Wetland vulnerability to climate change in the ACT

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1. INTRODUCTION

An assessment of climate change impacts on wetlands in the ACT is undertaken to determine their climate change vulnerability. This wetland assessment uses the Management Areas developed in the ACT HGL Framework project as planning units (Cowood *et al*. 2016). Mapping of Management Areas allows for detailed hazard assessments to understand the patterns in the chosen variables, facilitating management within the HGL Framework and consideration of landscape setting when identifying suitable locations to undertake Management Actions. The assessment uses the current (1990-2009) and near future (2020-2039) time periods from the NARCliM Project (Olson *et al*. 2014), but will individually assess consensus, wet-cool extreme and dry-hot extreme scenarios. Variables used in this assessment represented indicators of current anthropogenic pressure, future hydrological change in water sources and losses and future ecological change in vascular plant and amphibian communities. Statistical methods are used to group wetlands that are projected to experience similar levels of change in the future determining their climate change vulnerability and the principle components of change driving the variability. The variables are first attributed to the Management Areas across the ACT and then allocated to wetlands located within each Management Area. Hydrological change variables were refined for individual wetlands considering the unique water balance equations. The remainder of this section introduces the approach to choose the consensus, wet-cool extreme and dry-hot extreme scenarios and revised hydrological and ecological change data selection. Section 2 outlines the method for the wetland assessment, and the results are presented in Section 3. Section 4 discusses the overall variability of change between the 3 future climate scenarios as well as the wetland clusters within each climate scenario. The report summary is in Section 5.

It is recommended by the CSIRO Climate Adaptation Flagship that natural resource management planning must consider a range of likely futures and possible desired outcomes (Rissik *et al*. 2014; Timbal 2015). This recommendation has been adopted by the ACT Government when developing their ACT Climate Change Adaption Strategy (ACT Environment and Planning Directorate 2016). For the detailed wetland assessment, 3 NARCliM models representing different near future climate scenarios were chosen, using the 10km climate change projections for the ACT (Olson *et al*. 2014; NSW Office of Environment and Heritage 2015): a consensus scenario representing the multi-model mean of the 12 climate models; a wet-cool extreme scenario representing the single climate model with the coolest mean annual temperature and highest mean annual precipitation for the near future; and a dry-hot extreme scenario representing the single climate model with the hottest mean annual temperature and lowest mean annual precipitation for the near future (Table 1). Selection of future extreme scenarios used the same principles as the Climate Futures Framework (Clark *et al*. 2011; Whetton *et al*. 2012), where two climate variables, e.g. precipitation and temperature, are used to identify the range of plausible future scenarios such as the 'maximum consensus', 'best case' or 'worst case'. It should be understood that each of the 12 climate models used in the NARCliM Project will have inherent variability in gridded values for both the current time period and the near future time period. This is due to the treatment of the input daily time-series data by the individual global climate model and regionalisation methods used (Evans and Ji 2012a, 2012b; Evans *et al*. 2013, 2014; Ji *et al*. 2016).

Table 1 Determination of future extreme scenarios for the ACT through ranking of the 12 NARCliM project climate models by near future mean annual precipitation and temperature.

CLIMATE MODEL	**PRECIPITATION**		**TEMPERATURE**		
	mm	**RANK**	**°C**	**RANK**	
MIROC3.2 R2	1465.83	1	9.34	1	Wet-cool extreme
MIROC3.2 R3	1437.34	2	10.35	5	
MIROC3.2 R1	1433.15	3	9.43	2	
CSIRO-Mk3.0 R1	1373.12	4	9.65	4	
CSIRO-Mk3.0 R2	1240.39	5	9.54	3	
CSIRO-Mk3.0 R3	1159.68	6	10.80	6	
ECHAM5/MPI R2	1079.65	7	10.83	7	
ECHAM5/MPI R1	1068.00	8	10.97	9	
ECHAM5/MPI R3	1008.18	9	12.06	11	
CCCMA3.1 R2	849.51	10	10.91	8	
CCCMA3.1 R1	837.61	11	11.13	10	
CCCMA3.1 R3	711.48	12	12.47	12	Dry-hot extreme

