of response **to** known **stressors** and but ***respond to natural drivers***, and would be used in parallel with stress predictable indicators so that natural and stress induced variability can be distinguished.
- Stress-predictable indicators should be unambiguous and predictable even if responding to gradual rates of stress; they **have a well defined relationship to the stress**.
- Anticipatory indicators reflect a threshold response dynamic wherein an observed response occurs prior to an important reduction in system integrity (e.g. the canary should die before the miner). As with anticipatory monitoring, there may be uncertainty in the relationship between the indicator and the system response.
- Predictive management indicators should be scale-dependent and reflect the real temporal and spatial scales of management capabilities. Predictive management indicators cannot anticipate ecological catastrophes such as volcanoes or hurricanes.
- Integrative indicators should behave predictably across appropriate scales and can be aggregated to provide assessment of multi-scale systems (Brooks et al. 1998).

- Mechanistic indicators have a **known functional response** to ecosystem disturbances and stressors. These indicators have been adequately studied and the mechanisms of ecosystem response are well known.
- Diagnostic Indicators can be used to enhance the interpretation of ecosystem changes when determining system function.

It may be necessary for practitioners, in reviewing existing monitoring to consider each existing indicator in the programme and ask themselves what role the indicators are playing, rather than following any pre-determined assumption about what role they might be playing. Some of these indicator characteristics can occur together in one indicator, others, by nature of the characteristic need to remain separate. An obvious example is the stress sensitive indicator and the "minimal variability" indicator which is intended to track naturally driven variation – these two characteristics are mutually exclusive, i.e. an indicator could not have both characteristics.

Indicators may occur at any level of organization including landscape, community, population, or genetic levels, and may be compositional (referring to the variety of elements in a system), structural (referring to the organization or pattern of the system), or functional (referring to ecological processes) (Fancy 2003).

Adams (2002) undertook an assessment of biological indicators for aquatic ecosystem stresses, concluding that the term "ecological indicator" is too general and should be reduced to yield more appropriate specificity. Adams (2002) proposed the distinctions: "biocriteria", "biomarkers", and "bioindicators" with definitions as follows:

**Biocriteria** is defined within the context of "*regulatory processes at the population or community level*" and could include indices of the numbers and kinds of organisms present in an aquatic system of interest, such as the invertebrate family richness or SIGNAL score.

**Biomarkers** are considered as functional measures of exposure to environmental stressors that are usually expressed at a sub-organism level of organization such as molecular, biochemical and even physiological endpoints (Adams 2002).

**Bioindicators** are either structural entities such as sentinel species (Gestel & Brummelen 1996), or they can be functionally biological endpoints at higher levels of organization (Adams 1990).

These three terms are of value for WDEs and can be used to assist in classifying different indicators.

The U.S. Environmental Protection Agency's Office of Research and Development suite of evaluation guidelines for ecological indicators (Jackson et al. 2000: see the text box in Task 3.4) includes 15 recommended guidelines for the identification and selection of relevant ecological indicators. These are organised around four crucial questions:

1. Is the potential indicator relevant to management concerns and to the ecological resource or function at risk?
2. Is the potential indicator sampling methodology feasible, appropriate, and efficient for use in a long-term ecological monitoring programme?
3. Are the errors of measurement and range of natural variability over the relevant temporal and spatial scales sufficiently understood and documented?

4. Will the indicator convey information on ecological condition that is relevant to resource decision-making?

The intention of the USEPA guidelines, as summarised by Kurtz et al. (2001) (see the following text box), is to provide a flexible yet consistent framework for indicator review, comparison, selection, and to provide direction for research on indicator development. The USEPA states that the guidelines should not be viewed as criteria that can determine indicator applicability or effectiveness, rather, that the 15 guidelines provide a framework for asking relevant questions about indicator relevance, feasibility, variability, and utility (Kurtz et al. 2001).

In general, indicators or vital signs should:

a. Have broad sensitivity to human impacts.
b. Represent multiple levels of ecological organization such as individual, population, community or landscape.
c. Reflect key elements and processes (Angermeier 1997).

The chosen measures should be easy to understand, simple to apply, and provide information that is relevant, quantitatively sound, easily documented and cost-effective, i.e. the proverbial coal-mine canary (Stork et al. 1997; Lorenz et al. 1999).

Plumb (2003) undertook a thorough review of desirable indicator characteristics in his study of conceptual models for the US National Parks Service. In this report, these indicator characteristics have been combined with those specifically relevant to Australian wetland studies and rearranged, grouped and categorised according to:

1. How well the indicator does its job, or indicator effectiveness.
2. Whether it is broadly applicable.
3. Ease of use, cost to determine and how readily it communicates.

The following groups of indicator characteristics are derived from the work of Angermeier (1997), Green (1979), Karr (1987), Dale and Beyeler (2001) and Adams (2002). In general, key considerations are regarding the ability of the vital sign to represent system biological integrity, capture the complexity of system function and remain simple enough to routinely monitor.

### *Indicator effectiveness*

The majority of identified qualities for indicators relate to how well the indicator does it's job, these are many and varied and again can be broken down into sub-categories:

- Ecologically relevant
  - Is of ecological/biological relevance and significance and has dynamics that parallel those of the ecosystem or component of interest.
- Sensitive
  - Is sensitive to a wide range of impact types and levels; is sensitive to stresses on the system; is responsive to condition change at short and medium scales; is sensitive enough to provide an early warning of change.
  - Is anticipatory; sensitive to human impact prior to severe ecological damage; predictive of changes that can be averted by management action; monitoring data may be related to an ecosystem moving out of its normal range of variability.

- Selective
  - Is selective and can either distinguish between natural variation and impact-induced variation; has dynamics that are easily attributed to either natural cycles or anthropogenic stressors.
- Reliable
  - Has low natural variability; has low response variability.
  - Can demonstrate an effect through comparison with a control; is sufficiently valid and accepted; has a relationship to cause; has a known relationship with condition.
  - Is based on preliminary sampling that describe inherent variability; has a known response to disturbances, anthropogenic stressors, and changes over time; responds to ecosystem stressors in a predictable manner.
  - Describes what is being sampled with equal and adequate efficiency across the range of sampling conditions; arisen from a deliberate and defined protocol for identification of indicators.
- Repeatable
  - Is repeatable in its measure; can be implemented by anyone with appropriate training and/or using a detailed protocol; has measurable results that are repeatable with different personnel.
  - Can be accurately and precisely estimated.
  - Is representative (e.g. able to be measured with an equal number of randomly allocated replicate samples).
  - Is transparent so that data can be tested to see if error variation is homogenous, normally distributed, and independent of the mean.
- Integrative
  - Integrates ecosystem stresses over space and time; integrates the effects of natural variation; does not require frequent measurements (i.e. infrequent field visits).
- Diagnostic
  - Helpful in identifying the cause of an ecological problem.
- Sustainable
  - Is sustainable and measurable over the long-term; low impact to measure; non-destructive on the ecosystem.

### *Indicator applicability*

Applicability is used here to represent the scope of an indicator, or vital sign, to be used for monitoring in a wide range of systems and varying temporal and spatial scales. The following criteria were identified in the literature:

- Is distributed over a wide geographical area and/or are very numerous.
- Provides continuous assessment over a wide range of stress.
- Is applicable over multiple regions; universal (state-wide) applicability.
- Is applicable at a variety of scales of ecological organisation.
- Is able to provide information relevant to another scale.
- Is used over a wide range of climatic, soil, topographic and vegetation conditions.
- Addresses one or more environmental themes and issues.

- Is able to include appropriate size, density and distribution of samples.

*Indicator ease of use, cost and communicability*

- Ease of Use
    - Easy to measure and interpret; simple or a commonly measured parameter.
    - Is a reference condition available or easily determined?
- Cost
    - Has costs of measurement that are not prohibitive [relative to budget]; be cost effective and simple to apply.
- Communicability
    - Has monitoring results that can be interpreted and explained; interpretation is unambiguous.
    - Has results that can be understood by people who are not experts in water dependent ecosystem assessment; is meaningful to the public.
    - Is concise, coherent, and comprehensible.
    - Transparently reflects management long-term goals and objectives.

Ryan et al. (2003) state that these are general rules with many exceptions and that a complete list of Environmental Indicators applicable to the coastal zone can be found in the OzEstuaries database (http://www.ozestuaries.org) Indicator Fact Sheets.

*Application and relevance of key environmental indicators to different types of estuaries and coastal waterways (after Smith et al. 2002).*

| **Environmental Indicator (ANZECC & ARMCANZ 2000)** | **Relevance to Coastal Waterways** |
|---|---|
| Turbidity | Naturally higher in tide-dominated systems (Figures 23-35) because tidal currents resuspend fine sediment (Heap *et al*., 2001). |
| Chlorophyll a | Naturally lower in tide-dominated systems (Figures 23-35) because tidal mixing reduces the residence time of algae in the photic zone, and because sediment resuspended by tides increases turbidity, which reduces light available for photosynthesis (Monbet, 1992). |
| Dissolved Nutrients | Natural levels are probably higher in tide-dominated systems (Figures 23-35), because turbidity and mixing reduce the capacity of plants and algae to take up the nutrients. |
| Total nitrogen and total phosphorus | Natural levels are probably higher in tide-dominated systems (Figures 23-35) because turbidity and mixing reduce biological uptake, and because particulate nutrients are associated with suspended sediment. |
| pH | The pH of coastal waterways depends on many factors making differences between wave- and tide-dominated systems difficult to predict. However, tide-dominated systems (Figures 23-35) should have less photosynthetic consumption of carbon dioxide (for above reasons), and are more likely to be impacted by low-pH runoff from acid sulfate soils than wave-dominated systems. |
| Dissolved Oxygen | Dissolved oxygen in coastal waterways depends on many factors making differences between wave- and tide-dominated systems difficult to predict. However, tide-dominated systems (Figures 23-35) may have less photosynthetic production of dissolved oxygen but more replenishment of dissolved oxygen by tidal exchange. |
| Heavy Metals, toxicants (&organic matter) | The central basins of wave-dominated estuaries (Figures 10-14) and coastal lagoons (Figures 19-22) are important sinks for fine sediment, organic matter and sediment-bound contaminants. Flanking environments (mangroves and salt marshes) are the main sink for contaminants in tide-dominated systems (Figures 23-35). |
| Denitrification Efficiency | Denitrification efficiency is a good indicator of sustainable carbon loading rates in embayments, coastal lagoons, and wave-dominated estuaries, when it is coupled to nitrification occurring in the sediment. Denitrification efficiency is probably not a good indicator of sustainable carbon loadings in coastal waterways in which denitrification is linked to nitrate in the water column (Eyre and Ferguson, 2002a). High water column nitrate concentrations are likely to be found in waterways with large amounts of suspended sediment because these conditions reduce the amount of light available for photosynthesis, and therefore the ability of plants to take up nutrients. Denitrification efficiency is therefore not a good indicator in tide-dominated systems. |
| Mangrove area, Saltmarsh area | Mangroves and salt marshes are naturally more ubiquitous and widespread in tide-dominated systems (Figures 23-35) compared to wave-dominated systems (Figures 10-18). Whilst these habitats are more important in tide-dominated systems, the natural scarceness of mangroves in wave-dominated estuaries and deltas suggests that they are more vulnerable in these systems. |

# GROUP 3 – MONITORING PROGRAMME

## TASK 3.3 – CHOOSE MEASURES AND FREQUENCIES

**3: Monitoring programme**

| Review monitoring | Review/select indicators | **Choose measures and frequencies** | Consider resources |
|---|---|---|---|

### Measures and frequencies

There is a wealth of information in the literature on monitoring techniques, methods and measures. An in depth discussion of WDE health measures is beyond the scope of the current study, therefore a number of helpful and informative guidebooks are recommended.

- Downes et al. (2002) is an excellent text covering ecological monitoring for fluvial systems.
- ANZECC/ARMCANZ (2000) guidelines for water quality monitoring and reporting.
- Baldwin et al. (2005) contains many of the basics of monitoring for floodplain and wetland ecosystems and is a good starting point with many references to relevant guidebooks, manuals and standard procedures.
- Davis et al. (1999) is a manual for wetland bio-assessment.
- Goonan (1999) is the South Australian AUSRIVAS sampling and processing manual with a focus on macroinvertebrates.
- Green (1979) a useful resource on sampling and statistical methods for biological monitoring.
- Hötzel and Croome (1999) methods for phytoplankton recognition and evaluation.
- Seaman (2000a) provides a good overview of the chemical characteristics of WDEs, in particular covering salinity and turbidity.
- Turak et al. (2004) recommend Gooderham and Tsyrlin (2002), Hawking and Smith (1997) for macroinvertebrate identification and monitoring, and Sainty and Jacobs (1994) for Australian water plants.

# *GROUP 3 – MONITORING PROGRAMME*

## TASK 3.4 – CONSIDER RESOURCES

***3: Monitoring programme***

| Review monitoring | Review/select indicators | Choose measures and frequencies | **Consider resources** |
|---|---|---|---|

### Indicator guidelines

The following is a direct quote of the USEPA guidelines for indicators (Jackson et al. 2000) as summarised by Kurtz et al. (2001), with minor adaptations.

*The USEPA Office of Research and Development Evaluation Guidelines for Ecological Indicators.*

Phase 1: Conceptual Relevance

The indicator must provide information that is relevant to societal concerns about ecological condition. The indicator should clearly pertain to one or more identified assessment questions. These, in turn, should be germane to a management decision and clearly relate to ecological components or processes deemed important in ecological condition. Often, the selection of a relevant indicator is obvious from the assessment question and from professional judgement. However, a conceptual model can be helpful to demonstrate and ensure an indicator's ecological relevance, particularly if the indicator measurement is a surrogate for measurement of the valued resource. This phase of indicator evaluation does not require field activities or data analysis. Later in the process however, information may come to light that necessitates re-evaluation of the conceptual relevance, and possibly indicator modification or replacement. Likewise, new information may lead to a refinement of the assessment question.

Guideline 1: Relevance to the Assessment

Early in the evaluation process it must be demonstrated, in concept, that the proposed indicator is responsive to an identified assessment question and will provide information useful to a management decision. For indicators requiring multiple measurements (indices or aggregates), the relevance of each measurement to the management objective should be identified. In addition, the indicator should be evaluated for its potential to contribute information as part of a suite of indicators, designed to address multiple assessment questions. The ability of the proposed indicator to complement indicators at other scales and levels of biological organization should also be considered. Redundancy with existing indicators may be permissible, particularly if improved performance or some unique and critical information is anticipated from the proposed indicator.

Guideline 2: Relevance to Ecological Function

It must be demonstrated that the proposed indicator is conceptually linked to the ecological function of concern. A straightforward link may require only a brief explanation. If the link is indirect, or if the indicator itself is particularly complex, ecological relevance should be clarified with a description, or conceptual model. A conceptual model is recommended, for example, if an indicator is comprised of multiple measurements, or if it will contribute to a weighted index. In such cases, the relevance of each component to ecological function and to the index should be described. At a minimum, explanations and models should include the principal stressors that are presumed to impact the indicator, as well as the resulting ecological response. This information should be supported by available environmental, ecological and resource management literature.

Phase 2: Feasibility of Implementation

Adapting an indicator for use in a large or long-term monitoring programme must be feasible and practical. Methods, logistics, cost and other issues of implementation should be evaluated before routine data collection begins. Sampling, processing and analytical methods should be documented for all measurements that comprise the indicator. The logistics and costs associated with training, travel, equipment and field and laboratory work should be evaluated, and plans for information management and quality assurance developed.

Guideline 3: Data Collection Methods

Methods for collecting all indicator measurements should be described. Standard, well-documented methods are preferred. Novel methods should be defended with evidence of effective performance and, if applicable, with comparisons to standard methods. If multiple methods are necessary to accommodate diverse circumstances at different sites, the effects on data comparability across sites must be addressed. Expected sources of error should be evaluated. Methods should be compatible with the monitoring design of the program for which the indicator is intended. Plot design and measurements should be appropriate for the spatial scale of analysis. Needs for specialized equipment and expertise should be identified.

Sampling activities for indicator measurements should not significantly disturb a site. Evidence should be provided to ensure that measurements made during a single visit do not affect the same measurement at subsequent visits or, in the case of integrated sampling regimes, simultaneous measurements at the site. Also, sampling should not create an adverse impact on protected species, species of special concern, or protected habitats.

Guideline 4: Logistics

The logistical requirements of an indicator can be costly and time-consuming. These requirements must be evaluated to ensure the practicality of indicator implementation, and to plan for personnel, equipment, training and other needs. A logistics plan should be prepared that identifies requirements, as appropriate, for: field personnel and vehicles, training, travel, sampling instruments, sample transport, analytical equipment, and laboratory facilities and personnel. The length of time required to collect, analyze and report the data should be estimated and compared with the needs of the program.

Guideline 5: Information Management

Management of information generated by an indicator, particularly in a long-term monitoring programme, can become a substantial issue. Requirements should be identified for data processing, analysis, storage and retrieval, and data documentation standards should be developed. Identified systems and standards must be compatible with those of the programme for which the indicator is intended, and should meet the interpretive needs of the programme. Compatibility with other systems should also be considered, such as the internet, established federal standards, geographic information systems, and systems maintained by intended secondary data users.

Guideline 6: Quality Assurance

For accurate interpretation of indicator results it is necessary to understand their degree of validity. A quality assurance plan should outline the steps in collection and computation of data, and should identify the data quality objectives for each step. It is important that means and methods to audit the quality of each step are incorporated into the monitoring design. Standards of quality assurance for an indicator must meet those of the targeted monitoring programme.

Guideline 7: Monetary Costs

Cost is often the limiting factor when considering an indicator for implementation. Estimates of all implementation costs should be evaluated. Cost evaluation should incorporate economy of scale, since cost per indicator or cost per sample may be considerably reduced when data are collected for multiple indicators at a given site. Costs of a pilot study or any other indicator development needs should be included if appropriate.

Phase 3: Response Variability

It is essential to understand the components of variability in indicator results to distinguish extraneous factors from a true environmental signal. Total variability includes both: measurement error introduced during field and laboratory activities; and natural variation, which includes influences of stressors. Natural variability can include temporal (within the field season and across years) and spatial (across sites) components. Depending on the context of the assessment question, some of these sources must be isolated and quantified in order to interpret indicator responses correctly. It may not be necessary, or appropriate, to address all components of natural variability. Ultimately, an indicator must exhibit significantly different responses at distinct points along a condition gradient. If an indicator is composed of multiple measurements, variability should be evaluated for each measurement, as well as for the resulting indicator.

Guideline 8: Estimation of Measurement Error

The process of collecting, transporting and analyzing ecological data generates errors that can obscure the discriminatory ability of an indicator. Variability introduced by human and instrument performance must be estimated and reported for all indicator measurements. Variability among field crews should also be estimated, if appropriate. If standard methods and equipment are employed, information on measurement error may be available in the literature. Regardless, this information should be derived or validated in dedicated testing or a pilot study.

Guideline 9: Temporal Variability - Within the Field Season

It is unlikely in a monitoring programme that data can be collected simultaneously from a large number of sites. Instead, sampling may require several days, weeks, or months to complete, even though the data are ultimately to be consolidated into a single reporting period. Thus, within-field season variability should be estimated and evaluated. For some monitoring programmes, indicators are applied only within a particular season, time of day, or other window of opportunity when their signals are determined to be strong, stable and reliable, or when stressor influences are expected to be greatest. This optimal time frame, or index period, reduces temporal variability considered irrelevant to program objectives. The use of an index period should be defended and the variability within the index period should be estimated and evaluated.

Guideline 10: Temporal Variability - Across Years

Indicator responses may change over time, even when ecological condition remains relatively stable. Observed changes in this case may be attributable to weather, succession, population cycles or other natural inter-annual variations. Estimates of variability across years should be examined to ensure the indicator reflects true trends in ecological condition for characteristics that are relevant to the assessment question. To determine inter-annual stability of an indicator, monitoring must proceed for several years at sites known to have remained in the same ecological condition.

Guideline 11: Spatial Variability

Indicator responses to various environmental conditions must be consistent across the monitoring region if that region is treated as a single reporting unit. Locations within the reporting unit that are known to be in similar ecological condition should exhibit similar indicator results. If spatial variability occurs due to regional differences in physiography or habitat, it may be necessary to normalize the indicator across the region, or to divide the reporting area into more homogeneous units.

Guideline 12: Discriminatory Ability

The ability of the indicator to discriminate differences among sites along a known condition gradient should be critically examined. This analysis should incorporate all error components relevant to the program objectives, and separate extraneous variability to reveal the true environmental signal in the indicator data.

Phase 4: Interpretation and Utility

A useful ecological indicator must produce results that are clearly understood and accepted by scientists, policy makers and the public. The statistical limitations of the indicator's performance should be documented. A range of values should be established to define ecological condition as acceptable, marginal and unacceptable, in relation to indicator results. Finally, the presentation of indicator results should highlight their relevance for specific management decisions and public acceptability.

Guideline 13: Data Quality Objectives

The discriminatory ability of the indicator should be evaluated against programme data quality objectives and constraints. It should be demonstrated how sample size, monitoring duration and other variables affect the precision and confidence levels of reported results, and how these variables may be optimized to attain stated program goals. For example, a programme may require that an indicator be able to detect a twenty percent change in some aspect of ecological condition over a ten-year period, with ninety-five percent confidence. With magnitude, duration and confidence levels constrained, sample size and extraneous variability must be optimized in order to meet the programme's data quality objectives. Statistical power curves are recommended to explore the effects of different optimization strategies on indicator performance.

Guideline 14: Assessment Thresholds

To facilitate interpretation of indicator results by the user community, threshold values, or ranges of values, should be proposed that delineate acceptable from unacceptable ecological condition. Justification can be based on documented thresholds, regulatory criteria, historical records, experimental studies or observed responses at reference sites along a condition gradient. Thresholds may also include safety margins or risk considerations. Regardless, the basis for threshold selection must be documented.

Guideline 15: Linkage to Management Action

Ultimately, an indicator is useful only if it can provide information to support a management decision or to quantify the success of past decisions. Policy makers and resource managers must be able to recognize the implications of indicator results for stewardship, regulation or research. An indicator with practical application should display one or more of the following characteristics: responsiveness to a specific stressor; linkage to policy indicators; utility in cost-benefit assessments; limitations and boundaries of application; and public understanding and acceptance. Detailed consideration of an indicator's management utility may lead to a re-examination of its conceptual relevance and to a refinement of the original assessment question.

Application of the Guidelines

These USEPA guidelines were developed to guide indicator development and to facilitate indicator review. Researchers could use the guidelines informally to find weaknesses or gaps in indicators that could be corrected with further development. It was proposed that indicator development could also benefit from formal peer review, accomplished through panels or other appropriate means that bring experienced professionals together. These should include both technical experts and environmental managers, since the Evaluation Guidelines incorporate issues from both arenas.

# *GROUP 4 – IMPLEMENT AND ASSESS*

## TASK 4.3 – EVALUATE AND ASSESS

***4: Implement and assess***

| Implement | Collect data | **Evaluate and assess** | Review results against targets |
|---|---|---|---|

### Analysis

There are a vast number of textbooks that describe an almost bewildering array of statistical tests. The following are just a few that the authors have found useful.

Crawley, MJ 2005, *Statistics : an introduction using R*. John Wiley & Sons Ltd. Chichester, England.

Quinn, JP, & Keough, MJ 2002, *Experimental Design and Data Analysis for Biologists*, Cambridge University Press, Cambridge.

Scheiner, SM, & Gurevitch, J (eds.) 2001, *Design and analysis of ecological experiments*, Oxford University Press, New York.

Underwood, AJ 1997, *Experiments in ecology: their logical design and interpretation using analysis of variance*, Cambridge University Press, Cambridge.

Zar, JH 1999, *Biostatistical Analysis*, Fourth Edition, Prentice-Hall, New Jersey.

# APPENDICES

## 1. WATER DEPENDENT ECOSYSTEMS IN SOUTH AUSTRALIA

As reported in the Stakeholder Forum Report (Wilkinson et al. 2006), a great variety of WDEs are present in South Australia. The size of the State of South Australia (SA), almost 1 000 000 $km^2$, means these WDEs span a wide range of ecological zones. Consequently, as the nature of the systems differ greatly, so do the monitoring needs and objectives. Remoteness from centres of population mean that logistical considerations can play a major part in determining the means of monitoring and frequency of field visits, and importantly the cost of monitoring. Rather than attempt a full summary of WDEs in South Australia, this Appendix summarises information on nationally and internationally important WDEs and on a sub-category of WDE, the GDE (groundwater dependent ecosystem).

### Nationally and internationally important wetlands in SA

SA is the driest of all Australian States, with 75% of the area receiving less than 200 mm of rainfall a year. Nevertheless, SA contains an array of significant wetlands (Morelli & de Jong 2001; EPA 2003) (Tables A1–A3, Fig. A1).

The arid interior is notable for its mound springs, salt lakes and pristine freshwater river-floodplain systems of the Lake Eyre Basin. The coastline is 4000 km long containing two Gulf regions; notable features include sheer cliffs, sandy beaches for thousands of shorebirds, coastal embayments, and several mangrove/samphire and estuarine mud flat systems. Notable in the South East are the coastal salt lakes, freshwater ponds, shallow lagoons, peat fens and marshes. The Riverland region is noted for its freshwater swamps, channels, lakes and floodplains (Morelli & de Jong 2001).

Morelli and de Jong (2001) report that despite major alteration of wetlands in South Australia, since European settlement, due to: stock grazing; vegetation clearance; pollution; urban development; or hydrological changes, particularly in the southern agricultural regions, there are still "*some magnificent areas of wetlands which are highly valued for wildlife, of cultural, scientific and historical interest, and possessing great aesthetic and recreational appeal*".

Morelli and de Jong (2001), in compiling the directory of wetlands of national and international importance in SA, stated that "*the lack of data available for some wetlands highlights the need for systematic inventories, biological surveys and research programs in many areas of the State.*" In addition, they recommended that a state-wide survey be conducted for comparison with the results of Lloyd and Balla (1986), and that special attention should be given to the bioregions of the Great Victoria Desert, Flinders and Olary Ranges and Nullarbor, suggesting that "*present survey information is severely inadequate.*"

**Table A1. South Australian inland wetlands of national and international importance, by type (Morelli and de Jong 2001).**

| Inland wetlands | Total |
|---|---|
| 1. Permanent rivers and streams, includes waterfalls | 11 |
| 2. Seasonal and irregular rivers and streams | 6 |
| 3. Inland deltas (permanent) | 1 |
| 4. Riverine floodplains, includes river flats, flooded river basins, seasonally flooded grassland, savanna and palm savanna | 15 |
| 5. Permanent freshwater lakes (8 ha), includes large oxbow lakes | 10 |
| 6. Seasonal/intermittent freshwater lakes (>8 ha) floodplain lakes | 15 |
| 7. Permanent saline/brackish lakes | 10 |
| 8. Seasonal/intermittent saline lakes | 9 |
| 9. Permanent freshwater ponds (<8 ha), marshes and swamps on inorganic soils, with emergent vegetation waterlogged for at least most of the growing season | 7 |
| 10. Seasonal/intermittent freshwater ponds and marshes on inorganic soils, includes sloughs, potholes, seasonally flooded meadows, sedge marshes | 5 |
| 11. Permanent saline/brackish marshes | 4 |
| 12. Seasonal saline marshes | 4 |
| 13. Shrub swamps; shrub-dominated freshwater marsh, shrub carr, alder thicket on inorganic soil | 7 |
| 14. Freshwater swamp forest, seasonally flooded forest, wooded swamps, on inorganic soils | 4 |
| 15. Peatlands, forest, shrubs or open bogs | 7 |
| 16. Alpine and tundra wetlands, includes alpine meadows, tundra pools, temporary waters from snow melt | 0 |
| 17. Freshwater springs, oases and rock pools | 4 |
| 18. Geothermal wetlands | 0 |
| 19. Inland, subterranean karst wetlands | 2 |
| **Total** | **121** |

**Table A2. Environmental status from completed wetland inventories in South Australia (after EPA 2003).**

| NRM Region | High value | Moderate value | Low value | Total |
|---|---|---|---|---|
| Mount Lofty Ranges | 19 | 54 | 11 | 84 |
| Eyre Peninsula | 8 | 16 | 3 | 27 |
| Kangaroo Island | 6 | 15 | 6 | 27 |
| Northern & Yorke | 2 | 19 | 8 | 29 |
| **Total** | **35** | **104** | **28** | **167** |

**Table A3. Summary of nationally and internationally important wetlands in South Australia (Morelli and de Jong 2001).**

| IBRA region | IBRA code | No. of Sites | Area (ha) |
|---|---|---|---|
| Broken Hill Complex | BHC | 0 | 0 |
| Central Ranges | CR | 0 | 0 |
| Channel Country | CHC | 3 | 1 980 000 |
| Eyre and Yorke Blocks | EYB | 16 | 38 238 |
| Finke | FIN | 0 | 0 |
| Flinders and Olary Ranges | FOR | 1 | – |
| Gawler | GAW | 0 | 0 |
| Great Victoria Desert | GVD | 0 | 0 |
| Hampton | HAM | 0 | 0 |
| Lofty Block | LB | 18 | 50 750 |
| Murray-Darling Depression | MDD | 14 | 44 927 |
| Naracoorte Coastal Plain | NCP | 13 | 293 073 |
| Nullarbor | NUL | 0 | 0 |
| Simpson-Strzelecki Dunefields | SSD | 2 | 1 798 000 |
| Stony Plains | STP | 2 | 19 000 |
| **Total** | **15** | **69** | **2 205 750** |

An Australian wetland is considered nationally important if it meets at least one of the following criteria (Environment Australia 2001):

- It is a good example of a wetland type occurring within a biogeographic region in Australia.
- It is a wetland which plays an important ecological or hydrological role in the natural functioning of a major wetland system/complex.
- It is a wetland which is important as habitat for animal taxa at a vulnerable stage in their life cycles, or provides a refuge when adverse conditions such as drought prevail.
- The wetland supports 1% or more of the national population of any native plant or animal taxa.
- The wetland supports native plant or animal taxa or communities which are considered endangered or vulnerable at the national level, and/or
- The wetland is of outstanding historical or cultural significance.

The majority of South Australian wetlands are included in the Directory because they are important as habitat for animal taxa at a vulnerable stage in their life cycles, or provides a refuge during adverse conditions (Larmour 2001).

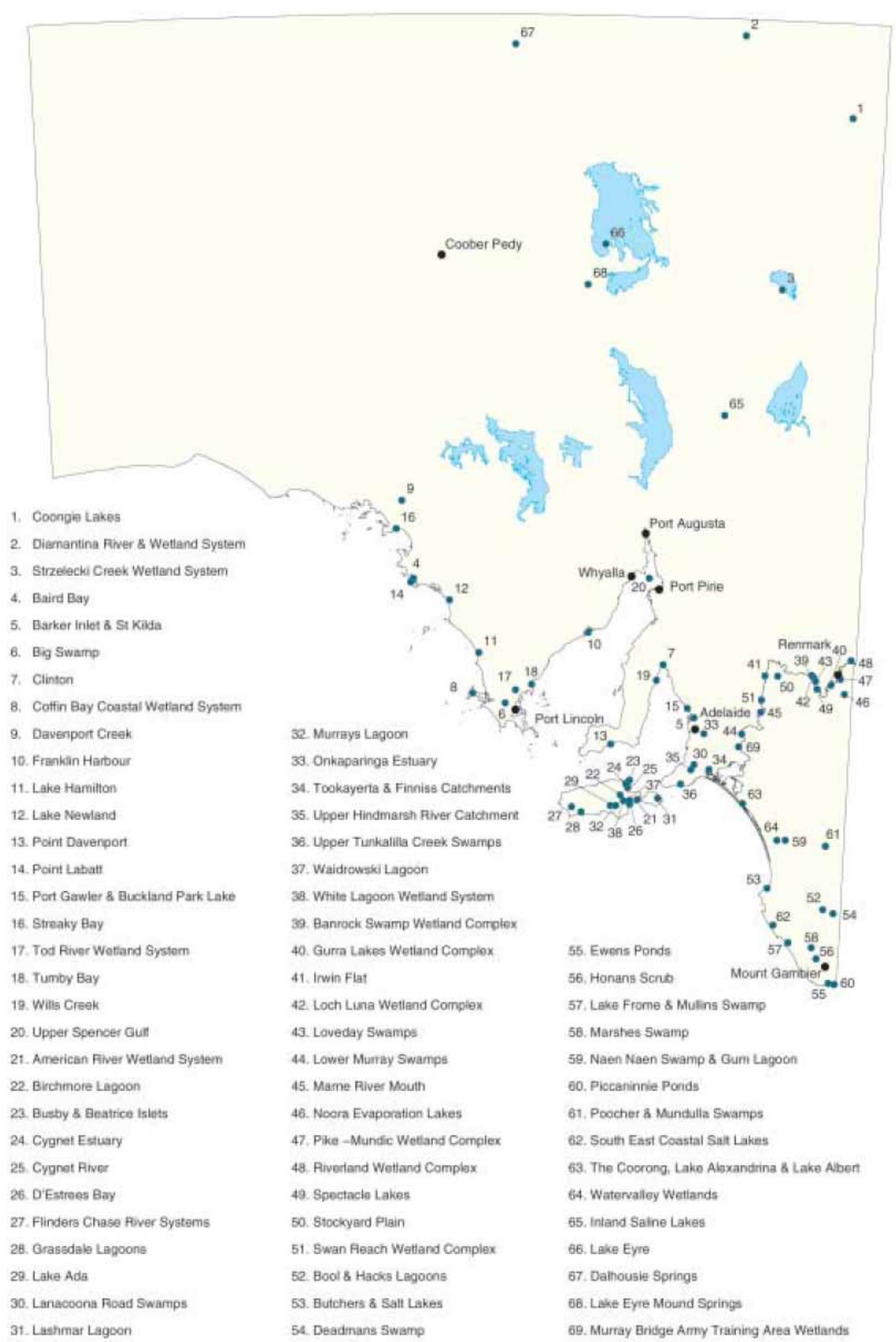


**Figure A1. Map of nationally and internationally significant wetlands in South Australia (EPA 2003).**

## The groundwater dependent ecosystems

Many of the WDE systems in South Australia are actually groundwater dependent, to a greater or lesser extent. This makes them Groundwater Dependent Ecosystems (GDEs), and thus they are relatively common in South Australia. GDEs are in some respects not well known and easily overlooked, and until recent years have received relatively little attention. Cook and Lamontagne (2002) provide a useful overview of environmental water requirement issues for GDEs in South Australia.

### *Degree of groundwater dependency*

The degree of groundwater dependency varies from system to system and can be loosely classified as follows (Lamontagne 2002):

- **Entire dependency:** total dependence on groundwater – some change or threshold might result in collapse of ecosystem.
- **High dependency:** changes in regime might seriously decrease ecosystem health and may result in collapse.
- **Proportional dependency:** health is proportional to the change in water regime.
- **Opportunistic use:** partial dependence; the ecosystem may only utilise groundwater during drought, and thus is still vulnerable in the long-term.
- **No apparent dependency:** Changes in groundwater regime not expected to impact ecosystem health.

Sinclair Knight and Merz (2001) grouped GDEs in Australia according to their degree of groundwater dependency, the subset of these in South Australia is summarised in Table A4.

**Table A4. GDEs in South Australia, and their degree of groundwater dependency.**

| Ecosystem | Threat | | Vulnerability to threat | Risk that threat realised | Conservation value of system |
|---|---|---|---|---|---|
| | Process | GW attribute | | | |
| **Entirely GW dependent** | | | | | |
| Mound springs | Water resource | Pressure | H | H | H |
| Karstic systems | Water resource, agriculture, mining | Level, quality | H | H | H |
| Arid zone calcrete | Water resource, mining | Level, quality | H | M | H |
| Riverine aquifer | Water resource, agriculture, urban and commercial development | Level, quality | H | H | M |
| Marine tide influenced cave | Water resource, mining | Level, quality | H | M | H |
| **Highly dependent** | | | | | |
| Unknown | | | | | |
| **Proportionally dependent** | | | | | |
| Permanent base flow fed swamps and pools of KI | Water resource, agriculture | Level, quality | M | H | M |
| Riparian swamplands in Mount Lofty Ranges | Water resource, agriculture | Level, quality | M | H | M |

| Ecosystem | Threat: Process | Threat: GW attribute | Vulnerability to threat | Risk that threat realised | Conservation value of system |
|---|---|---|---|---|---|
| Coastal swamp scrub sedgelands in near-coastal dunes of upper south east SA | Agriculture | Level | H | M | M |
| **Opportunistic systems** | | | | | |
| Coorong ecosystems | Agriculture, water resource | Level, quality | M | H | H |
| Terminal lakes and swamps of inland rivers draining SA ranges | Agriculture, water resource | Level | H | M | M |

### *GDE systems*

Lamontgne (2002) summarises GDEs in South Australia according to the types of system, these being.

#### GDE wetlands

A great variety of GDEs in SA are wetlands, in fact most, but not all, wetlands rely to some extent on groundwater (Lamontagne 2002). These include:

- Permanent lakes and ponds (e.g. Blue Lake and Piccaninnie Ponds in the South-East).
- *Eucalyptus camaldulensis* and *E. largiflorens* woodlands along the River Murray.
- Swamp forests and woodlands (various species) in the Mount Lofty Ranges.
- Peat swamps and freshwater swamps on the Fleurieu Peninsula.
- Saline swamps and coastal heath ecosystems on the southern and western Eyre Peninsula.
- *Melaleuca* swamps in internal drainages on the Yorke Peninsula and in the upper South-East.
- Permanent swamps and lakes in solution hollows on Kangaroo Island.
- Emergent herblands (fens) on Eight Mile Creek (lower South-East).

The mound springs of the GAB are entirely dependent on groundwater. In South Australia there are around 1700 individual springs located in 23 spring complexes. The GAB springs largely occur along the margins of the GAB, the Dalhousie Springs are an exception that occur in the in a faulted zone of the confining beds.

It is estimated that 66% of wetland area in South Australia has been lost since European settlement (Government of South Australia, 2006).

**Threats**: Declining water tables, drainage for agriculture, less frequent floods (due to river regulation), invasion by exotics and salinity.

#### Terrestrial vegetation

This includes plant communities that are dependent on groundwater; these are often similar to wetland communities but are located in areas where the water table is sub-surface. During winter, rain-derived soilwater may contribute to these communities and during summer groundwater is the sole source of water (Lamontagne 2002). Examples in SA include:

- *Eucalyptus camaldulensis* and *E. largiflorens* woodlands on the River Murray floodplain (also listed above).
- *Eucalyptus camaldulensis* woodlands on southern and western Eyre Peninsula.
- *Melaleuca halmaturorum* shrublands and *Eucalyptus* spp. woodlands in the South-East.

**Threats**: Declining water table, salinity, drowning (rising water tables).

**Baseflow systems**

Streams where flowing water is maintained during extended dry periods:

- Eight-Mile Creek and the Glenelg River in the South-East.
- Streams in the Mount Lofty Ranges and Kangaroo Island with permanent flow or permanent groundwater-fed pools, such as Christie Creek (Wilkinson et al. 2006).

**Threats**: Declining water table, salinity, decreased recharge from alluvial aquifers and pumping of water from permanent pools.

**Cave and aquifer ecosytems**

Life exists in a continuum at the interface between ground and surface water systems (Lamontagne 2002). Surface water organisms may seek refuge in groundwater, and true groundwater organisms are permanent cave or aquifer dwellers.

Cave organisms are known as stygofauna and are grouped by size:

- Macrofauna – typically in karstic systems; those with large pore sizes (e.g. fractured rock or coarse alluvium) and including invertebrates (such as crustaceans) and some fish.
- Meiofauna – small invertebrates and protozoans dominate in aquifers with small pore sizes (but probably exist in bigger systems).
- Microfauna – bacteria, fungi and small protists – these may be ubiquitous to all aquifer systems.

Additionally stygofauna may be grouped by habitat, in respect to their favoured zone within the groundwater system or interface with surface water (the hyporheic zone):

- Stygoxenes – accidentally occur in caves or stream sediments.
- Stygophiles – associated with the hyporheic zone of streams or alluvial aquifers, often taking refuge during unfavourable surface water conditions.
    - Occasional hyporheos – no requirement of sub-surface environment, but may be found there.
    - Amphibites – require both sub-surface and surface zone to complete life cycle.
    - Permanent hyporheos – complete life cycle in sub-surface zone, but could survive in surface zone.
- Stygobytes – subterranean organisms that cannot survive in surface environments.

Examples of stygofauna and cave/aquifer ecosystems in SA:

- Endemic stygobytes in south-eastern SA karst systems.
- Rare stromatolites in south eastern SA lakes and karst systems.
- Hyporheic communities at stream terminals draining the Flinders Ranges.

- Karst ecosytems in the south east and Nullarbor.
- Mount Lofty Ranges stygofauna in fractured bedrock aquifers.
- Murray-Darling Basin meiofauna and microfauna.

Aquifer ecosystems contribute to nutrient cycling, biological productivity in streams and eliminate pathogens and contaminants (Humphries 2002).

**Threats:** Declining water table, groundwater pollution (anoxia, salinity).

**Estuarine and near-shore ecosystems**

Submarine groundwater discharges can create special conditions that lead to the development of distinct ecosystem assemblages. Coastal swamps, mangroves, lagoons and marshes may be partly groundwater fed. Nutrient rich groundwater may also contribute to estuarine and coastal eutrophication. Submarine discharges in SA have received little attention (Lamontagne 2002).

**Terrestrial fauna and avifauna**

Groundwater systems contribute to the support of terrestrial fauna, e.g. migratory birds may rely on specific known watering holes on migratory paths and large terrestrial animals may rely on these during dry or drought periods.

**Threats:** Declining water table, salinity.

# 2. ECOLOGICAL DATA WAREHOUSE (EDW) FOR WATER DEPENDENT ECOSYSTEMS IN SOUTH AUSTRALIA: THE PROTOTYPE

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## 1. Introduction

Arid conditions in South Australia make the ecology of streams and floodplain wetlands distinctively water dependent. Therefore both streams and floodplain wetlands are considered as water dependent ecosystems in the context of this study.

Water quality monitoring as well as surveys of habitats and aquatic communities are being the common practice over the past few decades in order to assess the integrity and health of freshwater ecosystems. However monitoring and surveying activities were often independently initiated and undertaken by governmental organisations, water industries, local catchment boards and community groups with little coordination and standardisation. As a result a wealth of complex ecological data is currently being accumulated in a highly fragmented manner with little merits for data sharing, integration and exploration.

Recent developments in information technology such as metadata concepts and object-oriented programming facilitate novel data warehousing for both optimal management and mining of complex ecological data (e.g. Michener *et al.* 1997; Dolk 2000; Sen 2003; Eleveld, Schrimpf and Siegert 2003).

The present report provides the general scope, data structures and implementation of a prototype ecological data warehouse (EDW) designed for complex data from water dependent ecosystems in South Australia. It aims to facilitate the best practice frame work for monitoring and evaluation of water–dependent ecosystems as outlined by Wilkinson and Napier (2006).

## 2. Materials and Methods

### *2.1. General Scope of the Ecological Data Warehouse (EDW)*

Figure 1 shows the basic structure and functioning of the EDW designed for complex ecological data. It is accessible by a web based user interface that facilitates interactive communication. The EDW provides two major functions that are closely inter related: data management and data mining. Data management provides the framework for data acquisition, archiving, retrieval, sharing, documentation and visualisation. Data mining provides tools for statistics, ordination and clustering, as well as predictive modelling. Figure 2 shows the software components that facilitate the information flow and processing in the data warehouse. The data acquisition component provides an interface based on SQL for the loading and cleaning of either historical or on-line data. The data archiving component utilises ORACLE as platform and is closely linked to both metadata processing by means of XML as well as data analysis and modelling software implemented by JAVA, $C^{++}$ and GIS.

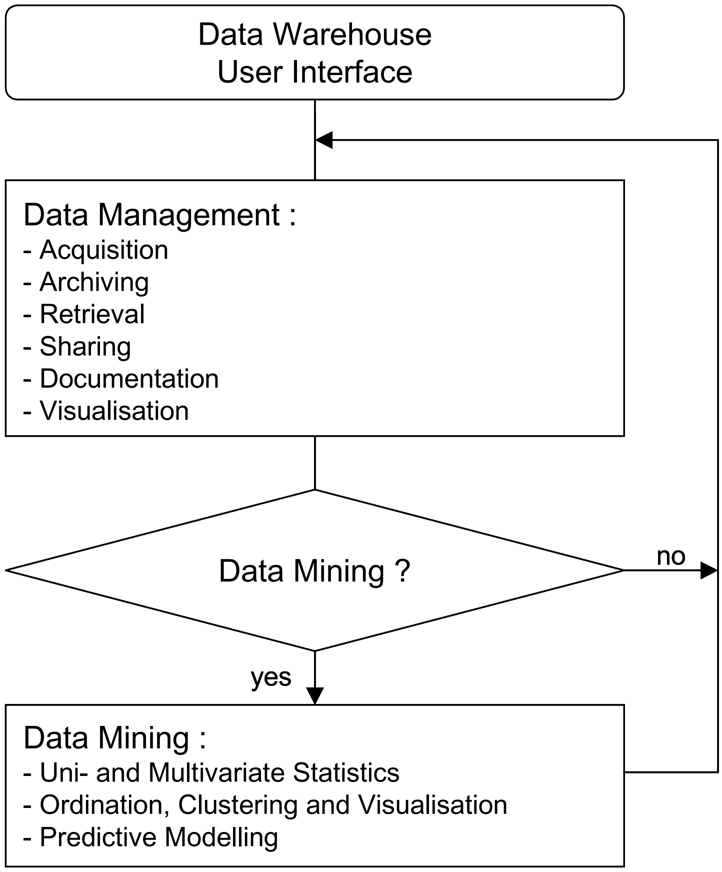



**Figure 1. Structure and functions of the EDW.**

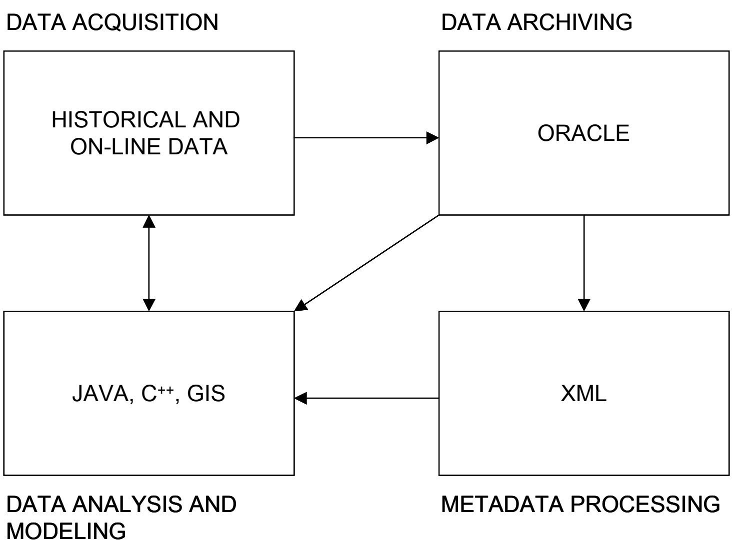



**Figure 2. Software components of the EDW.**

The Figure 3 illustrates the interactions between the data acquisition and archiving components.