Hydrological impact assessment data for the 3 chosen future climate scenarios was acquired from the NSW Office of Environment and Heritage. While the hydrological impact assessment dataset was produced originally at a 10km grid to match the scale of the NARCliM Project (Littleboy *et al*. 2015), the dataset used in the wetland assessment was produced using a downscaled 100m sampling grid. The downscaled hydrological impact assessment data was modelled using the same method (Littleboy *et al*. 2015), but the 100m sampling grid allowing for refined attribution of the landform, land use and soils input data to the model. Although the NARCliM climate variable input data was only available at a 10km resolution. The downscaled hydrological impact assessment data is better suited for attributing to Management Areas and undertaking a local scale detailed wetland assessment, in comparison to the use of 10km data outputs attributed to HGL Units in rapid assessments.

The CSIRO has developed a set of measures to understand the implications and nature of change in biodiversity by 2050 as a result of climate change (Williams *et al*. 2014). The first measure, potential degree of ecological change, represents ecological similarity between current composition and potential future composition of vascular plants, mammals, amphibians and reptiles. For this measure the lower the similarity value the greater the potential change in future biodiversity. If change is seen to occur further measures are used to characterise the nature of change. The second measure, disappearing ecological environments, represents current environments that may become absent from the entire continent in the future. The third measure, novel ecological environments, represents new environments that may arise in the future but which don’t exist anywhere on the continent currently. The measures have been developed for 2 different climate change scenarios representing mild and hot climate futures using a form of community level generalised dissimilarity modelling as described by Harwood (2014). The mild future uses the Model for Interdisciplinary Research on Climate produced by the Japanese research community (MIROC5) and the hot future uses the Canadian Earth System Model (CanESM2). Although this ecological data utilises different climate change projection models to the hydrological impact assessment of Littleboy *et al*. (2015), it represents the best available data of ecological change to be used in current research. Here we have paired the mild climate future ecological change measures with the consensus and wet-cool scenario hydrological change data, and the hot climate future ecological change measures with the dry-hot scenario. It is recommended that when datasets on the potential impacts of climate change for biodiversity and habitat threats using the NARCliM climate projections becomes available that this analysis is repeated.

2 METHODS

2.1 Wetland mapping, classification and water balance equation

2.1.1 Wetland mapping

Wetland spatial data layers were supplied by the ACT Environment, Planning and Sustainable Development Directorate and compiled into a single spatial layer of wetlands using ArcGIS 10.2.1 (ACT_WAPO, ACT_WETLANDS, ACT_bogs, ACT_peatlands, ACT_RAMSARginini). Further wetland spatial data layers were also sourced from the NSW Office of Environment and Heritage corporate data set to confirm all possible mapped wetlands and attribute data were included in the complied map layer (WetlandsNSW, WetlandsMurrayDarlingBasin, WetlandsImportant, BogsandFensSnowyMountains and GWDependantEcosystems). An additional peat wetland spatial data layer was sourced directly from Geoff Hope (Hope *et al.* 2009, 2012). All compiled wetland polygons were visually checked and wetland extent modified to match 10cm resolution imagery (ACT Environment, Planning and Sustainable Development Directorate, aerial photography flown 2012). Any overlapping polygons were edited or removed along with polygons no longer representing wetlands (i.e. loss through recent urban and peri-urban development). Wetlands were also allocated to a HGL Unit and Management Area during the visual checking process.