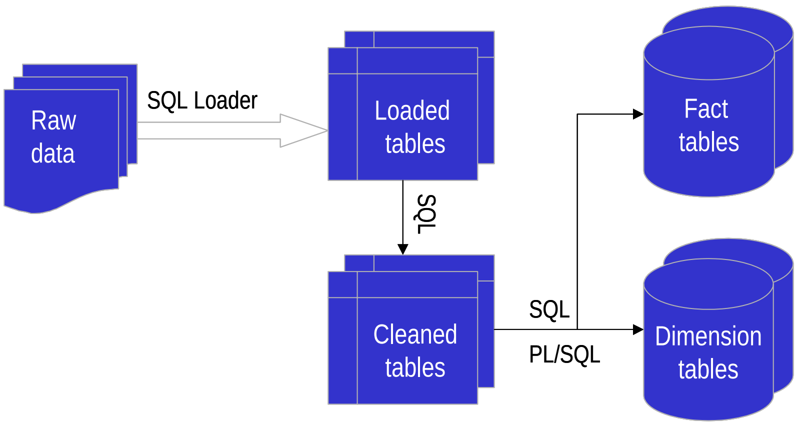



**Figure 3. Implementation of the data acquisition and archiving components of the EDW.**

## *2.2. General Data Structure of the Ecological Data Warehouse*

The data structure of the EDW reflects site-specific properties of habitats, water quality as well as communities of diatoms, macroinvertebrates as well as potentially macrophytes and fish in a standardised and highly flexible manner as shown in Figure 4. It also provides metadata on the geographic and geological properties of the landscape surrounding the site, the definitions of variables, sampling and measurement techniques as well as domain knowledge of stream and wetland ecology.

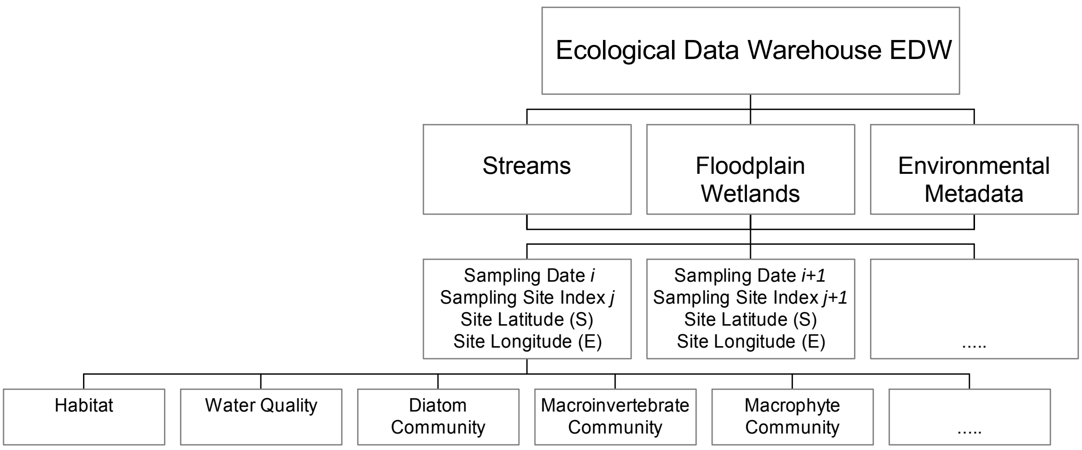



**Figure 4. General data structure of the EDW.**

The categorical and numerical variables that are considered for the description of habitat properties are summarised in Figure 5. These variables reflect pedo-, geo- and hydrological characteristics of stream beds and wetland sediments as well as average meteorological conditions at the study sites.

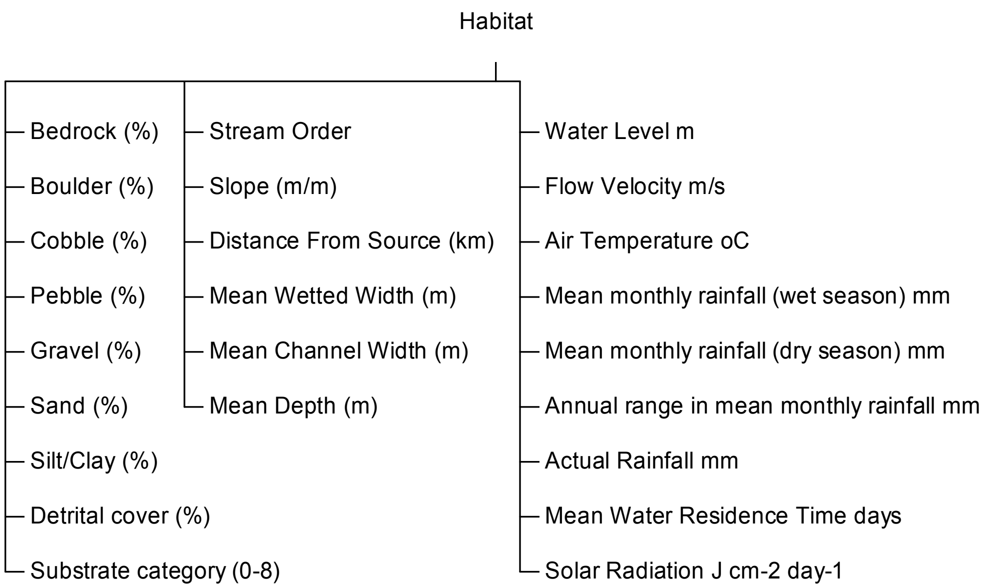



**Figure 5. Data structure for the site-specific description of habitats.**

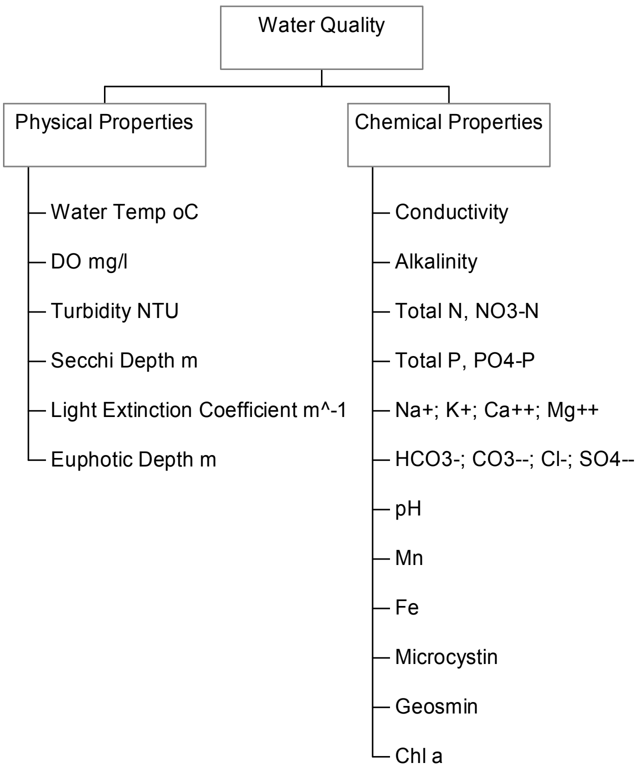



**Figure 6. Data structure for the site-specific description of water quality.**

The Figure 6 distinguishes physical and chemical properties that are typically monitored for the assessment of site-specific water quality. Whilst most of the chemical properties such as phosphorus and nitrogen compounds require sample-specific spectrophotometric analysis in the lab, some of the chemical and physical parameters can be electronically measured and telemetrically transmitted by on-line water quality dataloggers.

A typical data structure for describing diatom communities is represented in Figure 7 by providing details on species abundances in absolute or relative terms as well as presence and absence, and the site specific species richness or diversity.

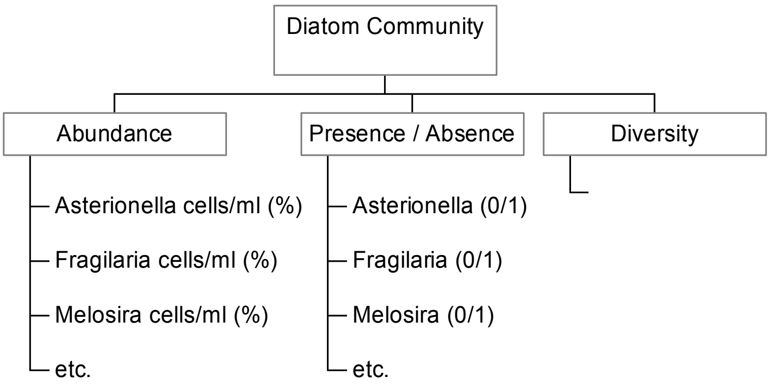



**Figure 7. Data structure for the site-specific description of diatom communities.**

Figure 8 shows a similar structure for the description of macroinvertebrate communities as for diatoms but distinguishes sampling techniques from where the community data originate.

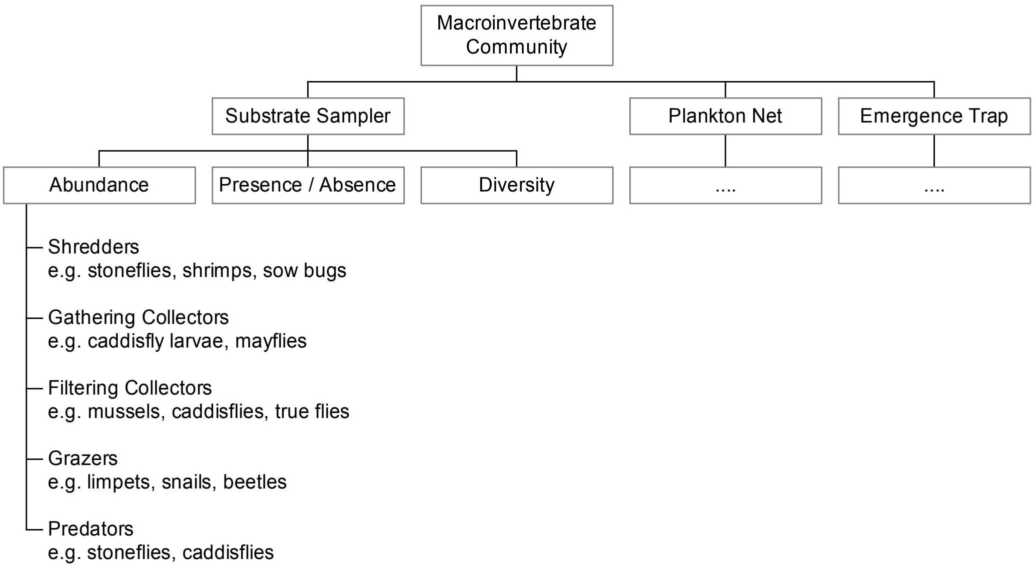



**Figure 8. Data structure for the site-specific description of macroinvertebrate communities.**

## *2.3. Data Sources*

The Tables 1a and b provide a summary of ecological stream and wetland data currently archived and processed in the EDW.

**Table 1a. Ecological data currently archived in the EDW.**

| ID | Catchment | Patawalonga and Torrens Catchment | | | Lower Murray Catchment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Source | Torrens and Patawalonga Catchment Water Management Board | | | Department for Environment and Heritage | | | The University of Adelaide | | | River Murray Catchment Water Management Board | | |
| | *Variables* | *Min* | *Avg* | *Max* | *Min* | *Avg* | *Max* | *Min* | *Avg* | *Max* | *Min* | *Avg* | *Max* |
| 1 | Algae | | | | 5.0 | 14.8 | 70.0 | | | | | | |
| 2 | Alkalinity | 7.0 | 172.4 | 611.0 | 11.5 | 101.7 | 1190.0 | | | | | | |
| 3 | Altitude | | | | 5 | 10 | 20 | | | | | Yes | |
| 4 | Ammonium | | | | | | | 0.092 | 4.712 | 92.722 | | | |
| 5 | Atrazine | 0.460 | 1.068 | 2.500 | | | | | | | | | |
| 6 | Bedrock | | | | 40 | 40 | 40 | | | | | | |
| 7 | Bicarb | 8.0 | 206.9 | 721.0 | 8.0 | 123.6 | 1450.0 | | | | | | |
| 8 | Boulder | | | | 5 | 12 | 30 | | | | | | |
| 9 | Cadmium | 0.00008 | 0.00011 | 0.00110 | | | | | | | | | |
| 10 | Calcium | 0.0002 | 6.5370 | 122.0000 | | | | | | | | | |
| 61 | Catchment Area | | | | 1008850 | 1024751 | 1038850 | | | | | | |
| 11 | Chloride | 24 | 290 | 122 | | | | | | | | | |
| 12 | Chromium | 0.001 | 0.012 | 1.360 | | | | | | | | | |
| 13 | Clay | | | | 5 | 27 | 90 | | | | | | |
| 14 | Cobble | | | | 2 | 12 | 30 | | | | | | |
| 15 | Coliforms | 1 | 10077 | 210000 | | | | | | | | | |
| 16 | Colour | 2 | 40 | 200 | | | | | | | | | |
| 17 | Copper | 0.002 | 0.019 | 0.566 | | | | | | | | | |
| 18 | Dacthal | 0.050 | 0.075 | 0.100 | | | | | | | | | |
| 56 | Depth | | | | | | | 0.063 | 0.294 | 1.092 | | | |
| 19 | Detritus | | | | 5 | 26 | 100 | | | | | | |
| | Diatoms (114 Species) | | | | | | | | 114 Species | | | | |
| 20 | Dieldrin | 0.030 | 0.030 | 0.030 | | | | | | | | | |
| 21 | Dissolved Oxygen | 0.400 | 8.837 | 24.800 | 1.030 | 9.460 | 20.250 | 1.482 | 7.780 | 13.752 | | Yes | |
| 57 | Distance from source | | | | 1930 | 2087 | 2218 | | | | | | |
| 22 | Electrical Conductivity | 81 | 1004 | 4960 | 118 | 11145 | 279881 | 134 | 6525 | 136550 | | Yes | |
| 23 | Faecal Coliforms | 11 | 1254 | 26000 | | | | | | | | | |
| 24 | Faecal Streps | 19 | 1334 | 19000 | | | | | | | | | |
| 25 | Flow Velocity | 0.020 | 0.214 | 1.000 | | | | | | | | | |
| 26 | Flow Volume | 0.0001 | 106.4632 | 15658.0200 | | | | | | | | | |
| 27 | Gravel | | | | 5 | 10 | 50 | | | | | | |
| 28 | Herbicides | 0.050 | 2.853 | 7.000 | | | | | | | | | |
| 29 | Insecticides | 0.030 | 0.030 | 0.030 | | | | | | | | | |
| 30 | Lead | 0.0004 | 0.0265 | 0.8040 | | | | | | | | | |

**Table 1b. Ecological data currently archived in the EDW.**

| ID | Catchment | Patawalonga & Torrens Catchment | | | Lower Murray Catchment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Source | Torrens and Patawalonga Catchment Water Management Board | | | Department for Environment and Heritage | | | The University of Adelaide | | | River Murray Catchment Water Management Board | | |
| | *Variables* | *Min* | *Avg* | *Max* | *Min* | *Avg* | *Max* | *Min* | *Avg* | *Max* | *Min* | *Avg* | *Max* |
| 55 | Macrophyte | | | | 5 | 30 | 60 | | | | | | |
| | Macroinvertebrates (<1243 Species) | | >459 Species | | | >433 Species | | | | | | >120 Species | |
| 31 | Magnesium | 3.2 | 36.6 | 130.0 | | | | | | | | | |
| 32 | Maximum Habitat Flow Velocity | | | | 0.050 | 0.120 | | | | | | | |
| 33 | Minimum Habitat Flow Velocity | | | | | 0.120 | 0.370 | | | | | | |
| 34 | Nitrate | | | | | | | 0.453 | 0.789 | 2.413 | | | |
| 35 | Nitrate+Nitrite | 0.002 | 0.622 | 27.800 | | | | | | | | | |
| 36 | Nitrite | 0.002 | 0.011 | 0.190 | | | | | | | | | |
| 37 | Pebble | | | | 5 | 11 | 35 | | | | | | |
| 38 | pH | 6.7 | 7.7 | 9.7 | 6.5 | 8.0 | 9.8 | 6.8 | 7.7 | 8.8 | | Yes | |
| 39 | Phosphate | 0.002 | 0.148 | 7.850 | | | | 0.003 | 0.034 | 0.250 | | | |
| 40 | Potassium | 1.7 | 7.0 | 26.5 | | | | | | | | | |
| 41 | Sand | | | | 5 | 27 | 100 | | | | | | |
| 42 | Silica | 0.990 | 10.734 | 31.000 | | | | 0.033 | 2.692 | 24.433 | | | |
| 43 | Silt | | | | 5 | 21 | 95 | | | | | | |
| 44 | Simazine | 0.560 | 3.336 | 7.000 | | | | | | | | | |
| 45 | Sodium | 18.2 | 167.7 | 814.0 | | | | | | | | | |
| 60 | Stream Order | | | | 8 | 8 | 8 | | | | | | |
| 59 | Stream Slope | | | | Yes | | | | | | | | |
| 46 | Sulfate | 6.6 | 49.7 | 218.0 | | | | | | | | | |
| 47 | Suspended Solids | 1.0 | 53.9 | 2010.0 | | | | | | | | | |
| 48 | TKN | 0.020 | 1.172 | 55.200 | | | | | | | | | |
| 49 | Total Dissolved Solids | 22 | 557 | 3700 | 120 | 6881 | 200000 | 112 | 5466 | 108617 | | | |
| 50 | Total N | 0.022 | 1.794 | 55.470 | | | | | | | | | |
| 51 | Total P | 0.002 | 0.403 | 9.160 | | | | | | | | | |
| 52 | Turbidity | 0.3 | 20.6 | 540.0 | 0.1 | 70.1 | 660.0 | 446.3 | 608.6 | 771.0 | | Yes | |
| 53 | Water Temperature | 7.00 | 15.58 | 28.00 | 9.50 | 19.06 | 39.83 | 6.95 | 12.87 | 19.95 | | Yes | |
| 54 | Zinc | 0.001 | 0.206 | 4.890 | | | | | | | | | |

## *2.4 Data Mining Techniques Integrated into the Ecological Data Warehouse*

The site specific abundance and diversity data for macroinvertebrates and diatoms as well as habitat and water quality data of the water dependent ecosystems considered in this study (see Tables 1a and b) are being archived in the prototype EDW. The EDW provides flexible access to two novel data mining techniques: Kohonen artificial neural networks (KANN) and hybrid evolutionary algorithms (HEA). Figure 9 shows how the two data mining techniques can be applied complementarily in order to facilitate health assessment and forecasting of water dependent ecosystems.

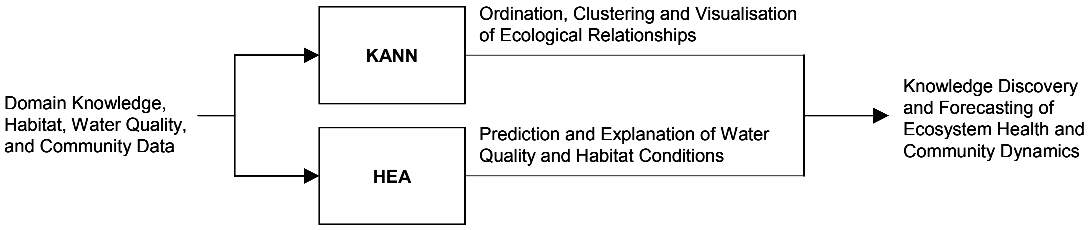



**Figure 9. Framework for the application of data mining by means of KANN and HEA.**

KANN (Kohonen 1995) can be used both to ordinate and cluster complex data, and to project high-dimensional nonlinear data into a lower dimensional space. It consists of an input and a competitive layer (Fig. 10). The competitive layer identifies topological similarities between inputs after their projection into a two-dimensional space. The resulting output can be visualised as clusters. In the context of the proposed project KANN will allow to identify ecological relationships and visualise relational patterns between the water quality, habitat and community data of the water dependent ecosystems. The KANN have successfully been applied for both terrestrial (Giraudel and Lek 2003) and aquatic data (Chon et al. 2003; Recknagel, Kim and Welk 2006; Horrigan et al. 2005; Recknagel et al. 2006; Recknagel, Talib and van der Molen 2006).

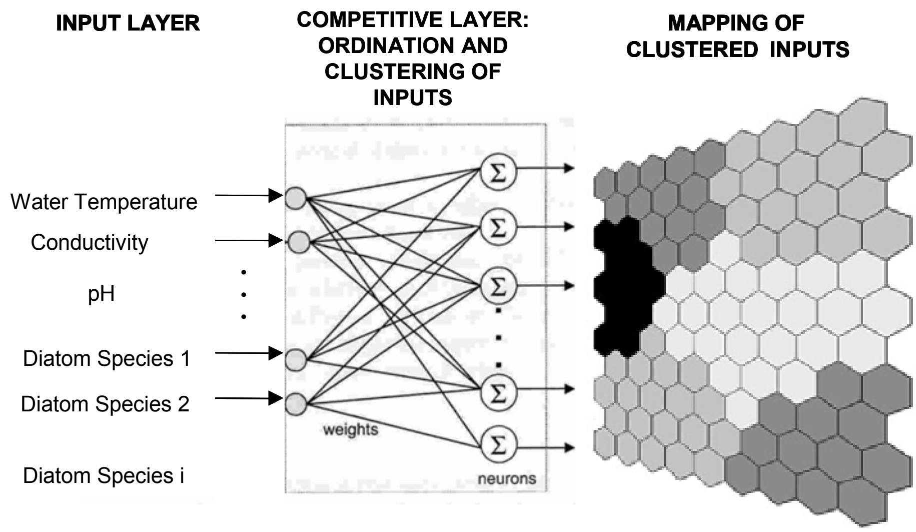



**Figure 10. General structure of a KANN.**

HEA (Cao et al. 2006a) provide an alternative technique for computational modelling based on principles of biological evolution such as natural selection, mutation and cross-over. The resulting rule sets or arithmetic functions discovered by evolutionary algorithms for ecological processes provide both explanation and forecasting for specific output variables such as habitat or water quality conditions (see Fig. 9). Bobbin and Recknagel (2003) and Whigham and Recknagel (2001) successfully applied evolutionary algorithms for the discovery of predictive rules and arithmetic functions for algal blooms in freshwater lakes, and Recknagel et al. (2002) demonstrated their superiority compared to alternative computational methods. The Figure 11 shows the novel hybrid implementation of evolutionary algorithms by Cao et al. (2006a) performing both discovery of predictive rules and multiple parameter optimisation. The algorithm allows to induce predictive and explanatory rule sets which combine domain knowledge with rules evolved from data. It has been successfully tested for modelling phyto- and zooplankton communities in lakes andrivers (Cao et al. 2006a; Cao et al. 2006b).

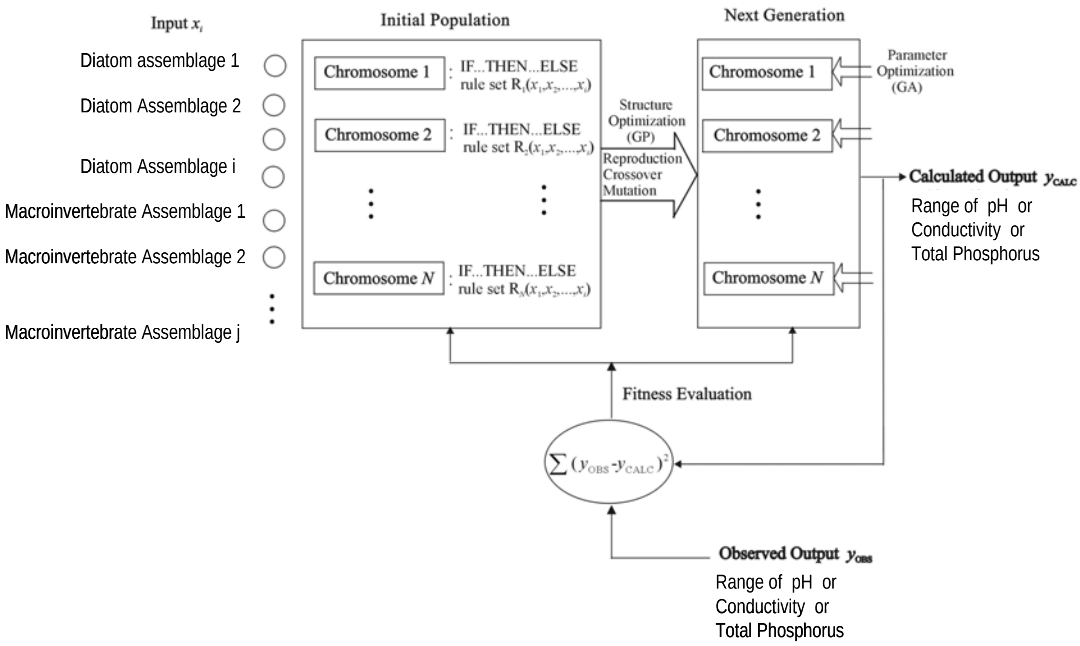



**Figure 11. General structure of HEA.**

## 3. Implementation of the EDW

### *3.1 Logical Design*

The EDW uses the star schema (Kimball 1996) as a structural design. To simplify the technical complexity, we currently design the EDW structure by means of the simple star schema as a prototype.

A simple star schema requires data with at least one fact table and a few dimension tables. A fact table is used to record numerical value of ecological data. A dimension table is used to record alphabetical information of ecological data. For example, the EDW fact table contains a field *pH*, the record of this *pH* field must be a numerical value such as 6.7. In a dimension table, for example, it only stores some information about when, where, and how to collect this *pH* value.

There can be more than one dimension table, which is defined by how many angles the data is viewed from. For example, ecologists usually observe a species' dynamics by the time series. Therefore, a time dimension table is needed to accelerate the query speed on a large amount of numerical data in the fact table. Similarly, a spatial dimension table represents the geographical information showing where to collect these data. In the EDW, the geographical information is categorized from country level to habitat level.

Figure 12 illustrates the whole EDW design structure by means of the simply star schema.

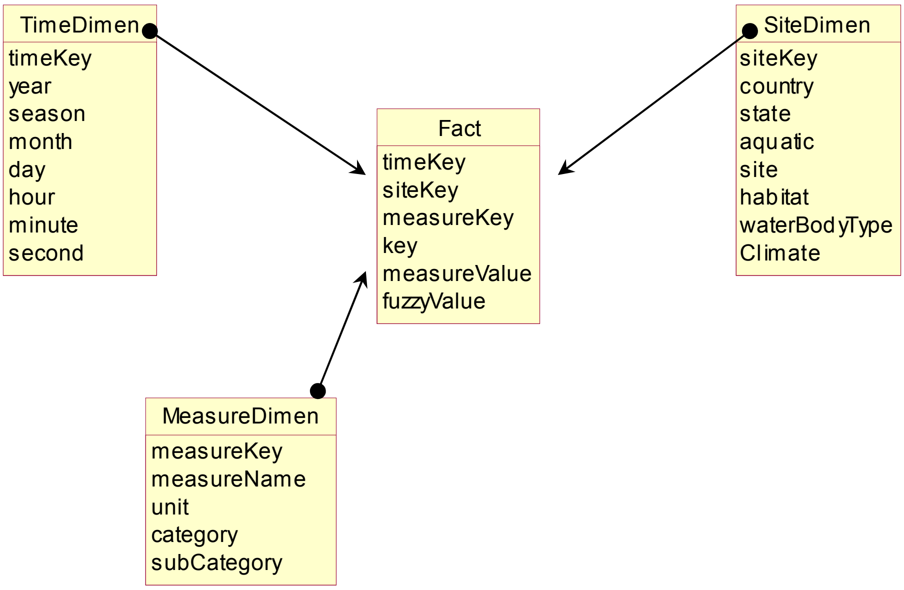



**Figure 12. Star scheme design of the EDW.**

The above paragraphs introduced the internal design of the EDW. To facilitate online analysis of these ecological data, external applications and tools are needed. The EDW uses Java technology to implement some online analysis functions such as queries, reports, or data mining algorithms. Figure 12 lists all of the components in the EDW including the fact table, the dimension tables, the web-enabled software applications and some relevant personnel.

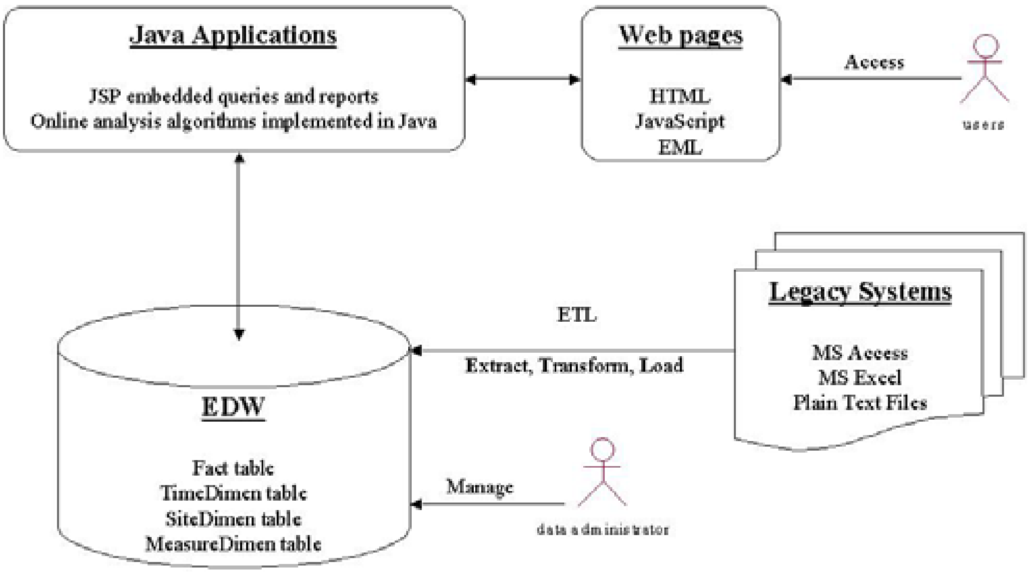



**Figure 13. Development and application of the EDW.**

Figure 13 represents the general process of building and using the EDW. First of all, ecological datasets are converted from raw datasets to the EDW container (cleaned dataset). A data administrator is required to perform this process, which involves some necessary operations such as extraction, transformation, and load (ETL). Secondly, some Java implemented programs perform online analysis functions on this cleaned dataset connected to the EDW. These programs are mainly implemented in Java technology. Alternatively, some commercial software programs can be used (e.g. Matlab). Finally, the EDW provides a user-friendly interface for users (e.g. ecologists, environmentalists, or government officials) to access the ecological data. These users can perform simple queries, or use various software tools to discover patterns from the data and even automatically view a report of the discovered patterns. Moreover, these operations can be done both online and standalone. Ideally, the EDW is available for continuous use, whenever, and wherever a user needs it.

### *3.2. Physical Design*

The EDW prototype only documents detailed physical design processes for the fact and dimension tables. The external applications and tools will be incrementally developed with the varying user requirements.

Inside the EDW tables, the physical design processes aim to complete design table structure, including the table name, the field name, the field type, the field limitation, the field format, and the table dependency (shown in Fig. 12), which are summarised in Table 2.

**Table 2a. The time dimension table structure.**

| NAME | NULL | TYPE | FORMAT | DEFAULT | COMMENT |
|---|---|---|---|---|---|
| TimeKey | pk | char(15) | yyyysmmddhhmmss | 000000000000000 | s: season<br>0: N/A;<br>1: Spring; 2: Summer; 3: Autumn;<br>4: Winter |
| Year | no | char(4) | yyyy | 0000 | |
| Season | yes | char(6) | ###### | | Spring, Summer, Autumn, Winter |
| Month | yes | char(3) | ### | | abbr. e.g. Jan, Jul, Nov, etc |
| Day | yes | char(2) | dd | | [1, 31] |
| Hour | yes | char(2) | hh | | [00, 23] |
| Minute | yes | char(2) | mm | | [00, 59] |
| Second | yes | char(2) | ss | | [00, 59] |

**Table 2b. The site dimension table structure.**

| NAME | NULL | TYPE | FORMAT | DEFAULT | COMMENT |
|---|---|---|---|---|---|
| SiteKey | pk | varchar2(12) | ISOCodes+ State+ SIteCodes+ HabitatCodes | | ISO Country Codes Queensland, Australia: AUQLD; South Australia Australia: AUSA The last two digital are the habitat code e.g. AUSA3455E1 means Angas Creek edge data in SA |
| Country | no | varchar2(50) | | N/A | Full national name |
| State | no | varchar2(50) | | N/A | Full state or province name |
| Aquatic | no | varchar2(30) | | N/A | Stream name |
| Site | no | varchar2(50) | | N/A | Sampling site name |
| Habitat | no | varchar2(10) | | N/A | see Appendix 1 |
| WaterBodyType | no | varchar2(20) | | N/A | see Appendix 2 |
| Climate | no | varchar2(30) | | N/A | e.g. tropical, mediterranean |

**Table 2c. The measure dimension table structure.**

| NAME | NULL | TYPE | FORMAT | DEFAULT | COMMENT |
|---|---|---|---|---|---|
| MeasureKey | pk | char(8) | | | e.g. MEAS0001 represents pH |
| MeasureName | no | varchar2(100) | | | |
| Unit | no | varchar2(10) | | N/A | |
| Category | no | varchar2(50) | | N/A | |
| Sub-category | no | varchar2(50) | | N/A | |

**Table 2d. The fact table structure.**

| NAME | NULL | TYPE | FORMAT | DEFAULT | COMMENT |
|---|---|---|---|---|---|
| TimeKey | fk | char(15) | | | |
| SiteKey | fk | varchar2(12) | | | |
| MeasureKey | fk | char(8) | | | |
| Key | | varchar2(14) | | | The date and time when loading data |
| MeasureValue | yes | number | | | |
| FuzzyValue | yes | number | | | |

The four above tables need to be coded by standard Structured Query Language (SQL), which will eventually create tables into a database product that supports the EDW. Users will be able to access these tables by queries. Figure 14 describes the table structure in SQL. Once these SQL are completed, any database product can execute the code using SQL interface. Oracle (the database product that we use in the EDW project) uses SQL*Plus to implement this function.

```sql
create table timedimen
(
        TimeKey char(15) primary key,
        Year char(4) not null,
        Season char(6),
        Month char(3),
        Day char(2),
        Hour char(2),
        Minute char(2),
        Second char(2)
);

create table sitedimen
(
        SiteKey varchar2(12) primary key,
        Country varchar2(50) not null,
        State varchar2(50) not null,
        Aquatic varchar2(30) not null,
        Site varchar2(50) not null,
        Habitat varchar2(10) not null,
        WaterBodyType varchar2(20) not null,
        Climate varchar(30) not null
);

create table measuredimen
(
        MeasureKey char(8) primary key,
        MeasureName varchar2(100) not null,
        Unit varchar2(10) not null,
        Category varchar2(50) not null,
        Subcategory varchar2(50) not null
);

create table fact3
(
        TimeKey char(15) constraint fk_time3 references timedimen(TimeKey),
        SiteKey varchar2(12) constraint fk_site3 references sitedimen(SiteKey),
        MeasureKey char(8) constraint fk_measure3 references measuredimen(MeasureKey),
        Key varchar2(14) not null,
        MeasureValue number,
        FuzzyValue number,
        constraint pk_fact3 primary key (TimeKey, SiteKey, MeasureKey, Key)
);

create index time_index on fact3 (timekey);
create index site_index on fact3(sitekey);
create index meas_index on fact3(measurekey);
```

**Figure 14. The SQL code for the EDW tables.**

The EDW is ready to be used after creating these tables in Oracle 9i.

### *3.3. Data Processing*

Data processing basically involves a number of operations that enable access to faultless data. In terms of data warehousing, these operations are commonly called ETL (Extract, Transfer, and Load), which generally encompasses various operations such as data cleaning and standardization. ETL operations have responsibility to convert raw to clean datasets. For example, a raw dataset contains one ‘pH’ column that indicates zero values in some rows. This effect makes no sense in the natural world and therefore the zero values need to be deleted from this dataset. However, zero values do mean something for macroinvertebrates. In case of biotic variables, it is important to keep the zero values.

As far as data standardization is concerned, all dataset from different data sources should match one unified standard such as the unit. For instance, the conductivity variable may use ‘mS/cm’ or ‘µS/cm’ as unit format. The database tables only can accommodate one unit format in order to keep efficient information against ad hoc queries. It is crucial to define and adopt one unified standard for all variables before loading cleaned datasets into the database product. Otherwise, data administrators would be overwhelmed to maintain the database tables in the future.

Finally, the metadata issue needs to be addressed during data processing. Metadata means the data about data. For example, it is important to know who collected when by which method specific data. General, metadata is applied to describe structural information. The structural information is different from relational information. The question whether information is structural or relational varies from case to case. Thus, it is recommended to consider the metadata issue in the early stage of data processing.

## *3.4. Deployment*

### 3.4.1 The Simple Deployment of the EDW

The EDW needs to be deployed in at least two workstations. Figure 15 shows an admin console and a server.

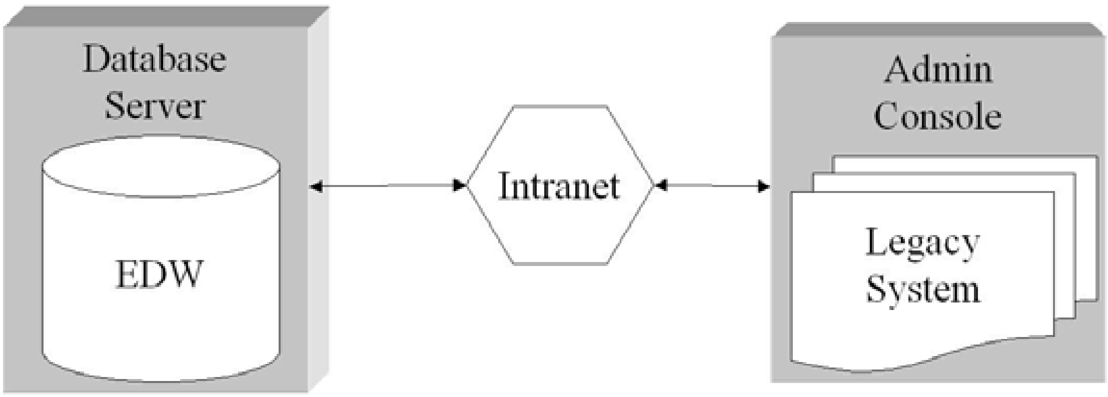



**Figure 15. Server and admin console of the EDW.**

The admin console can be any terminal computer such as a desktop or a laptop. This terminal must install a legacy system that stores the raw ecological data regardless of the data format. These data can be in any format such as plain text file, MS Access, MS Excel, or some image files. The left part of Figure 15 represents a database server, which is a mainframe computer that configures with the Oracle 9i product. All the files in the legacy system need to eventually transfer to the Oracle database in the mainframe.

The deployment process can be time consuming and highly costly. Fortunately, this project takes advantage of the usage of facilities in the University of Adelaide. Therefore, some crucial requirement including computer equipment and database administrator employment will not be discussed in this report.

### 3.4.2 The Comprehensive Deployment of the EDW

The EDW will need two extra machines to deploy Java applications and web-enabled applications. Figure 16 shows a comprehensive deployment of the EDW.

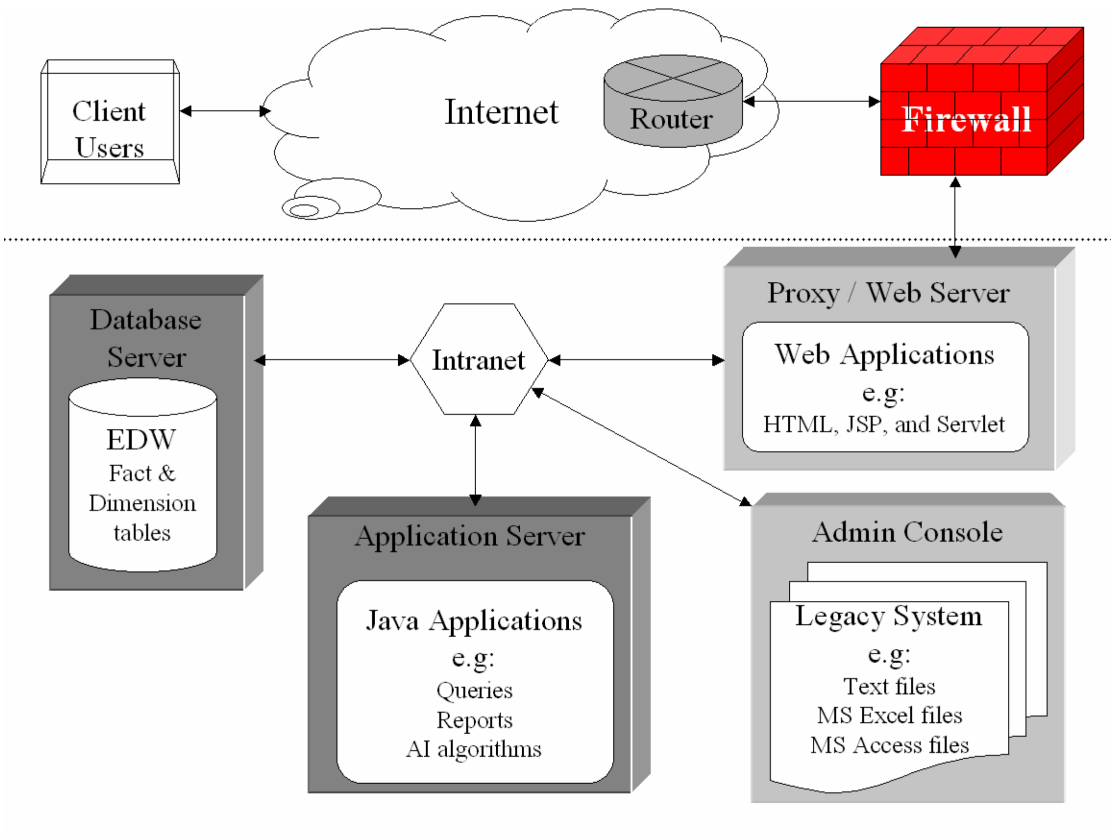



**Figure 16. The EDW comprehensive deployment.**

The dashed line separates the Intranet and the Internet. These two parts are connected by a proxy sever in the Intranet part and a router (through a firewall) in the Internet part. As far as the Intranet part is concerned, the database server and the admin console are exactly as same as the ones in Figure 15. But this deployment strategy needs an application server to contain Java applications, which performs a number of required functionalities of data usage such as queries, reports, and some artificial intelligence algorithms. In addition, a web sever is needed to contain web-enabled applications such as web-based queries, reports, and even security control. In our project, the University of Adelaide may not provide these two servers, and therefore the final target EDW product possibly requires extra equipment.

Above the dashed line, the Internet part represents a terminal connected to the Internet accesses the EDW web pages as a client user. The issue of the Internet part is beyond the discussion of this report.

## *3.5 Demonstration example*

### 3.5.1 Online access to the EDW

This demonstration shows a simple web-based query from the EDW. Suppose a user attempts to review some major chemical variables about water quality, such as pH, NO3, and PO4 value, at Torrens River in 1999. This user can open an Internet Explorer program (IE), and type URL http://envbio398.envbiology.adelaide.edu.au/wdw2/selection.jsp at the IE address bar to open the web-based user interface of the EDW, displayed in Figure 17.

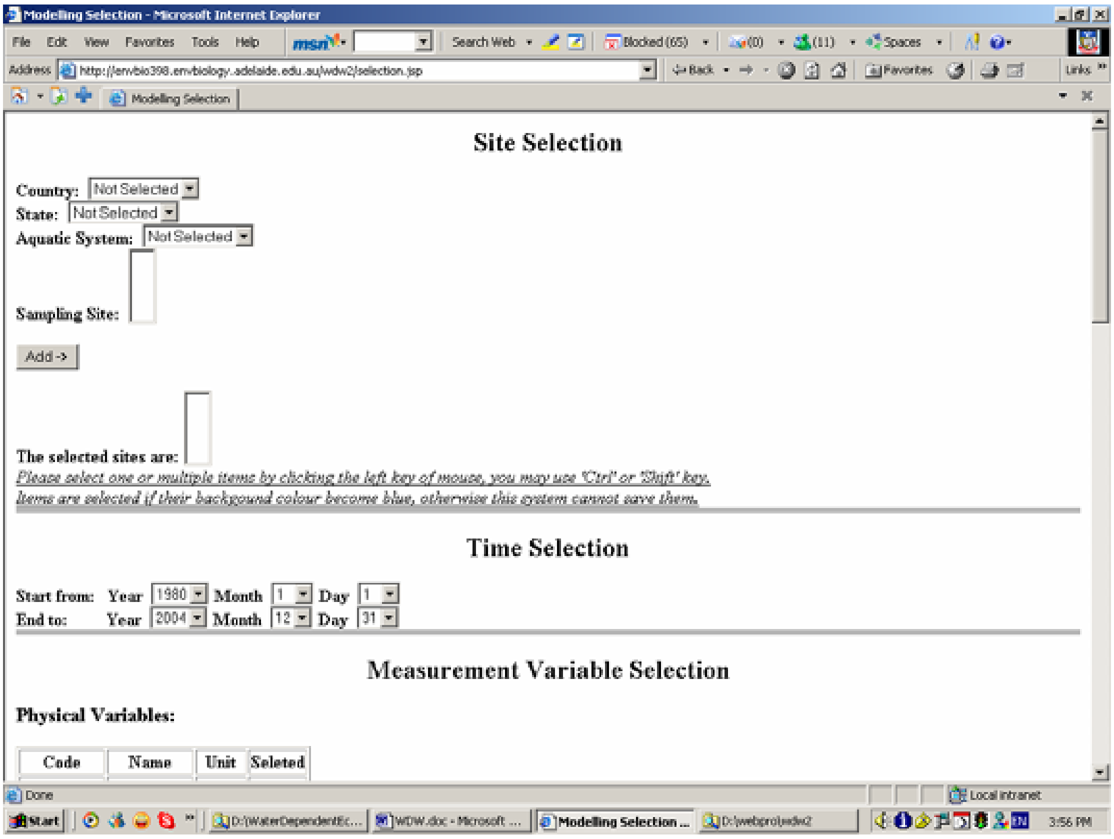



**Figure 17. The web-based user interface of the EDW.**

This user interface allows the user to select Torrens River, 1999, and chemical variables: pH, NO3, and PO4 by clicking the items in the dropdown menu. Therefore, all of the sampling sites for the Torrens River are selected in the *Site Selection* part, as well as the *Time Selection* part to include a time period from Jan 1$^{st}$, 1999 ends to Dec 31$^{st}$, 1999 (Fig. 18).