2.1.2 Wetland classification

Wetlands were designated a system type of riverine, floodplain, lacustrine or palustrine, as per the ANAE classification (Aquatic Ecosystems Task Group 2012). Riverine system type was assigned to those polygons that were representative of river or stream reaches and adjacent riparian areas. This designation was made using the Geofabric mapped stream spatial layer, sourced via the Bureau of Meteorology 'Australian Hydrological Geospatial Fabric' data portal (www.bom.gov.au/water/geofabric/index.shtml). Floodplain wetlands are those which are situated within the 1 in 10 year flood extent. Spatial layers designating flood extents within the ACT were sourced from the ACT Emergency Services Agency corporate data set. The ACT Emergency Services Agency does not utilise a consistent 1 in 10 year flood extent in their planning and management, typically producing either 1 in 100, 1 in 50 or 1 in 10 year flood extents. A combination of which were used for assigning a floodplain system (Ginninderra Creek 1 in 50, Jerrabomberra Creek 1 in 100, Molonglo River 1 in 10, Queanbeyan River 1 in 100, Sullivans Creek 1 in 10 and Tuggeranong Creek 1 in 10). This information was then refined to 1 in 10 year flood extent with expert advice. Lacustrine system wetlands are those that are greater than 8 hectares in surface area with less than 30% emergent vegetation, or greater than 2m in depth. In this application modified water bodies, such as urban constructed waterbodies and rural/peri-urban farm dams, were also included as lacustrine. Palustrine system wetlands were assigned if they were less than 8 hectares in surface area, had greater than 30% emergent vegetation, or were less than 2m in depth. All assigned wetland system types were verified using the 10cm resolution imagery.

Application of the ANAE classification (Aquatic Ecosystems Task Group 2012) to all mapped wetlands was undertaken using the methodology of Brooks *et al.* (2014), developed for the wetland systems present within the Murray Darling Basin. The wetland classification evaluates the wetland characteristics of landform, soil type, river confinement, water source, water regime, water type and vegetation assemblage to assign a wetland class (Table 2).

Table 2. Wetland attributes used to differentiate ANAE wetland type as per the classification system by of Brooks *et al*. (2014). Estuarine attributes are not listed.

CHARACTERISTIC	**ATTRIBUTE**
WETLAND SYSTEM	Lacustrine
	Palustrine
	Riverine
	Floodplain
	Estuarine
LANDFORM	High energy upland
	High energy slope
	Low energy upland plateau
	Lowland
SOIL	Porous organic peat
	Porous mineral soil
	Porous sand
	Non-porous rock
RIVER CONFINEMENT	Unconfined floodplain
	Semi-confined discontinuous floodplain
	Confined non-floodplain
WATER SOURCE	Localised rainfall
	Surface water
	Groundwater
	Both surface and groundwater
WATER REGIME	Commonly wet (inundated 70%)
	Periodically wet
	Water logged
WATER TYPE	Fresh (<3ppt)
	Brackish (3-5ppt)
	Saline (>5ppt)
	Acidic (pH <6)
	Neutral (pH 6-8)
	Alkaline (pH >8)
VEGETATION	Forest
	Shrubland
	Sedgeland / grassland / forbs
	No emergent vegetation

Landform was designated using the Multi-resolution Valley Bottom Flatness (mrVBF) and Multi-resolution Ridge Top Flatness (mrRTF) spatial layers of Gallant and Dowling (2003), sourced via the CSIRO data access portal (https://data.csiro.au/dap). Landform classes, and associated thresholds, were upland high energy (mrVBF < 3 and mrRTF ≤ 3), upland low energy (mrVBF < 3 and mrRTF > 3), transitional (mrVBF $= 3$) or lowland (mrVBF > 3). Soil type was designated to soil order (Isbell 2002) using the Australian Soil Classification spatial layer (NSW Office of Environment and Heritage corporate data set). Vegetation structure took into consideration both regional scale sub-formation and local scale community mapping (ACT Environment, Planning and Sustainable Development Directorate corporate data set). Additionally, the presence of emergent vegetation was designated as present or absent by visual assessment of each wetland polygon using the 10cm resolution imagery. For riverine wetland polygons only, the level of confinement was designated as confined, semi-confined or unconfined using the mrVBF and NSW River Styles spatial layers (Brierley and Fryirs 2000; Brierley *et al*. 2002; Fryirs and Brierley 2005; NSW Office of Environment and Heritage corporate data set). The confined classification was allocated if 0-10% of the stream segment was located in the valley bottom (mrVBF >3), semi-confined if 10-50% and unconfined if 50-100%. No information for water type was available.

Water regime was designated as commonly wet (inundated >70% of time), periodic inundation (inundation <70% of the time) or water logged. Wetland polygons that intersected the Geofabric mapped stream, waterbody or hydro area spatial layers were assigned the existing 'perennial' attribute, while wetland polygons intersecting the peat wetland layer were assigned water logged given the descriptions in Hope *et al.* (2009, 2012). For non-intersecting wetland polygons, lacustrine wetlands were assigned commonly wet, palustrine and floodplain wetlands as periodic inundation. This was also aided by visual assessment of each wetland polygon using the 10cm resolution imagery assessing the level of current inundation and evidence of recent inundation. Designation of water sources is detailed in Section 2.1.3.