The user can view the *Measurement Variable Selection* option by dropping down the scroll bar on the right of the user interface. There are four categories for all the measurement variables: physical, chemical, habitat, and biological ones. The user can easily locate pH, NO3, and PO4 variables from the *chemical variables* list. Figure 18 illustrates the ticked pH, NO3, and PO4 variables item. Finally, the query results will be displayed in the next web page after the user clicks the *Submit* button on the bottom of this user interface. These results are listed in Figure 20.

These queried data can be used in rule set discovery by means of Artificial Neural Network (ANN) algorithms.

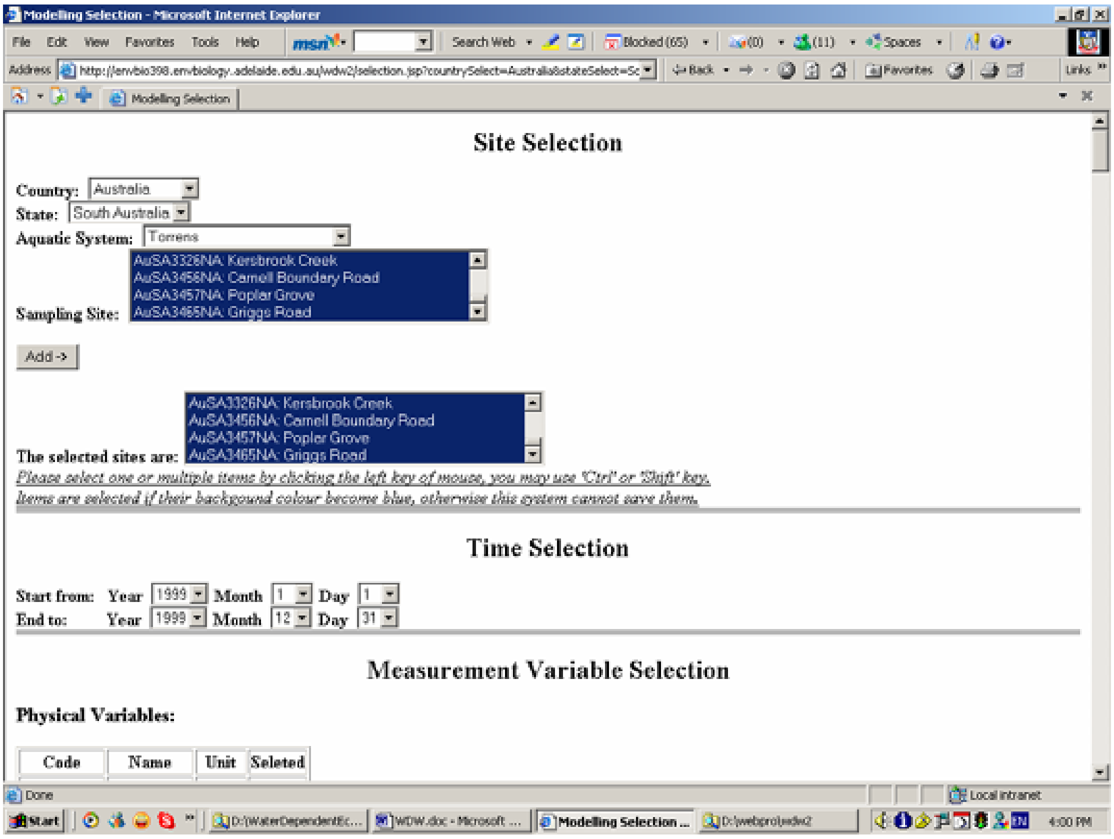


Figure 18. The user selection of all Torrens River sampling sites in 1999.

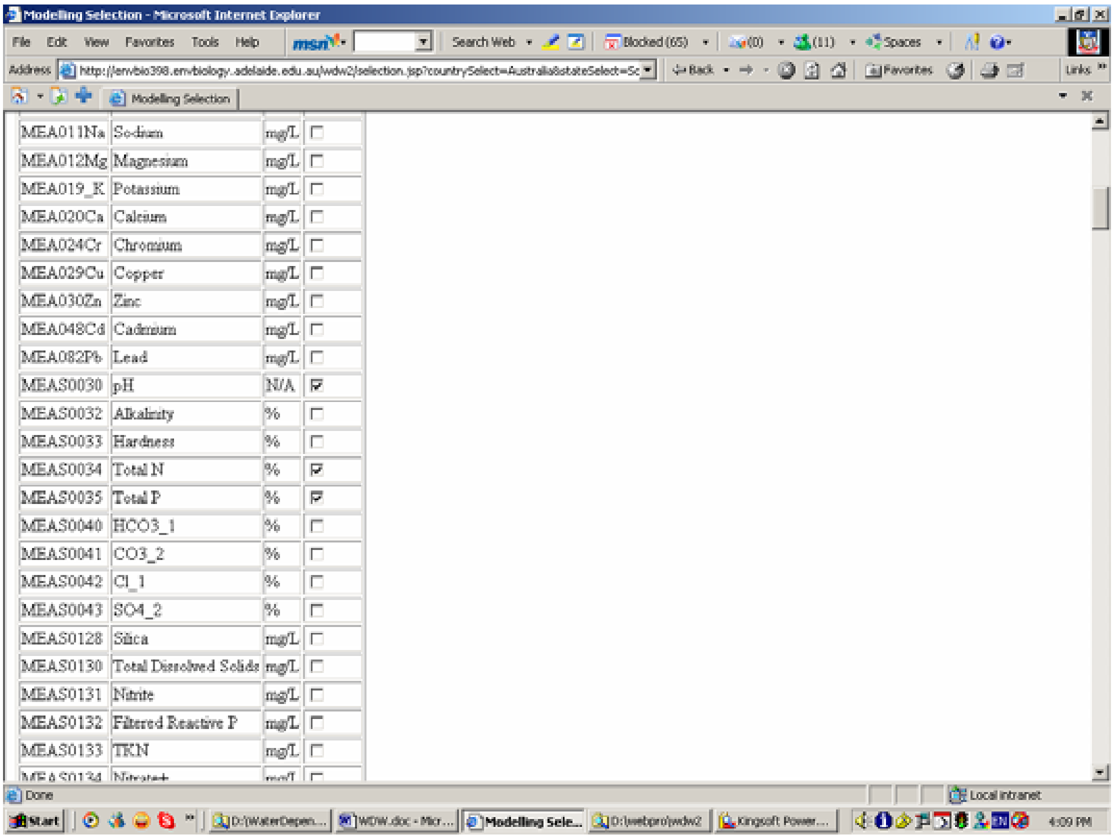
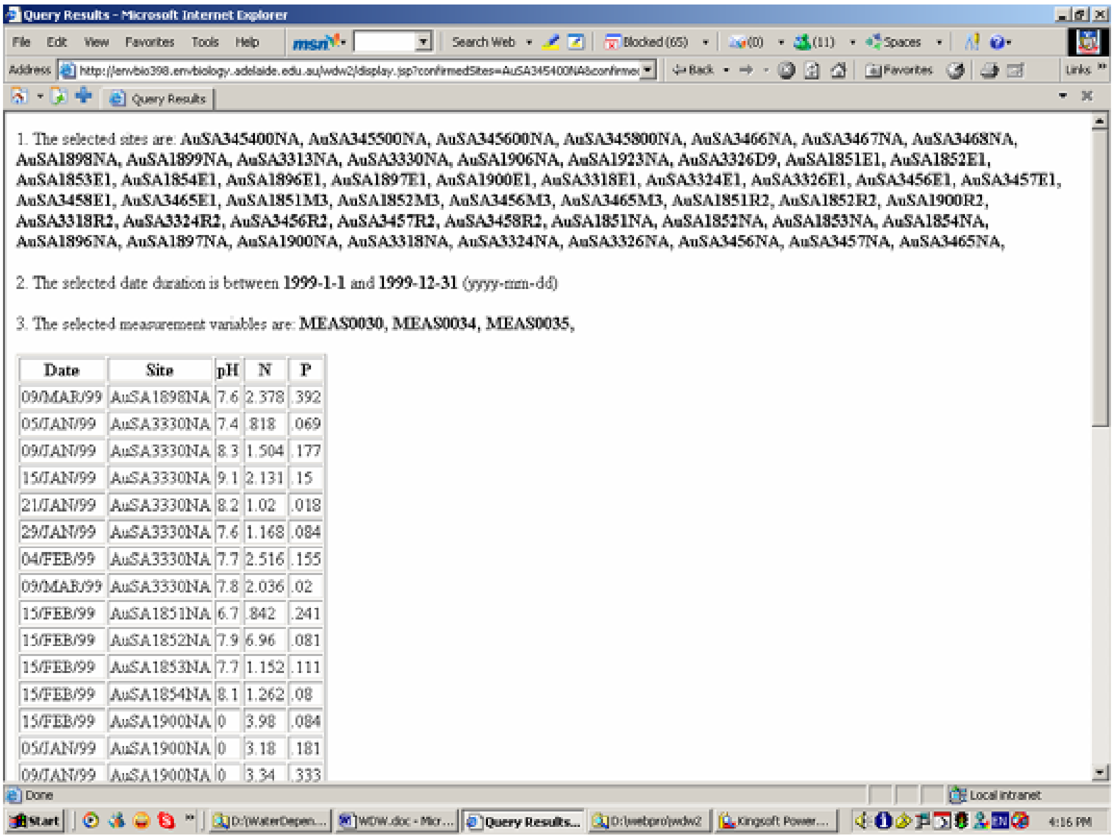


Figure 19. The user ticks pH, NO3, and PO4 variables item.



1. The selected sites are: **AuSA345400NA, AuSA345500NA, AuSA345600NA, AuSA345800NA, AuSA3466NA, AuSA3467NA, AuSA3468NA, AuSA1898NA, AuSA1899NA, AuSA3313NA, AuSA3330NA, AuSA1906NA, AuSA1923NA, AuSA3326D9, AuSA1851E1, AuSA1852E1, AuSA1853E1, AuSA1854E1, AuSA1896E1, AuSA1897E1, AuSA1900E1, AuSA3318E1, AuSA3324E1, AuSA3326E1, AuSA3456E1, AuSA3457E1, AuSA3458E1, AuSA3465E1, AuSA1851M3, AuSA1852M3, AuSA3456M3, AuSA3465M3, AuSA1851R2, AuSA1852R2, AuSA1900R2, AuSA3318R2, AuSA3324R2, AuSA3456R2, AuSA3457R2, AuSA3458R2, AuSA1851NA, AuSA1852NA, AuSA1853NA, AuSA1854NA, AuSA1896NA, AuSA1897NA, AuSA1900NA, AuSA3318NA, AuSA3324NA, AuSA3326NA, AuSA3456NA, AuSA3457NA, AuSA3465NA,**

2. The selected date duration is between **1999-1-1** and **1999-12-31** (yyyy-mm-dd)

3. The selected measurement variables are: **MEAS0030, MEAS0034, MEAS0035,**

| Date | Site | pH | N | P |
|---|---|---|---|---|
| 09/MAR/99 | AuSA1898NA | 7.6 | 2.378 | .392 |
| 05/JAN/99 | AuSA3330NA | 7.4 | .818 | .069 |
| 09/JAN/99 | AuSA3330NA | 8.3 | 1.504 | .177 |
| 15/JAN/99 | AuSA3330NA | 9.1 | 2.131 | .15 |
| 21/JAN/99 | AuSA3330NA | 8.2 | 1.02 | .018 |
| 29/JAN/99 | AuSA3330NA | 7.6 | 1.168 | .084 |
| 04/FEB/99 | AuSA3330NA | 7.7 | 2.516 | .155 |
| 09/MAR/99 | AuSA3330NA | 7.8 | 2.036 | .02 |
| 15/FEB/99 | AuSA1851NA | 6.7 | .842 | .241 |
| 15/FEB/99 | AuSA1852NA | 7.9 | 6.96 | .081 |
| 15/FEB/99 | AuSA1853NA | 7.7 | 1.152 | .111 |
| 15/FEB/99 | AuSA1854NA | 8.1 | 1.262 | .08 |
| 15/FEB/99 | AuSA1900NA | 0 | 3.98 | .084 |
| 05/JAN/99 | AuSA1900NA | 0 | 3.18 | .181 |
| 09/JAN/99 | AuSA1900NA | 0 | 3.34 | .333 |

**Figure 20. The query results of pH, NO3, and PO4 value at Torrens River in 1999.**

### 3.5.2 Sites Comparison in Satellite Maps

The EDW web-GUIs also provide site comparison function. Users can select more than one site for comparison purpose. Basically, the data that occur at different sites would only be available at a certain time point such as the same day. Figures 21 (a)–(f) show an example of six-selected sites to be compared on 7 Nov 2002. Figure 21(d) lists the query results in the form of tables regarding to the selected sties, time, and measure variables (pH, Water Temperature, and some macroinvertebrates). There is a link ‘Show Map’ in the bottom of Figure 21(d). User can click it to view the real satellite map that indicates the selected sites (Fig. 21(e)). Alternatively, user can view the macroinvertebrate distribution at one certain site by clicking the blue site code. The result is showed in Figure 21(f).

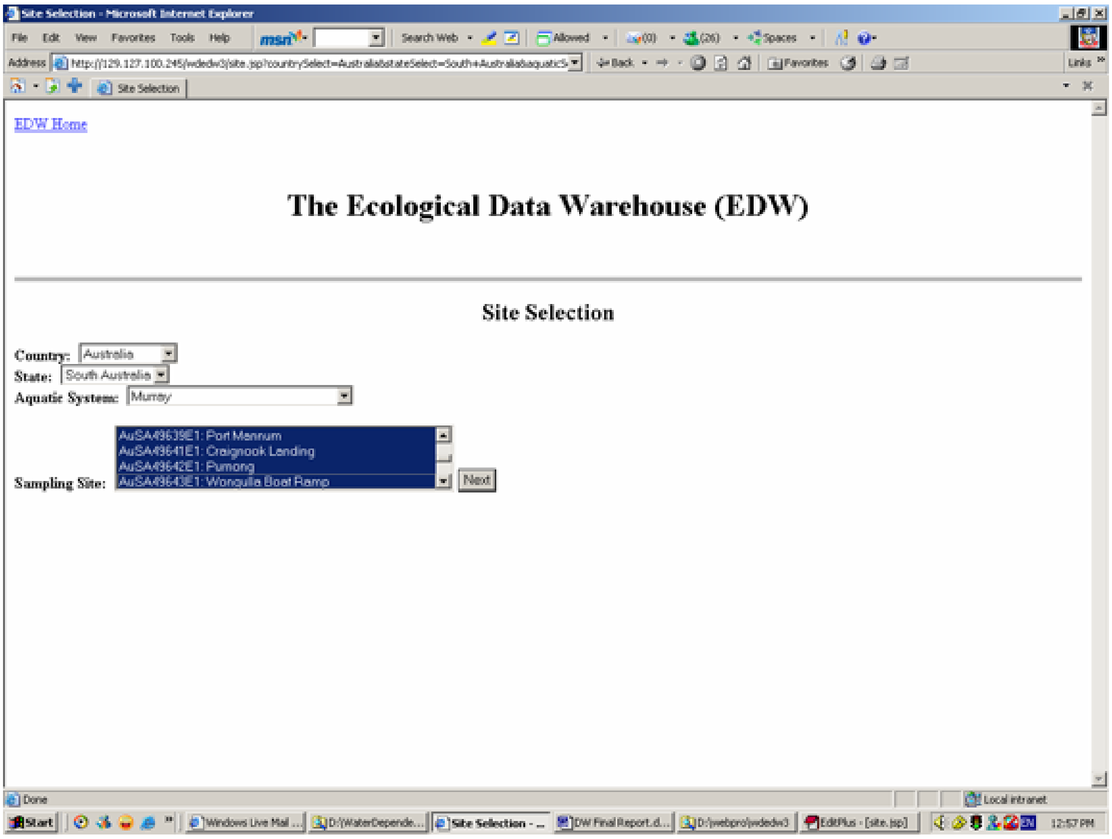



**Figure 21(a). Site selection web page – select the comparable sites.**

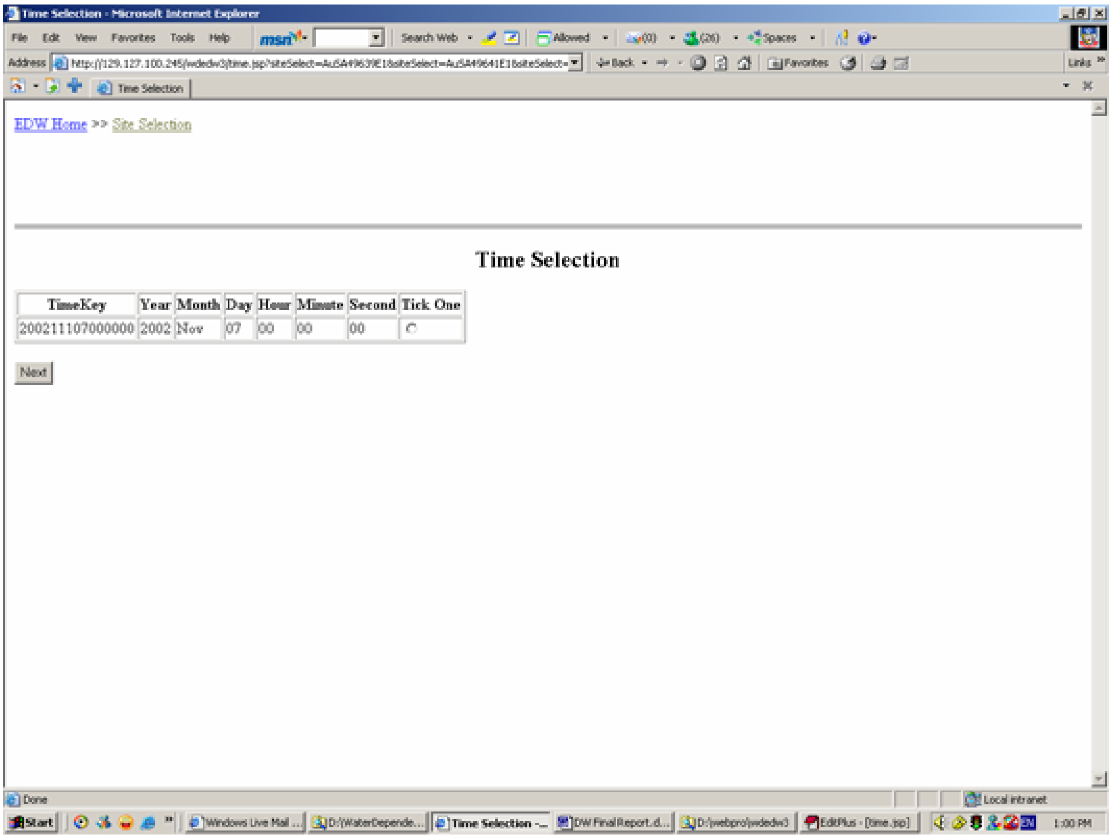



**Figure 21(b). Time selection web page – select the day that compares the sites.**

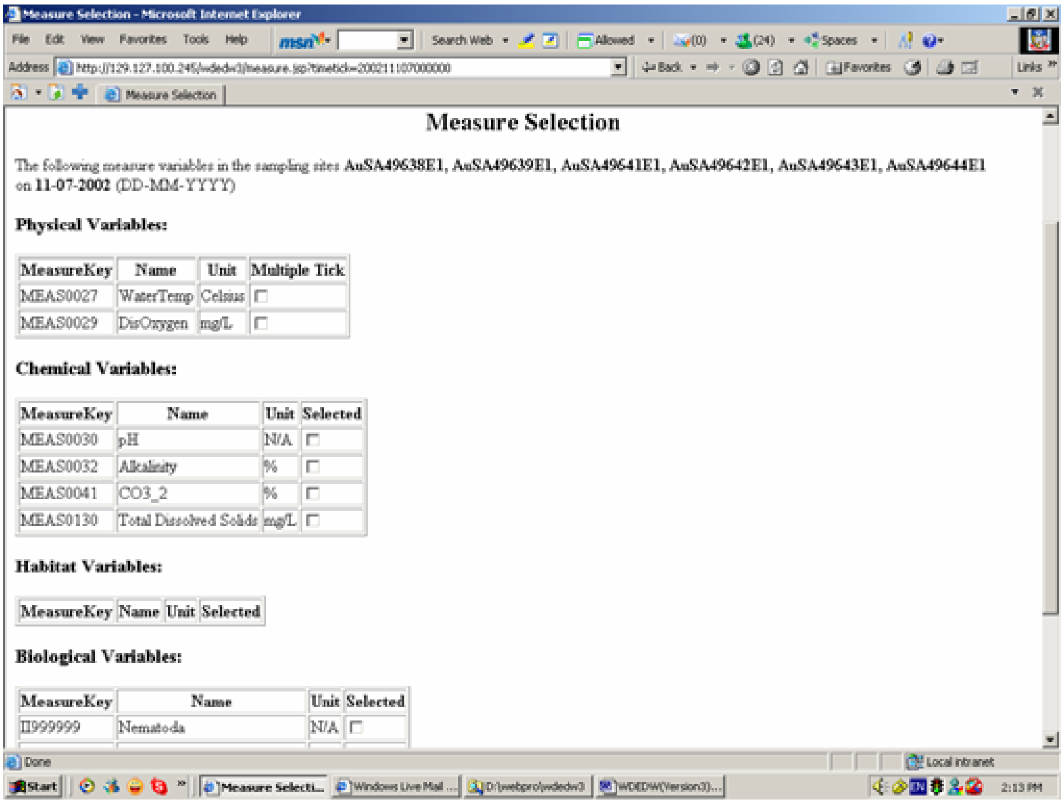
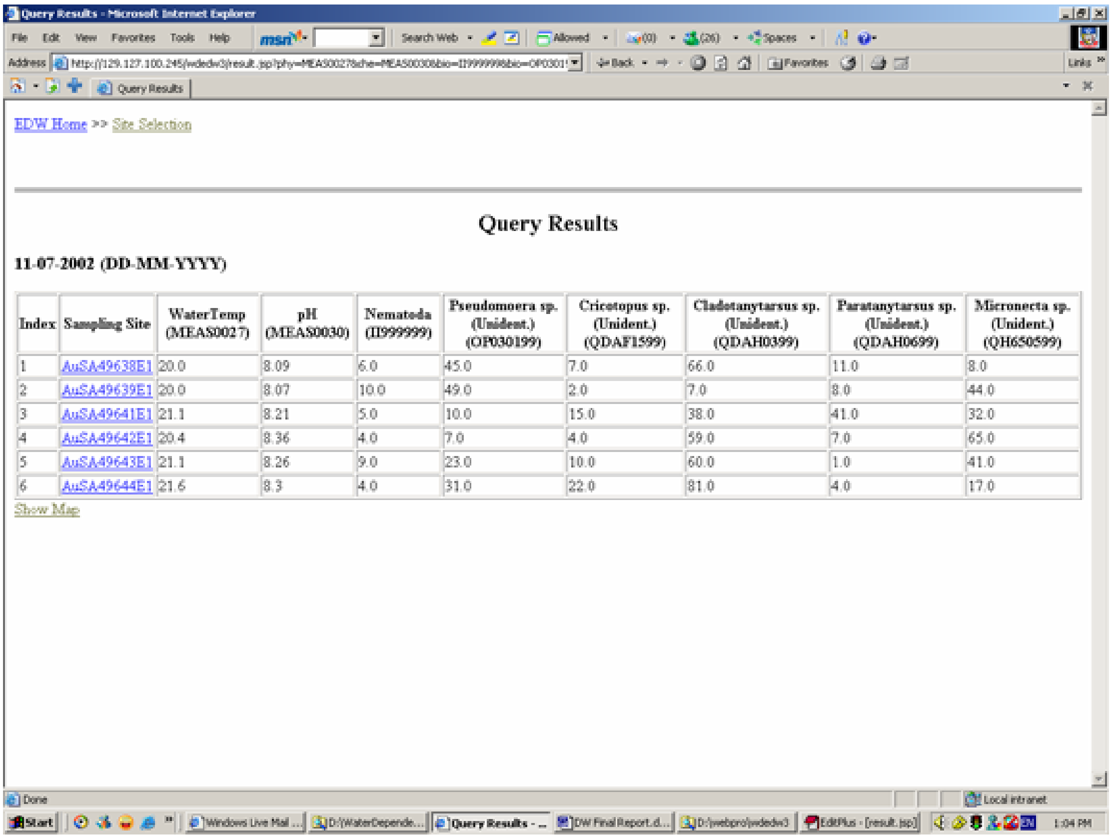