2.1.3 Wetland water balance equation

All wetlands were designated with the default equation of precipitation and surface runoff water sources and water loss through evapotranspiration. The equation remained the default if no other water sources or losses were identified. Stream flow was added as a source or loss if the wetland polygon intersected the Australian Hydrological Geospatial Fabric (Geofabric) 'Geofabric AHGF Mapped stream' spatial layer (Bureau of Meteorology 2012). The number of stream inflow and/or outflow intersections was noted as well as if the intersection was with a major or minor river or stream. The Geofabric stream spatial layer was sourced via the Bureau of Meteorology data portal (www.bom.gov.au/water/geofabric/index.shtml). Concentrated surface runoff was added as a source or loss if the wetland polygon intersected the Digital Topographic Database 'HydroLine' spatial layer (NSW Land and Property Information 2013), sourced from the NSW Office of Environment and Heritage corporate data set. The number of drainage line inflow and/or outflow intersections that were not already considered as stream flow were noted.

Groundwater discharge and recharge was added as a source and loss if the wetland polygon intersected 1 or more of 4 separate groundwater interaction spatial layers. Given the level of uncertainty regarding the nature of the spatially derived groundwater interaction (Woodward *et al.* 2016), and that no comprehensive validation could be undertaken as part of this research, a confidence level was also assigned based on the number of spatial layers the wetland polygon intersected: 0 for no intersection through to 4 having intersected all groundwater spatial layers. The first 2 spatial layers were the 'Reliant on Surface Expression of Groundwater' and 'Reliant on Subsurface Expression of Groundwater' from the National Atlas of Groundwater Dependant Ecosystems spatial layer (Sinclair Knight Merz 2012). If the intersection had a high, moderate or low potential for groundwater interaction area as classified within the spatial layer this was noted. These spatial layers were sourced via the Bureau of Meteorology data portal (www.bom.gov.au/water/groundwater/gde).

Two additional spatial layers were derived by running the FLAG model for the ACT (Roberts *et al.* 1997). In the model a DEM was used to derive the shape and curvature of a given landscape, expressed as fuzzy membership values and combined using fuzzy set theory with assumptions regarding the water cycle, to predict the likely location and extent of waterlogged areas resulting from groundwater discharge. Training sets were required to interpret the FLAG outputs and scale according to local conditions. The FLAG method has previously been used to delineate landforms (Summerell *et al.* 2005; Murphy *et al.* 2005; Cowood *et al.* 2016), identify waterlogged and seasonally wet soils (Dowling *et al.* 2003; Summerell *et al.* 2004) and wetland extent in a small area of New Zealand (McKergow *et al.* 2007).

Both 30m and 10m resolution FLAG outputs were generated for the ACT using FLAG software and ArcInfo, following the method of Roberts *et al*. (1997). Input DEMs used were the 1 second Shuttle Radar Topography Mission DEM (Gallant *et al*. 2011) and the 10m DEM developed in this research following the method of Hutchinson and Dowling (1991). Given the different DEM resolutions, an 8x8 pixel smoothing window was used for the 30m DEM and a 13x13 pixel smoothing window for the 10m DEM. The mapped wetlands for the ACT (Section 2.1.1) were used to develop 3 training sets to interpret FLAG outputs: training set 1 was all mapped wetlands; training set 2 removed riverine wetlands; and training set 3 removed riverine and modified wetlands (Section 2.1.2). Each training set was used to compare the individual 30m and 10m total predicted waterlogged area versus actual mapped wetland area, developing a series of quantitative measures to evaluate the FLAG outputs: accuracy, efficiency, discrimination and power. The maximum power measure for each training set was used to select an alpha-cut threshold value to scale the FLAG output to derive predicted wetlands for the study area.