**Figure 21(c).** **Measure selection web page – the available measurement variables regarding to the selected sites and time.**




| Index | Sampling Site | WaterTemp (MEAS0027) | pH (MEAS0030) | Nematoda (II999999) | Pseudomoera sp. (Unident.) (OP030199) | Cricotopus sp. (Unident.) (QDAF1599) | Cladotanytarsus sp. (Unident.) (QDAH0399) | Paratanytarsus sp. (Unident.) (QDAH0699) | Micronecta sp. (Unident.) (QH650599) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | AuSA49638E1 | 20.0 | 8.09 | 6.0 | 45.0 | 7.0 | 66.0 | 11.0 | 8.0 |
| 2 | AuSA49639E1 | 20.0 | 8.07 | 10.0 | 49.0 | 2.0 | 7.0 | 8.0 | 44.0 |
| 3 | AuSA49641E1 | 21.1 | 8.21 | 5.0 | 10.0 | 15.0 | 38.0 | 41.0 | 32.0 |
| 4 | AuSA49642E1 | 20.4 | 8.36 | 4.0 | 7.0 | 4.0 | 59.0 | 7.0 | 65.0 |
| 5 | AuSA49643E1 | 21.1 | 8.26 | 9.0 | 23.0 | 10.0 | 60.0 | 1.0 | 41.0 |
| 6 | AuSA49644E1 | 21.6 | 8.3 | 4.0 | 31.0 | 22.0 | 81.0 | 4.0 | 17.0 |

**Figure 21(d).** **Query results web page – pH, water temperature, and some macroinvertebrates**

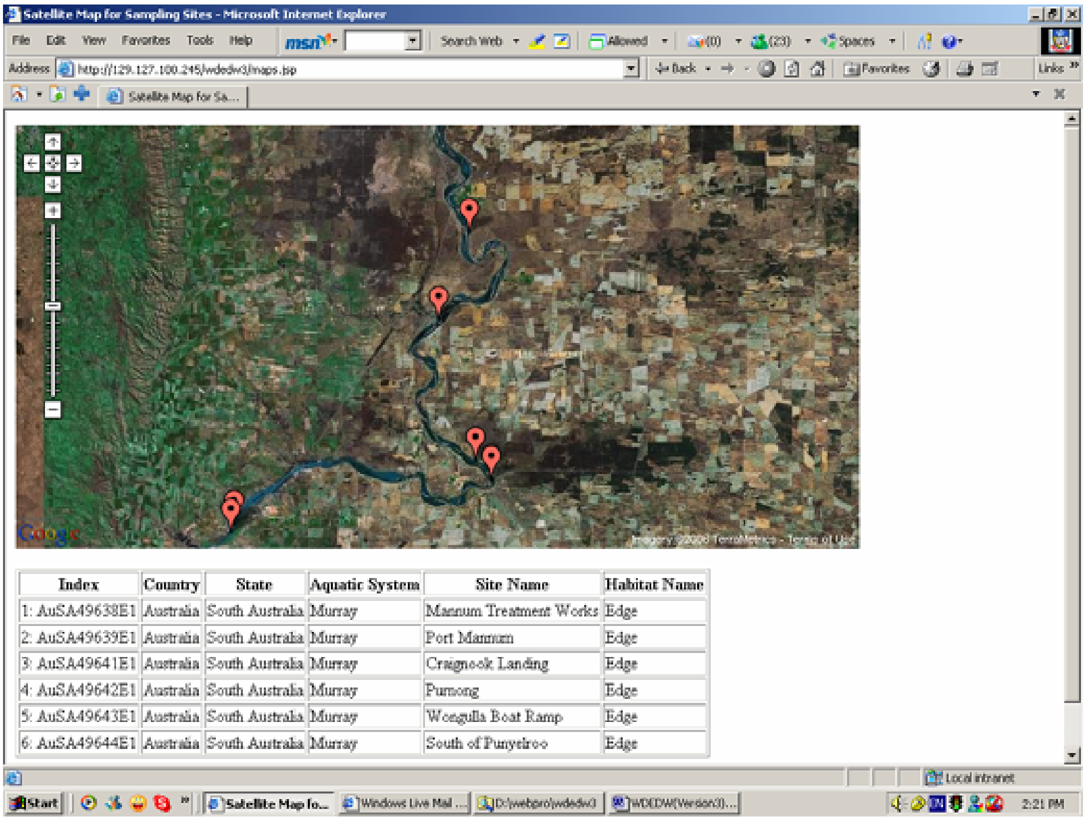



**Figure 21(e). Satellite map web page**

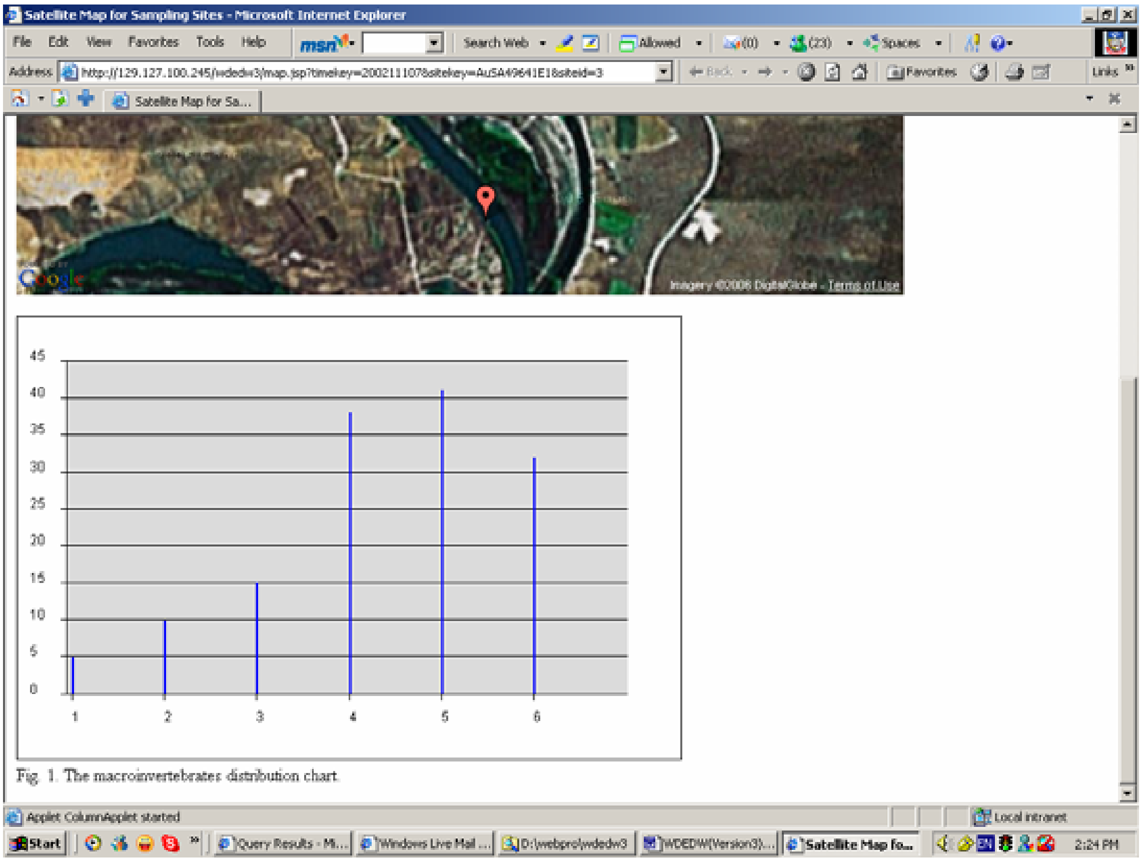



**Figure 21(f). Macroinvertebrate distribution chart at a single site web page**

### 3.6. Conclusions

The design and implementation of the prototype EDW has demonstrated that:

1. an integrated and standardised data warehouse for the archiving and processing of highly complex and fragmented ecological data is feasible
2. both data management and mining can be integrated
3. user-friendly and interactive access to the EDW as well as data sharing through the www are achievable
4. both manual and on-line data entry can be facilitated.

The key for the successful implementation of the prototype EDW to its current stage was the close communication and collaboration with researchers who are collecting and utilising ecological data of water dependent ecosystems. This collaboration enabled us to iteratively standardise ecological data originating from different sources and tailor the design of the EDW for most common applications and purposes.

The future work on the EDW should aim at:

1. extending the current EDW to a state-wide EDW archiving and processing both terrestrial and aquatic ecological data in an integrated and standardised manner in order to facilitate the assessment of ecosystems and landscapes health
2. the physical integration of data mining algorithms tailored for ordination and clustering by KANN and predictive modelling by HEA into the EDW
3. the integration of spatial and temporal visualisation of archived and processed ecological data into the EDW by means of multi-dimensional cluster analysis and GIS.

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## *Appendix*

### A Software Usage

| Software Tools | Version | Cost | Usage |
|---|---|---|---|
| Oracle | 9i | Licence from the university of Adelaide | Data warehouse |
| http://www.oracle.com/technology/products/oracle9i/index.html | | | |
| The J2SE Development Kit (JDK) | 1.5 | Free | Java software application development |
| http://java.sun.com/j2se/1.5.0/download.jsp | | | |
| The J2SE Runtime Environment (JRE) | 1.5 | Free | Java software application running |
| http://java.sun.com/j2se/1.5.0/download.jsp | | | |

## B The Measure Variable Category Tree

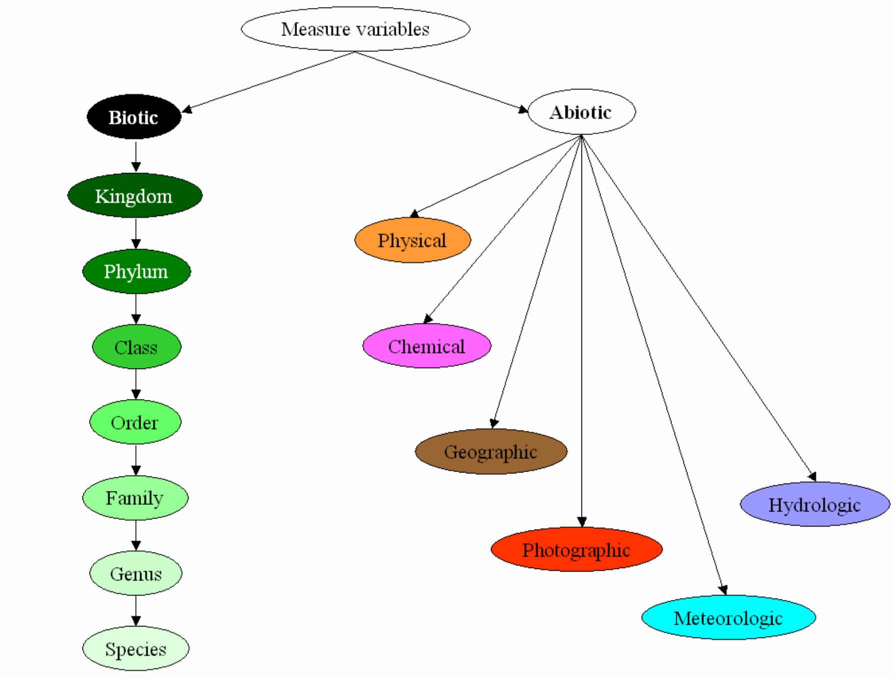


**Figure 22. The measure variable category tree.**

# 3. SUMMARY OF WORKSHOP 2

The second stakeholder meeting of the Best Practice Framework for Monitoring and Evaluation of WDEs was a workshop, held on 21 September 2006, and intended to trial completed sections of the draft framework; Groups 1 and 2 as Groups 3 and 4 were assembled in outline only.

The workshop was run with a similar format to that of the initial stakeholder forum (Wilkinson et al. 2006), with participants grouped according to regional interests. Framework worksheets and instructions were handed-out and the groups asked to select a WDE with existing monitoring and to use Groups 1 and 2 of the framework to review that monitoring. Participants had been primed and asked to assemble the necessary material prior to attending the workshop. Members of the BPF team sat with each group and the primary author circulated amongst the groups to facilitate.

## The working groups

Three groups were formed by the workshop participants. The group's headings, team members and reports from flip charts were as follows:

### *Adelaide and Mount Lofty Ranges (AMLR) – river rehabilitation*

- Team members – Paul McEvoy (spokesperson), Chris Madden, Qi Feng Ye, Peter Shulz, and Kelly Marsland.

The AMLR group found that there was lots of information that they needed to catch-up on, that they were thrown in at the deep end, that there was alot of complexity. They preferred starting with the conceptual model. The issues faced in the chosen WDE were easy to conceive from talking within the group. The Stommel Diagram was novel and useful to the group. They could derive large-scale NRM indicators that could be compiled. They reported the value of having repeated prompts to re-examine issues from differing perspectives. They appreciated the way the framework helped to channel thought processes, but highlighted the need for local examples, and it was suggested that a reduced executive version of the framework should be issued.

### *WDEs at the landscape level relative to land use*

- Team members – Tom Nilsen (spokesperson), Jason van Laarhoven, Glen Scholz, Ann Fordham, Belinda McGrath-Steer, Scott Evans and Matt Miles.

This group focussed on the larger scale regional ecosystem health reporting level, and contributed many of the positive feedback and practical issues comments. This group made an additional point not made elsewhere, that it would be of value to identify the various entry points into the Framework. They also highlighted the distinction between an indicator and a vital sign.

### *River Murray e-flows and salt interception schemes (SIS)*

- Team members – Nick Souter (spokesperson), Li Wen, Byron He Zhang, Richard Mills, Paul Wainwright and Tumi Bjornsson.

The Murray group put a lot of thought into their example and appreciated the validation exercise afforded by the two framework stages. They reported that the framework could be used for either; research or intervention purposes and the tools can be used to attack an issue from a variety of perspectives. The key questions were particularly useful in helping to answer ‘why’. They highlighted the need to focus on a prime objective. There was some confusion between the role of drivers and stressors and it was suggested that bigger paper was needed to produce the conceptual diagram in a workshop environment (*ideally a whiteboard*). The Stommel Diagram was helpful for overlaps but it was suggested a focal question would be useful (*the question comes from the monitoring objectives or needs*).

## Workshop outcomes

The workshop raised a number of interesting points which were, in part, addressed in this report or remain to be addressed.

### *Positive feedback*

1. The approach gives a framework and process to work with.
2. The two stages of the draft framework were found to provide a transparent guide.
3. The key questions (Task 1.1) were found to be a valuable validation exercise for re-affirming the need to monitor.
4. The summary tables are good for the site-specific focus, but less useful for big strategy.
5. The Stommel diagram (Task 2.2) was found to be a useful means of visualising information about small and large scale together.
6. The structure was found to provide a helpful and logical flow.
7. The repetition was effective at facilitating fresh views of the systems being monitored.
8. The ability to start at various points was welcomed by workshop participants.
9. It was helpful that the framework has utility for intervention or research.

### *Practical issues*

The authors’ response to the points and questions arising from the workshop are provided in *italics*:

1. A clearer overview of the framework was requested. *An overview is provided in the Framework document Introduction*.
2. A need for more local examples with which comparison could be made was identified. *Examples have been provided in the Technical Resource document.*
3. Improved definitions of the terms driver and stressor were requested (*provided in the Framework document under Task 2*).
4. It was suggested that a system overview with a conceptual model might be a better starting point for the framework. *It is suggested at the beginning of the Framework document that many of the tasks within the Framework may develop simultaneously and are complimentary to one another. It may, therefore, be desirable to build the conceptual diagram at the same time as completing Group 1, since the two can feed back into one another.*

5. A means to identify, differentiate and prioritise primary and secondary monitoring objectives was requested (*see Task 1.2 of the Framework document*).
6. The methodology should include a means of documenting and recording the rationale behind monitoring. *This is formalised by the provision of numerous tables for recording information – this aspect may require further future expansion.*
7. A slimline version on the framework was requested. It was suggested that a large report may be off-putting. *Separate Framework and Technical Resource documents have been produced.*
8. Need for reference to the data destination – the database. *Reference is made to the WDE database project undertaken by Adelaide University* (Recknagel et al., 2006 App. 1).
9. The framework should direct practitioners towards the highest level of biological organisation. *Issues of scale are addressed in the Technical Resource document.*

### Planning and policy level issues

1. Policy objectives are often loosely defined and vague (frequently referred to as *fluffy*). The workshop attendees reported that whilst they do not set these objectives, they are the ones tasked with turning these vague objectives into a reportable reality.
2. How can more regional needs for reporting be engaged, and therefore suit both State and Federal reporting needs?
3. How does this framework meet the needs of higher-end policy perspectives and what tools are there for this purpose?
4. It was asked where monitoring for larger areas fits into the framework? The answer to this really lies within the tools offered, in that, recognising the objectives or monitoring needs, the scales and indicators can be chosen appropriately and the process may be run for different scales of interest (see Groups 1 and 2 of the Framework).
5. How can monitoring at the field or site scale be balanced with the high-level reporting needs? By encapsulating an overview of the stress response relationship, indicators, monitoring needs, management objectives and end-point indicators; the WDE information diagram provides a tool to meet this need (eg Figure 4 in the Framework document).

The workshop was a valuable exercise and the findings have fed directly into this report and are carried-forward into the development needs as outlined in the Framework Introduction.

# 4. WDE DRIVERS, STRESSORS AND ATTRIBUTES (ADDITIONAL MATERIAL)

The model and text presented below is reproduced from Perkins et al. (2005) and was developed by Dr. Darren Carlisle of the United States Geological Service for the US Heartlands Inventory and Monitoring Network. Perkins adapted the model to fit the needs of the US Southern Plains Network. A wetland model developed for the US Great Lakes Network (again developed by Dr. Carlisle) was also used by Perkins in the development of the model presented below. This material is presented here to give an insight into the drivers, stressors and ecosystem attributes of wetlands.

INTRODUCTION

The term "wetland" is a generic descriptor of a wide variety of places, including saltwater marsh, freshwater marsh, tidal marsh, wet meadow, wood swamp, bog, muskeg, mire, pothole, vernal pool, river bottom, mangrove forest, and floodplain swamp. The commonality among these environments is the presence of water sufficient to inundate the ground. The following U.S. Fish and Wildlife Service definition by Cowardin et al. (1979) is widely accepted

> *"Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water…wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes, (2) the substrate is predominantly undrained hydric soil, and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year."*

Wetlands naturally form in places where surface water periodically collects for some time or where groundwater discharge is sufficient to saturate soils. Such places include depressions surrounded by upland and with or without a drainage system; relatively flat, low-lying areas along major water bodies; shallow portions of large water bodies; sloped areas below sites of groundwater discharge; arctic and subarctic lowlands; and slopes below melting snow banks and glaciers. Although wetlands often comprise a small portion of the world's land surface (4–6%, Mitsch and Gosselink 2000), they contribute greatly to local and regional biological diversity (National Research Council [NRC] 1995). Wetland-dependent fish, waterfowl, furbearers, and timber provide important and valuable harvests and recreational opportunities. Wetland ecosystems moderate floods, improve water quality, and have heritage and aesthetic values that are difficult to quantify. On a global scale, wetlands contribute to stable levels of available nitrogen, atmospheric sulphur, carbon dioxide, and methane. Wetland habitats are required for the survival of a disproportionately high percentage of threatened and endangered species. Despite comprising <10% of the landscape in North America, wetlands are important habitat for 68% of birds, 66% of mussels, and 75% of amphibians on the U.S. list of threatened and endangered species (Mitsch and Gosselink 2000).

Despite the obvious benefits of wetland environments, they have been extensively modified or destroyed by human development. In the contiguous United States, ~53% of all wetlands have been lost in the last century (NRC 1995, Mitsch and Gosselink 2000). The U.S. government actually encouraged the widespread destruction of wetlands via established policies until the 1970s (NRC 1995). Currently, wetlands are the only ecosystem type that is comprehensively regulated across all public and private lands within the United States (NRC 1995). Nevertheless, wetland losses have continued over the past two decades (Dahl 2000). Urban development, rural development, and agriculture accounted for 30, 21, and 23%, respectively, of these recent losses (Dahl 2000).

Numerous definitions and classifications have been developed for wetlands, but the system adopted by the U.S. Fish and Wildlife Service and the National Park Service (Cowardin et al. 1979) is the one most commonly used by scientists worldwide (Mitsch and Gosselink 2000). This classification system is hierarchical and all-encompassing and SOPN will adopt also use this classification system. Cowardin et al. (1979) summarised three general types of wetlands as follows.

*Emergent Wetland, Persistent (Freshwater Marshes)*

This class and subclass belongs to palustrine wetlands group as classified by Cowardin et al. (1979). Palustrine systems are wetlands dominated by persistent vegetation (Fig. 1). Wetlands without persistent vegetation are also included in this system if they are <20 acres (8 ha), <6.5 feet (2 m) deep during low water times, and no portion of the boundary contains wave-formed or bedrock shoreline (Cowardin et al. 1979). Freshwater marshes include a very diverse group of wetlands that are characterized by: 1) emergent, soft-stemmed aquatic plants such as cattails, arrowheads, reeds, and other species of grasses and sedges; 2) a shallow water regime; and 3) generally shallow deposits of peat.

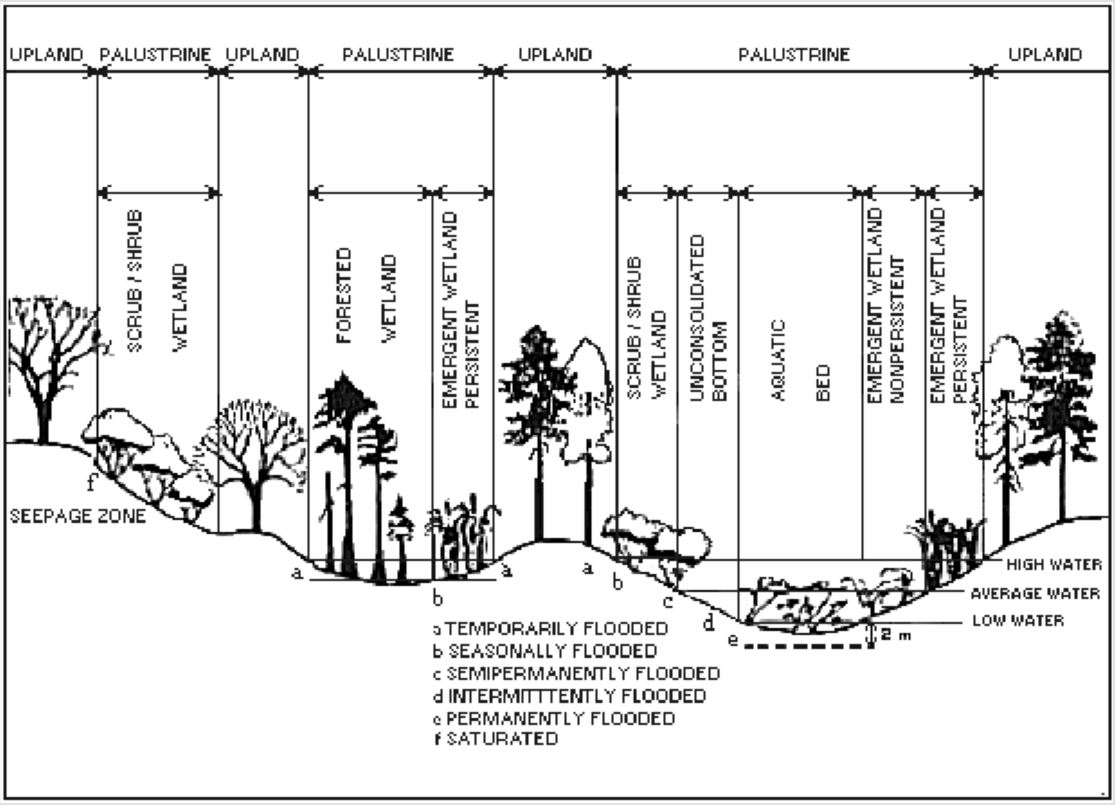


**Figure 1. Distinguishing features and examples of habitats in the Palustrine System (from Cowardin et al. 1979).**

*Riverine Ecosystems*

Riverine ecosystems generally include all wetlands and deepwater habitats contained within a channel. They are bounded by uplands, by wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, or where the channel enters a lake or reservoir. Water is usually, but not always, flowing in this system. Upland islands or Palustrine wetlands may occur in the channel, but they are not included in the Riverine System (Cowardin et al. 1979).

*Lacustrine Ecosystems*

The Lacustrine System includes permanently flooded lakes and reservoirs, intermittent lakes, and tidal lakes with ocean-derived salinities below 0.5%. Typically, there are extensive areas of deep water and there is considerable wave action. The lacustrine system includes wetlands and deepwater habitats with all of the following characteristics: (1) situated in a topographic depression or a dammed river channel; (2) lacking trees, shrubs, persistent emergents, emergent mosses or lichens with greater than 30% areal coverage; and (3) total area exceeds 20 acres (8 ha) (Cowardin et al. 1979). Similar wetland and deepwater habitats totalling less than 20 acres (8 ha) are also included in the lacustrine system if an active wave-formed or bedrock shoreline feature makes up all or part of the boundary, or if the water depth in the deepest part of the basin exceeds 6.5 feet (2 m) at low water. Lacustrine systems formed by damming a river channel are bounded by a contour approximating the normal spillway elevation or normal pool elevation, except where palustrine wetlands extend lakeward of that boundary (Cowardin et al. 1979).

DRIVERS

All ecosystems are influenced by natural and anthropogenic forces. By virtue of being wetlands, hydrology is the major driver for freshwater marsh ecosystems. The periodic drying and inundation is crucial to the ecosystem function of freshwater marshes (Fig. 2).

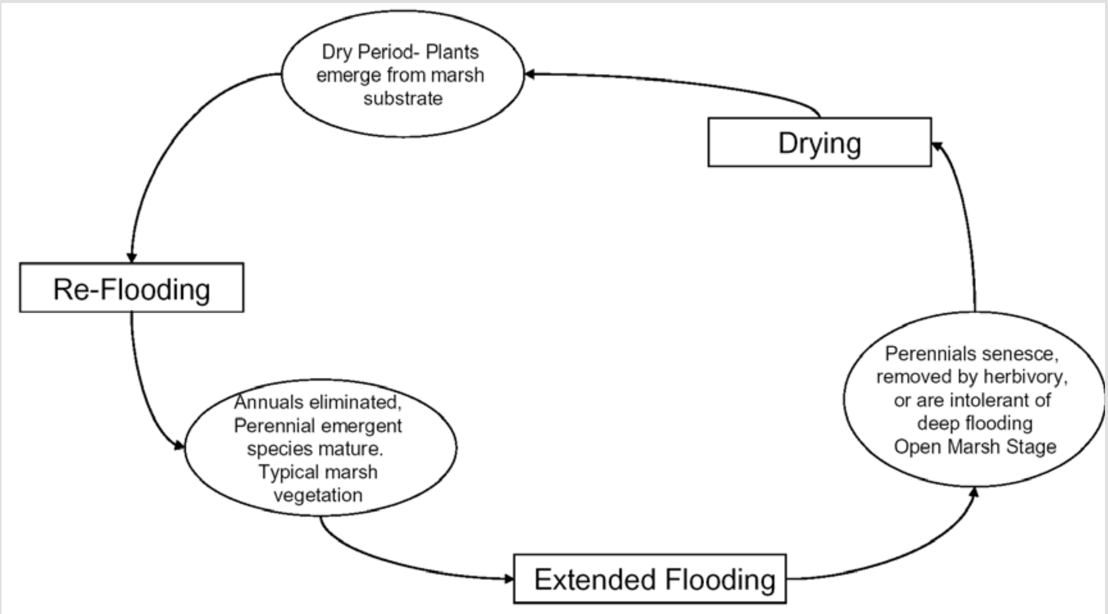


**Figure 2. Typical hydrologic cycle of a freshwater marsh.**

Variation in climate, succession, herbivory, and fire are also all important natural processes controlling all wetlands. Climatic fluctuations over the past century have resulted in changes in local watershed hydrology which directly affect the condition of freshwater marsh ecosystems. Long-term droughts not only reduce water levels but they diminish groundwater supplies. Human accelerated climate change may create more erratic climatic fluctuations and could potentially produce extended droughts.

STRESSOR TYPES

The definition of stress offered by Barrett et al. (1976) is used in this model. Specifically, “Stress is defined here as a perturbation (stressor) applied to a system (a) which is foreign to that system or (b) which is natural to that system but applied at an excessive [or deficient] level.” (Barrett et al. 1976). Hence, agricultural pesticides are a stressor foreign to wetlands. Similarly, nutrients and fire suppression are stressors applied at unnaturally high and low levels respectively. For the purposes of this model, there are three major stressors that influence wetland ecosystems. They are represented by rectangles in Figure 3.

*Natural Processes*

Hydrology is the most important factor in wetland ecosystem maintenance and processes. The hydrologic regime is defined as the magnitude, frequency, duration, timing, and rate of change of water level fluctuation (Poff et al. 1997). The hydrologic regime affects soil bio-geochemical processes, nutrient cycling, and nutrient availability. These processes, in turn, influence the biological communities that can be supported in a wetland. Wetland biological communities exert strong influences on the hydrologic regime. For example, accumulation of senesced plants can hinder water circulation. Duration, frequency, and timing of water level fluctuations are the primary determinants of hydroperiod, which is characteristic of different wetland types. Climatic variation can cause large seasonal and annual fluctuations of the hydroperiod, leading to profound changes in wetland ecosystem structure and function. The dynamics of succession, or ecosystem development, have been documented in a variety of wetlands. Although alternative theories of succession exist, the collective evidence suggests that wetland biological communities undergo natural changes due to external influences on the hydrologic regime (e.g., climate change) and internal processes that alter environmental conditions (e.g., accumulation of organic matter) (Mitsch and Gosselink 2000).

*Urbanization*

In the United States Urbanization is the leading cause of wetland loss (Dahl 2000). Compared to land converted to agriculture, wetland losses to urban and suburban development are small. Nevertheless, wetlands that are not directly affected (e.g., removed or altered) by development are subject to a variety of indirect influences. Drainage and physical disturbance are stressors directly to wetlands if development occurs on the wetland itself. Adjacent development and navigation corridors may alter wetland hydrology, usually by means of hydrologic stabilization. Polluted runoff from urban areas contains toxicants, nutrients, and sediments that potentially enter nearby wetlands. Water diversion, flood control, and reservoir projects often associated with local human population growth, cause permanent flooding in wetlands. Finally, fire suppression generally accompanies urban development due to fears of property loss.

*Agriculture*

Conversion to agricultural land is the major cause of wetland loss worldwide (Mitsch and Gosselink 2000). Runoff contaminated with sediment, nutrients, and pesticides reach wetlands through waterways and drainages that have inadequate buffer zones. Aerial deposition of pesticides and nutrients has been documented in wetlands downwind of agricultural areas. Wetland destruction and fragmentation on adjacent lands threatens wetland species dependent on migration or dispersal corridors. The primary stressors associated with agricultural activity are drainage, sediments, nutrients, and toxicants. With the discovery of atmospheric contaminant deposition and global climate change, it appears likely that every ecosystem in the biosphere is or will be influenced by humans (Vitousek et al. 1997).

INDIVIDUAL STRESSORS

All of these individual stressors are a direct or indirect result of one of the major stressor types. The individual stressors are represented in Figure 3 by ovals. All of these stressors affect one or more of the major processes (represented by diamonds) of freshwater marsh ecosystems.

*Toxicants*

“Toxicants” in this model refers to any anthropogenic chemical that reaches wetlands and potentially elicits toxic effects on organisms, communities, or the ecosystem (Rand 1995). Wetlands receive toxicant inputs from upstream water sources, direct releases, and deposition. Polluted streams, runoff, and groundwater transport toxicants from adjacent or distant sources. Natural or artificial wetlands are often used specifically for filtering contaminants that are released directly into the system. Finally, wetlands receive toxicant inputs from aerial deposition, which has become recognized by widespread mercury contamination of water bodies (Wiener et al. 2002). The well-known ability of wetlands to assimilate contaminants and "purify" water (Mitsch and Gosselink 2000) is largely due to the perception that contaminants entering wetlands are eventually "locked-up" in sediments, and therefore benign to organisms. However, there is mounting evidence that contaminants buried in wetland soils and sediments are still available to biota and therefore threaten aquatic and terrestrial ecosystems (Landrum and Robbins 1990, McIntosh 1991). For example, up to 2% of the total amount of organochlorines present in lake's sediments were removed from the lake as sediment-dwelling insects emerged into the terrestrial environment. The contaminated insects became a source of contamination to aquatic and terrestrial food webs (Fairchild et al. 1992). Toxicants influence biota at varying levels of ecological organization. Typically, toxicant exposure is first manifested by the presence of detoxifying enzymes or toxicant metabolites in organism tissues. These so-called "bio-markers" are an active area of research and have the potential to signal early warnings of toxicant exposure. As toxicant exposure time or levels increase, organisms suffer malformations, tumours, stunted growth, lost reproduction, and eventually death. Populations are therefore affected when sufficient individuals suffer toxic effects and alter population abundance, biomass, and productivity. Disproportionate losses of populations lead to changes in community composition, and conceivably alterations in ecological processes.

*Nutrients*

The most common reason for impairment of surface waters in the US is eutrophication caused by excessive inputs of nitrogen and phosphorus from non-point sources. More than half of the rivers and lakes that currently fail to meet water quality standards are impaired by nutrients (United States Environmental Protection Agency [USEPA] 1998). The dominant source of nutrients is non-point runoff from agricultural and urban areas (Carpenter et al. 1998). Excessive nitrogen and phosphorus can cause drastic changes in plant communities. The most prominent effect of nutrient enrichment is a proliferation of algae, which can lead to a wide array of additional problems. Algal blooms cause fish kills as decomposition and respiration consume large amounts of oxygen. High algal biomass reduces water transparency, which hinders growth of submergent plants. Aesthetic, recreational, and drinking water values are also reduced by eutrophication.

*Sediment*

Sediment considered in this model is comprised of mostly inorganic particles <2 mm in diameter, thus encompassing sand, silt, and clays (Wood and Armitage 1997). Although sediments are a natural part of most aquatic ecosystems, human activities have dramatically increased sediment inputs to lakes, streams and wetlands. Most sediment enters wetlands through urban and agricultural runoff. When suspended in water, fine sediments increase turbidity, decrease light penetration, and alter primary productivity. Sediment particles <63 micrometers (μm) in size are frequently adsorbed by a variety of contaminants, especially nutrients and heavy metals (Wood and Armitage 1997). Consequently, sediments are an integral part of nutrient and toxicant related effects in wetlands. In some cases, excessive sediment accumulation can alter the hydrologic regime.

*Drainage*

Draining, dredging, filling, and ditching are human modifications specifically designed to dry out wetlands. By removing the source of water influx, wetlands are desiccated and the land used for urban development, highway construction, or agriculture. Levees are often constructed with the primary goal of preventing water from entering the former wetland area. This practice has led to farming and development in the floodplains of many rivers, which has also caused widespread property damage and loss of life when rivers flood. Wetland removal and subsequent fragmentation of remaining habitats is associated with declines in the diversity of wetland organisms (Lehtinen et. al. 1999).

*Flooding*

Wetlands are sometimes flooded as part of water development and management programs. The most common scenario is the loss of riparian wetlands by reservoir construction. A related human impact is the stabilization of wetland hydrology, typically a result of dams designed to reduce flooding. Because the hydrologic regime is unquestionably the most important controller of wetland ecosystems, human alterations of water flow have damaged wetlands on a grand scale. The effects of drainage, flooding, or any other hydrologic alteration are variable. On one extreme, wetlands are drained and entirely obliterated. On the other hand, many wetlands are cut off from their water source by roads or levees, but remain physically in tact. The loss or alteration of water influx reduces inputs of sediments, nutrients, and propagules. Consequently, long-term changes in plant and animal community composition are the most common effects of hydrologic alteration.

*Invasive Exotic Plants*

The invasion of non-indigenous species seriously threatens wetland ecosystems in the US (U.S. Congress 1993). Most invasive species in wetlands have escaped landscaping cultivation or were intentionally planted to stabilize sites already disturbed by human activities. Lacking natural enemies, many exotic species rapidly infest wetlands and displace native flora and fauna. Historically, climate, fire, and grazing controlled the diversity and abundance of vegetation in prairie wetlands. Changes in grazing patterns and animals and altered hydrology often favour the survival of introduced species. Invasive species not only alter the communities they have invaded, they are difficult to remove. In the US, for example, tamarisk can repeatedly resprout after fire, cutting, or browsing, and it survives in very wet, very dry, or very salty soils (Gladwin and Roelle 1998; Smith et al. 1998). In prairie wetlands, disruption of natural processes such as fire has led to domination by robust, emergent plants, particularly in the prairie pothole region. Cattail (*Typha spp.*) and purple loosestrife (*Lythrum salicaria*), once rare on the Great Plains, have spread across thousands of prairie wetlands and threatening waterways across the United States (U.S. Congress 1993; Malecki and Blossey 1994), and may be increasing fire frequencies and subsequently increasing in dominance after fire (Busch 1995).

ECOSYSTEM ATTRIBUTES

The twelve attributes shown in Figure 2.2.7 are represented by hexagons and are characteristics of the physical (e.g. hydrologic regime), biological (e.g. macroinvertebrates) and chemical (e.g. water chemistry) environment. Potential vital signs are shown in parallelograms below each attribute in Figure 3.

*Physiology and Organism Health*

Some attributes of physiological processes and organism health are indicative of stress on ecosystems and therefore useful in long-term monitoring. Contaminant-induced biochemical processes provide evidence that organisms are being exposed to contaminants in their environment. For example, exposure to heavy metals stimulates cellular production of metallothionein, a protein used to regulate essential metals in most organisms. Cellular damage is minimized because the toxic metal is sequestered by metallothionein and effectively removed from circulation (Klaverkamp et al. 1991). Similarly, analyses for contaminants that accumulate in the tissues of organisms provide important information exposure. Finally, growth and reproduction, which are essential for all organisms, are often indicative of anthropogenic stress (e.g., Beyers et al. 1999).

*Sediment Quality and Chemistry*

Sediment is defined here as the organic and inorganic soils and substrates of wetlands. Sediments are a major part of biogeochemical cycling in wetland ecosystems (Mitsch and Gosselink 2000) and provide habitat for many organisms. Most anthropogenic chemicals eventually accumulate in sediments due to a variety of hydrological and chemical processes (Ingersoll 1995). Sediment contamination is a widespread problem in aquatic ecosystems of the U.S. and poses significant threats to ecological and human health (NRC 1989). Contaminated sediments may be directly toxic to organisms or can be a source of contamination in the food chain. The most common contaminants found in sediments are heavy metals, pesticides, persistent organic chemicals, and hydrocarbons.

*Primary Production and Decomposition*

Ecosystem processes, and the biogeochemical cycles they control, are fundamental attributes of all ecosystems. Primary production, which is the rate of plant biomass accumulation, is sensitive to anthropogenic alteration of the nutrient budget, hydrologic regime, and natural disturbance processes. Primary production in freshwater marshes often equals or exceeds cultivated crops (Mitsch and Gosselink 2000). Primary production in freshwater swamps is highly influenced by the duration and timing of flooding, and therefore sensitive to anthropogenic alterations of wetland hydrology. Decomposition, which is the rate at which carbon from organic matter is metabolized and released as carbon dioxide, is a significant part of wetland ecosystems. Decomposition is slow in anaerobic or permanently wetted environments (Mitsch and Gosselink 2000). Wetlands are therefore a major carbon sink in the biosphere because they tend to accumulate dead organic matter (Mitsch and Gosselink 2000). Hence, much of the food webs supported in these ecosystems are ultimately dependent on detritus and microbes.

*Submergent Plant Populations*

Submergent plants have their photosynthetic tissues completely submerged, but flowering structures often extend above the water surface (Richardson and Vymazal 2001). Submerged plant communities are important habitat for numerous wetland animals. For example, many fish species rely on submergent beds for spawning and larval development (Tiner 1999). The productivity and distribution of submergents is strongly influenced by light penetration to the benthic environment. Consequently, anthropogenic increases in suspended inorganic particles or phytoplankton biomass are detrimental to submergent plant populations.

*Water Quality and Chemistry*

Water quality is fundamental to the functioning of all aquatic and semi-aquatic ecosystems. Although water quality standards for lakes and streams are well-established, chemical and biological criteria for wetlands are still under development. The U.S. Environmental Protection Agency mandated that states would have water quality standards for wetlands by 1993 (USEPA 1990). However, most states are still developing standards and criteria (Apfelbeck 2001).

*Macroinvertebrate Community*

Insects, crustaceans, and other invertebrates are highly diverse and abundant, and play central roles in aquatic food webs. Within most taxonomic groups there are typically many species with a variety of environmental requirements and sensitivity to stressors. As a result, macroinvertebrate communities have been used for over three decades in ecological evaluations of aquatic systems (Rosenberg and Resh 1993) and are currently being used by the Heartlands Network and Prairie Cluster Prototype (Peterson et al. 1999).

*Algal Community*

Algae occur in most wetlands that contain standing water for even short periods. Algae are important sources of wetland primary production, transform and retain nutrients, stabilize substrates, provide habitat for other taxa, and are an important food source for many animals (Stevenson 2001). Algae are useful for wetland biological assessments because they are diverse, abundant, and have a wide range of known tolerance to environmental (e.g., water quality) factors (Mayer and Galatowitsch 1999). Taxonomy is sufficiently developed to ensure consistency and relative ease in identifying most common algal genera.

*Emergent Plant Populations*

Emergent macrophytes are the dominant form of plant life in most wetlands (Richardson and

Vymazal 2001). In general, they produce aerial stems and leaves and an extensive root system. These plants are morphologically and physiologically adapted to growing in waterlogged environments, and are therefore used to delineate wetlands (NRC 1995). Emergent macrophytes are a major component in wetland food webs and nutrient cycles. Because many emergent plants have narrow tolerances of hydrologic conditions, salinity, water chemistry, and nutrient levels, population and community-level monitoring can be used to detect changes in environmental conditions (Tiner 1999).

*Hydrologic Regime*

As discussed above, the hydrologic regime is the dominant environmental control of wetland ecosystems. Consequently, the hydrologic regime itself is an important ecosystem component and requires monitoring in addition to other physical, chemical, and biological attributes. This model adopts the definition of hydrologic regime given by Poff et al. (1997), which includes magnitude, frequency, duration, timing, and rate of change of flows in river systems. Each of these attributes of river hydrology apply to wetland ecosystems as well, and are briefly described below. The magnitude refers to the water that inundates a wetland, and can be measured by water depth or volume. The frequency refers to how often a wetland is inundated. Seasonal inundation is most common, but annual time scales are relevant for many wetlands. The duration is the period of time associated with a specific inundation level and may be weeks or years depending on the type of wetland and climate. The timing refers to the regularity with which inundation occurs. For example, although many wetlands are predictably inundated during specific seasons, others may be inundated intermittently and unpredictably based on weather conditions. The rate of change refers to how quickly water levels change and strongly influences the water residence time in wetlands. This, in turn, has important implications for numerous ecological processes. Lent et al. (1997) developed indicators for monitoring wetland hydrologic regimes.

*Fish and Amphibian Populations*

Although small, ephemeral wetlands rarely support fish, deeper wetlands that are hydrologically connected to larger water bodies may support great varieties and abundance of fish species. The relatively warm, productive habitat with abundant plants provides ideal nursery habitat for many fish species. Population monitoring of such fish species would provide an important linkage between vegetation communities and vertebrate populations (Mitsch and Gosselink 2000). Amphibian species are currently in a global decline (Blaustein and Wake 1990), and have therefore received much attention in scientific and public dialogue. Because their life cycle integrates aquatic and terrestrial systems amphibians are excellent indicators of overall watershed condition. Amphibians are also an important trophic link between aquatic invertebrates and birds, reptiles, and mammals.

*Native Species Diversity*

The Endangered Species Act is a legislative affirmation that the preservation of native species is a long-standing priority in the United States. The NRC (2000) also identified native species diversity as an important indicator of ecosystems. In general, native species diversity is negatively associated with the degree of human disturbance in ecosystems, and therefore represents a useful indicator of the human imprint on the land (NRC 2000). This indicator would undoubtedly be useful in wetland ecosystem monitoring.