2.2 Assigning indicator values to wetlands

2.2.1 Assigning current anthropogenic pressure variables

For wetlands 2 anthropogenic pressure variables were assigned: overall subcatchment land use pressure and immediate pressure at or directly adjacent to the wetland. Anthropogenic pressure for WaterWatch monitored subcatchments (O’Reilly *et al*. 2015) was determined using the GIS based landscape hazard assessment developed by the QLD Department of Science, Information Technology, Innovation and the Arts (2015). The landscape hazard assessment is part of the Queensland Wetland Programs framework for assessing and monitoring the ecological character and potential hazards of wetlands (QLD Department of Environment and Heritage Protection 2014). Australian Land Use and Management Classification classes (Australian Bureau of Agricultural and Resource Economics and Sciences 2011) were grouped to be consistent with the 15 land use groups in the QLD Department of Science, Information Technology, Innovation and the Arts (2015) landscape hazard assessment (Table 3). Overall land use pressure was then calculated based on the percent area of each land use group within a subcatchment and the corresponding weighting value from Table 3. The overall land use pressure values were then attributed to each wetland within the relevant subcatchment. Immediate land use pressure was assigned by intersecting the wetland mapping and the converted land use group spatial layers. If the wetland polygon intersected multiple land use groups the land use with the highest weighting value was assigned (Table 3).

2.2.2 Assigning future ecological change

The vascular plant and amphibian potential degree of ecological change measure, for both the mild and hot climate futures, were sourced directly from the authors (Williams *et al*. 2014). The data is also available via the CSIRO data portal (www.data.csiro.au/dap). The ArcGIS ‘intersect’ tool was used to integrate spatial mapping of Management Areas with the ecological change data, geoprocessed within ArcGIS 10.2.1 software. Further analysis of the resulting database file was conducted within Microsoft Excel, where the mean value for each ecological change variable, for each future climate scenario, was calculated for all Management Areas. The values were attributed to individual wetlands based on the HGL Unit and Management Area allocation.

Table 3 Land use group, associated weighting value and corresponding Australian Land Use and Management codes (Australian Bureau of Agricultural and Resource Economics and Sciences 2011; QLD Department of Science, Information Technology, Innovation and the Arts 2015).

LAND USE GROUP	ALUM CODE	WEIGHTING
Conservation and natural environments	1.1, 1.2, 1.3	0.10
Extensive grazing	2.1	0.44
Intensively managed grazing	3.2, 4.2	0.41
Production from natural forests	2.2	0.30
Plantation forestry	3.1, 4.1	0.21
Dryland cropping and horticulture	3.3, 3.4, 3.5, 3.6	0.30
Irrigated cropping and horticulture	4.3, 4.4, 4.5, 4.6, 5.1	0.46
Aquaculture	5.2.6	0.33
Intensive animal production	5.2.1, 5.2.2, 5.2.3, 5.2.4, 5.2.5, 5.2.7, 5.2.8, 5.2.9	0.31
Manufacturing and industrial	5.3	0.25
Waste management and disposal	5.9	0.25
Urban	5.4, 5.5, 5.6	0.76
Transport	5.7	0.38
Mining	5.8	0.41
Water (artificial)	6.2, 6.4	0.36
Water (natural)	6.1, 6.3, 6.5, 6.6	0.00

2.2.3 Assigning future hydrological change

Downscaled 100m grid hydrological impact assessment data, for the consensus, wet-cool and dry-hot scenarios, were acquired from the NSW Office of Environment and Heritage. The absolute change (mm) between current and near future annual and seasonal volumes of precipitation, evapotranspiration, surface flow and groundwater recharge for each scenario was integrated with Management Area mapping using the ArcGIS ‘intersect’ tool. Further analysis of the resulting database file was conducted within Microsoft Excel. The mean value for each annual hydrological change variable, for each future climate scenario, was calculated for all Management Areas.

The seasonal gridded values were used to determine the current and future seasonality of delivery for the hydrological variables as per the method of Williams *et al*. (2010a, 2010b). This developed 2 new attributes representing the seasonality ratio values for all grid cells: the balance between summer (positive values) and winter (negative values) dominance in delivery; and the balance between spring (positive values) and autumn (negative values) dominance in delivery. The greater the ratio value (positive or negative) the stronger the seasonal pattern. The mean current and future ratio value for the summer/winter and spring/autumn variables, for each climate scenario, was calculated for all Management Areas. The absolute change in ratio values between current and near future seasonality, for each future climate scenario, was also determined for all grid cells. The mean value for each seasonality absolute change variable, for each future climate scenario, was also calculated for all Management Areas.