*Landscape Level Attributes*

The size, position, and number of wetlands, as well as land use and land characteristics in the vicinity of wetlands are examples of this category. These attributes, often measurable through an analysis of a series of remote sensing or aerial images, can affect all of the other attributes described above. Sediment supply (e.g., through erosion), concentration of nutrients and toxins (e.g., through nonpoint and point source pollution), changes in hydrology (e.g., through dams, shoreline stabilization, dredging, diking, and flooding), introduction of invasive species, and metapopulation dynamics (e.g., through vicinity of and corridors between wetlands) may all be affected by landscape level attributes. Increasing the percent cover of impervious surfaces within a watershed will increase runoff and the sediments, nutrients, and toxins carried by runoff. Shoreline stabilization may decrease the areal extent of a wetland. Invasive species may be introduced to a wetland more readily if the wetland is surrounded by urban or agricultural land use. Fewer wetlands and loss of connective corridors between wetlands may contribute to population extinctions or genetic bottlenecks through restricted gene flow.

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# 5. THE SOUTH EAST QUEENSLAND EHMP EXAMPLE: INDICATORS AND REPORTING

## EHMP Indicators

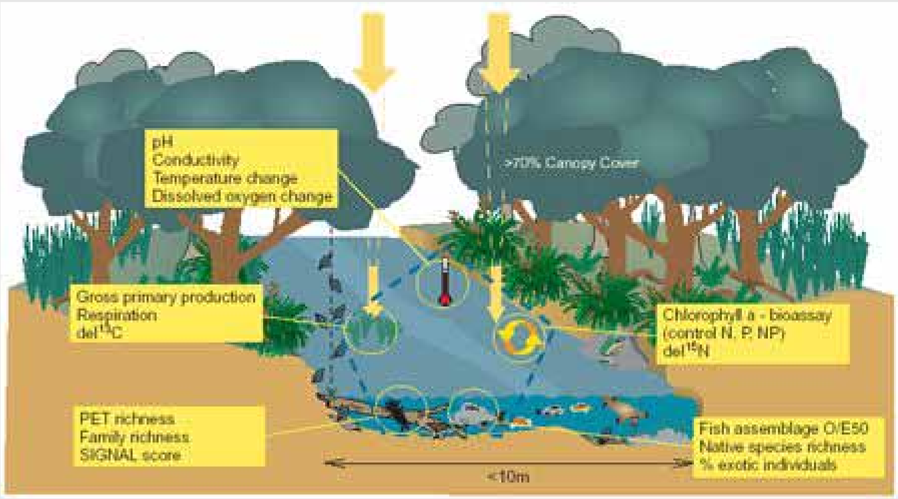
In 1999 a study team was formed to oversee the development of the South-East Queensland (SEQ) Ecosystem Health Monitoring Programme for freshwaters (predominantly rivers) (http://www.ehmp.org/ehmp). The team comprised freshwater ecologists, natural resource managers, statisticians, water quality experts and community group representatives. A rigorous, six-step process to identify the best indicators for assessing ecosystem health in rivers and streams in SEQ was devised and is reproduced below:

| | |
|---|---|
| STEP 1<br>**Derive list of potential indicators** | Based on experience, local knowledge, expert opinion, and the scientific literature, the team produced a comprehensive list of potential indicators addressing physical, chemical and biological attributes of stream health. |
| STEP 2<br>**Develop Conceptual Models** | Conceptual models (simple schematic diagrams) were developed to highlight the important ecological attributes of streams and show how these are affected by various disturbances. These models were then used to pinpoint the most important attributes of stream health and reduce the list of indicators so only relevant indicators were retained. |
| STEP 3<br>**Classify region into different river types** | The study area was divided into different river types on the basis of rainfall, stream size, slope, and altitude. Four broad stream types were identified: Upland, Lowland, South Coastal, and North Coastal. This was an important step which ensured that any comparisons of health were between similar types of streams. |
| STEP 4<br>**Perform pilot studies to assess less-proven indicators** | Pilot studies (small field and lab experiments) were undertaken to assess less-proven indicators. These included techniques that measure aspects of stream health that have not been routinely investigated in biomonitoring programs. Indicators that performed well in the pilot studies were included in the major field trial: those that did not were dropped. |
| STEP 5<br>**Perform major field trial to compare indicators** | In September 2000, four teams of field workers trialed a range of potential indicators at 53 sites in SEQ. Results for each indicator were assessed against a known gradient of disturbance caused by land clearing. Those indicators that responded strongly to the land clearing disturbance gradient were included in the monitoring programme while those that responded poorly were omitted. |
| STEP 6<br>**Make recommendations for Ecosystem Health Monitoring Programme** | Results of the major field trial showed that **five** types of indicator responded well to the land clearing disturbance gradient. Importantly, these groups each tell us something different about the nature of the disturbance. The five types recommended for the EHMP include two indicators of stream processes, two biodiversity measures, and one concerning water quality. |

### EHMP Reporting

This example is taken directly from the EHMP website http://www.ehmp.org/ehmp, and presents the general mode of reporting used in the South-East Queensland ecosystem health monitoring programme.

All assessments of stream health are made by comparison with data collected from minimally disturbed *reference* sites. These are sites where human impact has been kept to a minimum and ecological integrity is very much intact. Data from *reference* sites have been used to derive regionally relevant guidelines for each of the five indicators. Results from the freshwater EHMP are compared with these guidelines to assess the condition of a site.

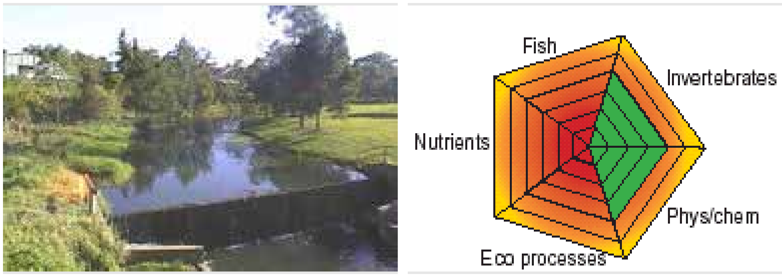



For the five indicators used in the freshwater monitoring programme, results are depicted using pentagons, with each wedge of the pentagon representing one indicator. A *traffic light* approach is used for reporting stream health where the background of each pentagon is coloured orange and red, then the score for each indicator, represented by a green wedge, is placed over the background. The better the score the larger the green wedge. As such, a perfectly healthy site would be represented by an all green pentagon, whereas a heavily disturbed site would be predominantly orange and red.

Individual wedges can be used to diagnose the cause of a disturbance because the colour of each wedge reflects the score for that particular indicator, and because the different indicators have been shown to respond to different disturbances. As such, the size and shape of the five wedges, and the overall colour of the pentagon, all reveal information about stream health.

Two examples of pentagons are given to illustrate differences between disturbed and undisturbed sites.


Undisturbed site on Back Creek near Canungra where all indicators depict a healthy “reference” condition




Disturbed site on Petrie Creek in Nambour where poor scores for fish, nutrients and ecosystem processes indicate barrier effects, loss of riparian cover, and degraded in-stream habitat

# 6. STATE-AND-TRANSITION MODELS (ADDITIONAL MATERIAL)

Evenden et al. (2002) provide a valuable discourse on state-and-transition models. Whilst their focus is on US National Parks' lands the principles outlined are directly transferable to the study of water dependent ecosystems:

*"Ideas related to ecological thresholds are represented in a variety of existing conceptual models. The most common approach for modeling threshold phenomena in relation to management is through state-and-transition models. State-and-transition models are management-oriented tools for organizing information and posing hypotheses about ecological thresholds, irreversible transitions among states, and effects of management activities on transition probabilities (Westoby et al. 1989, Stringham et al. 2001, Jackson et al. 2002, Bestlemeyer et al. 2003). In the application of state-and-transition models used here, a state is defined as "a recognizable, resistant and resilient complex of two components, the soil base and the vegetation structure" (Stringham et al. 2001:4). These two ecosystem components interactively determine the functional status of the primary ecosystem processes of energy flow, nutrient cycling, and hydrology (water capture, retention, and supply). A threshold is defined as "a boundary in space and time between any and all states, or along irreversible transitions, such that one or more of the primary ecological processes has been irreversibly changed and must be actively restored before return to a previous state is possible" (Stringham et al. 2001:5). Thus states and thresholds are defined with respect to the functioning of primary ecosystem processes. Transitions are defined as "trajectories of change that are precipitated by natural events and/or management actions which degrade the integrity of one or more of the state's primary ecological processes" (Stringham et al. 2001:5). In terms of resistance and resilience, a threshold is crossed when the capacities for resistance and recovery of one or more primary processes are exceeded. After the threshold is crossed, the transition is irreversible under current climatic conditions without substantial inputs of energy by management (Stringham et al. 2001). In this type of application, a specific state-and-transition model is developed for a specific ecological site1. For monitoring applications, state-and-transition models should be accompanied by mechanistic models describing how stressors affect key ecosystem components and processes (e.g., biotic functional groups, disturbance regimes, and soil/water resources and dynamics) and influence transition probabilities.*

*Whisenant (1999) presented a process-based conceptual model that identified two types of thresholds in relation to restoration and management. As in the application of state-and-transition models described above, primary ecological processes in his model include water capture and retention, nutrient cycling, and energy capture and flow. Whisenant's approach is based in part on earlier work by Archer (1989) and Milton et al. (1994), and it is closely allied with concepts of rangeland health and landscape function (National Research Council 1994, Ludwig et al. 1997, Ludwig and Tongway 2000, Pellant et al. 2000, Rosentreter and Eldridge 2002). The fundamental hypothesis underlying these approaches is that health and sustainability of arid-land ecosystems are dependent on maintaining the capacity of these systems to capture and retain water and nutrients (Whitford 2002).*

***More on State-and-Transition models***

*A fundamental goal of ecologists and natural resource managers is to acquire an understanding of ecological systems that permits them to predict the effects of management actions. Management of many systems has been based on the concept of succession and a climax state as proposed early in the 1900's (Clements 1916; Tansley 1935). The guiding principle of this concept is that ecological communities move along a relatively deterministic pathway towards a single climax state. The theory postulates that disturbances tend to move a system towards an earlier state, and upon removal of the disturbance the system will again return to a pathway leading to a climax state. This model of succession-regression-succession was almost universally used to guide natural resource management for decades, even though there was early recognition that some systems, once disturbed, did not return to an earlier state over any time frame we could observe (Muller 1940; Glendening 1952; Scheffer et al. 2001). A response to the lack of congruence between theory and observations in rangelands was development of conceptual models that represented rapid transitions between different vegetation states (Westoby 1989). These models, referred to as "state-and-transition models", represent multiple plant communities and the processes thought to lead to rapid (and sometimes effectively irreversible) transitions between communities. In many areas, especially arid and semi-arid rangelands, state-and-transition models were particularly appealing because quantitative models did not accurately represent observed rapid transitions from one stable vegetation type to another. Rapid transitions in rangelands (e.g., from grass to shrub-dominated vegetation) were attributed to management actions such as changes in fire frequency or grazing regime. In many cases, these transitions were unidirectional and removal of stress or disturbance did not lead to "recovery".*

*State-and-transition models were rapidly and widely adopted by land management agencies, mostly in arid and semi-arid regions (Laycock 1991; Ash et al. 1994; Stringham et al. 2001, 2003). These models have certainly contributed to communication of ecological processes and provided a conceptual basis for management decisions. However, state-and-transitions models are fundamentally phenomenological and the mechanistic underpinning of observed dynamics is only vaguely acknowledged in some models. In this case, it is difficult to link a quantitative endpoint for an indicator directly to such a model. Difficulties in linking indicators to state-and-transition model remain, even when the underlying mechanisms are reasonably well understood (e.g.,Trimble and Mendel 1995; Breshears and Barnes 1999; Bestelmeyer et al. 2003). In the context of the monitoring program, state-and-transition models can be accompanied by more mechanistic models that represent dynamics internal to a particular state and/or that represent transitions between particular states. A combination of these models offers the significant advantages of both approaches.*

*State-and-transition models have usually been presented as an alternative to "equilibrium" approaches such as the succession-climax model. However, Briske et al. (2003) noted that ecological patterns and processes are highly scale-dependent, and that theoretical investigations of equilibrium and non-equlilibrium models explicitly emphasize the importance of scale. At smaller scales, there may be dramatic changes in vegetation composition or structure, while at a landscape scale there can be little or no change (Ryerson and Parmenter 2001). Furthermore, Briske et al. (2003) stressed similarities of "equilibrium" and "non-equilibrium" systems and they noted that the distinction between these systems are more related to spatial and temporal scale than processes or functions. This interpretation is more consistent with the concept of a dynamic equilibrium, where systems are regulated by a combination of equilibrium and non-equilibrium dynamics (Ellis and Swift 1988; Jackson et al.*

*2002).*

*An approach that can combine the strengths of state-and-transition type models and simulation models is “frame-based modeling” (Starfield et al. 1993; Hahn et al. 1999). Simulation models that operate on spatial and temporal scales relevant to management are often unable to accurately simulate major changes in vegetation structure or composition, even thought they may accurately represent dynamics (e.g., hydrological functions, N flows, plant growth, etc) within the relevant vegetation types. For example, it is typically very difficult to mechanistically simulate the transition from a grass to shrub-dominated system, even though simulation models accurately simulate primary production in either grass or shrub dominated systems. Frame-based modeling provides a means that can potentially harness the predictive ability of a mechanistic model to, e.g. forecast grass production or cover, and employ a state-and-transition approach to represent major state changes that are difficult to simulate.” (END QUOTE)*

# GLOSSARY

**Adaptive management:** A management approach, often used in natural resource management, where there is little information and/or a lot of complexity and there is a need to implement some management changes sooner rather than later. The approach is to use the best available information for the first actions, implement the changes, monitor the outcomes, investigate the assumptions and regularly evaluate and review the actions required. Consideration must be given to the temporal and spatial scale of monitoring and the evaluation processes appropriate to the ecosystem being managed.

**Ambient:** The background level of an environmental parameter (e.g. a background water quality like salinity).

**Anabranch:** A branch of a river that leaves the main stream and later rejoins.

**Aquifer:** An underground layer of rock or sediment which holds water and allows water to percolate through.

**Baseflow:** The water in a stream that results from groundwater discharge to the stream. This discharge often maintains flows during seasonal dry periods and has important ecological functions.

**Basin:** The area drained by a major river and its tributaries.

**Biological diversity (biodiversity):** The variety of life forms: the different life forms including plants, animals and micro-organisms, the genes they contain and the *ecosystems (see below)* they form. It is usually considered at three levels — genetic diversity, species diversity and ecosystem diversity.

**Biota:** All of the organisms at a particular locality.

**BOD:** Biochemical oxygen demand.

**BOM:** Bureau of Meteorology.

**Buffer zone:** A neutral area that separates and minimises interactions between zones, whose management objectives are significantly different or in conflict (e.g. a vegetated riparian zone can act as a buffer to protect the water quality and streams from adjacent land uses).

**Catchment:** The area of land determined by topographic features within which rainfall will contribute to runoff at a particular point.

**Drivers:** exert major forcing influences on natural systems and are associated with large-scale processes. Examples include: climate, landform, geology/soils and time.

**DWLBC:** Department of Water, Land and Biodiversity Conservation. Government of South Australia.

**Electrical Conductivity (EC):** 1 EC unit = 1 micro-Siemen per centimetre (μS/cm) measured at 25 degrees Celsius, commonly used to indicate the salinity of water.

**Ecological processes:** All biological, physical or chemical processes that maintain an ecosystem.

**Ecology:** The study of the relationships between living organisms and their environment.

**Ecosystem:** Any system in which there is interdependence upon and interaction between living organisms and their immediate physical, chemical and biological environment.

**Ecosystem process/response (attributes):** are physical, chemical or biological factors that respond to the drivers and stressors. This response may either be positive or negative. Examples include: community and population dynamics, water and sediment quality; flow regime; stream geomorphology; physiology; and organism health.

**Ecosystem services:** All biological, physical or chemical processes that maintain ecosystems and biodiversity and provide inputs and waste treatment services that support human activities.

**EHMP:** Ecosystem Health Monitoring Programme.

**Environmental water requirements (EWR):** The water regimes needed to sustain the ecological values of aquatic ecosystems, including their processes and biological diversity, at a low level of risk.

**EPA:** Environment Protection Agency.

**Ephemeral streams/wetlands:** Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

**Erosion:** Natural breakdown and movement of soil and rock by water, wind or ice. The process may be accelerated by human activities.

**Estuaries:** Semi-enclosed waterbodies at the lower end of a freshwater stream that are subject to marine, freshwater and terrestrial influences, and experience periodic fluctuations and gradients in salinity.

**Eutrophication:** Degradation of water quality due to enrichment by nutrients (primarily nitrogen and phosphorus), causing excessive plant growth and decay. *(See algal bloom).*

**Floodplain:** Of a watercourse means: (a) the floodplain (if any) of the watercourse identified in a catchment water management plan or a local water management plan; adopted under Part 7 of the Water Resources Act 1997; or (b) where paragraph (a) does not apply — the floodplain (if any) of the watercourse identified in a development plan under the Development Act 1993, or (c) where neither paragraph (a) nor paragraph (b) applies — the land adjoining the watercourse that is periodically subject to flooding from the watercourse.

**GAB:** Great Artesian Basin.

**GIS (geographic information system):** Computer software that allows geographic data (for example land parcels) to be linked to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis.

**Greenhouse effect:** The balance of incoming and outgoing solar radiation which regulates our climate. Changes to the composition of the atmosphere such as the addition of carbon dioxide through human activities, have the potential to alter the radiation balance and to effect changes to the climate. Scientists suggest that changes would include global warming, a rise in sea level and shifts in rainfall patterns.

**Groundwater:** Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground.

**Groundwater Dependent Ecosystem (GDE):** An ecosystem that derives a part of its water budget from groundwater.

**Habitat:** The natural place or type of site in which an animal or plant, or communities of plants and animals, lives.

**Health:** A measure of ecosystem integrity based on vigor, resilience and organisation. High levels of each of these factors indicate a healthy ecosystem.

**Heavy metal:** Any metal with a high atomic weight (usually, although not exclusively, greater than 100), for example: mercury, lead and chromium. Heavy metals have a widespread industrial use, and many are released into the biosphere via air, water and solids pollution. Usually these metals are toxic at low concentrations to most plant and animal life.

**Hydrology:** The study of the characteristics, occurrence, movement and utilisation of water on and below the earth's surface and within its atmosphere. *(See hydrogeology.)*

**Hyporheic zone:** The wetted zone among sediments below and alongside rivers. It is a refuge for some aquatic fauna.

**Indigenous species:** A species that occurs naturally in a region.

**Irrigation:** Watering land by any means for the purpose of growing plants.

**Lake:** A natural lake, pond, lagoon, wetland or spring (whether modified or not) and includes: part of a lake; and a body of water declared by regulation to be a lake; a reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

**M&E:** *see Monitoring and Evaluation.*

**MAT:** Management Action Target.

**Macroinvertebrates:** Animals without backbones that are typically of a size that is visible to the naked eye. They are a major component of aquatic ecosystem biodiversity and fundamental in food webs.

**Measurements:** Measures of the vital sign/indicator. A measure of water quality may be electrical conductivity and a measure for the macroinvertebrate community may be structure and composition.

**Model:** A conceptual or mathematical means of understanding elements of the real world which allows for predictions of outcomes given certain conditions. Examples include, estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change.

**Monitoring and Evaluation:** The process of undertaking regular data collection, data that is then comprehensively analysed to determine if the programme aims and objectives are being met.

**NAP:** National Action Plan for Salinity and Water Quality.

**NO3_N:** aqueous nitrogen in the form of the highly mobile nitrate anion, and expressed as nitrate_nitrogen, i.e. 1mg/L NO3_N ≡ 4.429 mg/L NO3 (1xN [m.w. 14] + 3xO [m.w. 16]).

**Natural recharge:** The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc.) *(See recharge area, artificial recharge.).*

**NHT:** Natural Heritage Trust.

**Natural Resources:** Soil; water resources; geological features and landscapes; native vegetation, native animals and other native organisms; and ecosystems.

**Natural Resources Management (NRM):** All activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively.

**OECD:** Organisation for Economic Co-operation and Development

**Owner of land:** In relation to land alienated from the Crown by grant in fee simple — the holder of the fee simple; in relation to dedicated land within the meaning of the *Crown Lands Act 1929* that has not been granted in fee simple but which is under the care, control and management of a Minister, body or other person — the Minister, body or other person; in relation to land held under Crown lease or licence — the lessee or licensee; in relation to land held under an agreement to purchase from the Crown — the person entitled to the benefit of the agreement; in relation to any other land — the Minister who is responsible for the care, control and management of the land or, if no Minister is responsible for the land, the Minister for Environment and Heritage.

**Phreaphytic vegetation:** Vegetation that exists in a climate more arid than its normal range by virtue of its access to groundwater.

**Phytoplankton:** The plant constituent of organisms inhabiting the surface layer of a lake; mainly single-cell algae.

**Pollution, diffuse (or non-point) source:** Pollution from sources that are spread out and not easily identified or managed (e.g. an eroding paddock, urban or suburban lands and forests).

**Pollution, point source:** A localised source of pollution.

**PP:** Primary productivity.

**Ramsar Convention:** This is an international treaty on wetlands titled The Convention on Wetlands of International Importance Especially as Waterfowl Habitat. It is administered by the International Union for Conservation of Nature and Natural Resources. It was signed in the town of Ramsar, Iran in 1971, hence its common name. The Convention includes a list of wetlands of international importance and protocols regarding the management of these wetlands. Australia became a signatory in 1974.

**RCT:** Resource Condition Target.

**Rehabilitation (of waterbodies):** Actions that improve the ecological health of a waterbody by reinstating important elements of the environment that existed prior to European settlement.

**Restoration (of waterbodies):** Actions that reinstate the pre-European condition of a waterbody.

**Riparian zone:** That part of the landscape adjacent to a waterbody that influences and is influenced by watercourse processes. This can include landform, hydrological or vegetation definitions. It is commonly used to include the in-stream habitats, bed, banks and sometimes floodplains of watercourses.

**Seasonal watercourses or wetlands:** Those watercourses and wetlands that contain water on a seasonal basis, usually over the winter/spring period, although there may be some flow or standing water at other times.

**SOE:** State of Environment.

**Stressors:** cause significant changes in ecological components, patterns and relationships. Barrett et al. (1976) give this definition: "*Stress is defined here as a perturbation (stressor) applied to a system (a) which is foreign to that system or (b) which is natural to that system but applied at an excessive [or deficient] level.*" Examples may include changes in: salinity and nutrients, groundwater level, flooding regime and invasion of exotic species.

**Surface water:** (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir.

**Taxa:** General term for a group identified by taxonomy, which is the science of describing, naming and classifying organisms.

**Vital sign/indicator:** Any "information rich" feature of an ecosystem that may be independent or integrative and may be measured or estimated to provide insight into the condition of the ecosystem. Examples may include water quality and the macroinvertebrate community.

**Waterbody:** Waterbodies include watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers.

**Water Dependent Ecosystems (WDE):** Those parts of the environment, the species composition and natural ecological processes, which are determined by the permanent or temporary presence of flowing or standing water, above or below ground. The in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water-dependent ecosystems.

**Wetlands:** Defined by the Act as a swamp or marsh and including any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic/intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tides does not exceed six metres.

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