The absolute change values were attributed to individual wetlands based on the HGL Unit and Management Area allocation. Wetlands that had not been allocated a stream flow (base flow component) or groundwater source or loss to individual water balance equations

(Section 2.1.3) had allocated annual and seasonal groundwater recharge values manually changed to 0. Future change in groundwater systems would not be considered to directly affect these wetlands.

2.3 Identifying clusters of similar wetlands

An agglomerative hierarchical cluster analysis was undertaken to group wetlands considered similar with regard to the 16 current anthropogenic pressure and future ecological and hydrological change variables for each future climate scenario (Table 4). Analysis was undertaken in SPSS Statistics 23, using the Ward's minimum variance method (Ward 1963) and the squared Euclidean distance measure to determine dissimilarity between wetlands. For each future climate scenario the appropriate number of output clusters was determined by examining the cluster dendrogram and agglomeration coefficients (Manning and Munro 2007). This was assisted by a series of Kruskal-Wallis one-way analyses of variance tests (Kruskal and Wallis 1952), to further explore the similarity and dissimilarity between clusters for each variable within a future climate scenario dataset. The non-parametric test was chosen as the majority of the 16 variables were not normally distributed. To further explore the identified clusters and identify the common or unique indicator variables driving variability within a future climate scenario, a series of principle component analyses were also undertaken. The orthogonal varimax rotation was used (Kaiser 1958), with Eigenvalues of greater than 1, suppressing small coefficients below 0.3. The results of the Kruskal-Wallis one-way analysis of variance, principle component analysis and calculated mean value for each cluster for the 16 variables, all facilitated the characterisation of each cluster.

Table 4 Variables used in the agglomerative hierarchical cluster analysis of wetlands.

INDICATOR	VARIABLES
Anthropogenic pressure	Immediate land use pressure
	Subcatchment land use pressure
Ecological change	Ecological change index for vascular plants
	Ecological change index for amphibians
Hydrological change	Absolute change in annual precipitation
	Absolute change in annual surface flow
	Absolute change in annual groundwater recharge
	Absolute change in annual evapotranspiration
	Absolute change in summer/winter seasonality of precipitation
	Absolute change in spring/autumn seasonality of precipitation
	Absolute change in summer/winter seasonality of surface flow
	Absolute change in spring/autumn seasonality of surface flow
	Absolute change in summer/winter seasonality of groundwater recharge
	Absolute change in spring/autumn seasonality of groundwater recharge
	Absolute change in summer/winter seasonality of evapotranspiration
	Absolute change in spring/autumn seasonality of evapotranspiration

5.2.4 Assigning climate change vulnerability to wetland clusters

Characterisation and calculation of mean values for each cluster allowed for ranking of wetland clusters as experiencing low, moderate or high levels of current anthropogenic pressure and projected future ecological and hydrological change for each future climate scenario. The distribution of ranks across the 3 categories for each variable provided the overall climate change vulnerability for the cluster: lower, moderate or higher climate change vulnerability.

It is at this stage of the wetland assessment that an assumption is made surrounding the consequences of water source and loss fluctuations that control the depth of water, wetted extent and seasonal timing of transition between wetter and drier periods for a wetland (Casanova and Brock 2000; Capon 2003, 2005; Bunn *et al*. 2006; Tockner *et al*. 2000; Thorp *et al*. 2008). It is understood that the hydrological dynamics of a wetland will influence the habitat types available, composition and succession of the biotic assemblage and factors such as primary productivity, anaerobic conditions, light and nutrient availability (Westlake *et al*. 1998; Cronk and Fennessy 2001; Keddy 2010). The assumption is made that an increase in water storage at a wetland can have negative effects, just as a decrease in water storage could. Therefore all positive and negative mean values for each cluster were considered absolute values during ranking.

3 RESULTS

3.1 ACT wetlands and water balance equations

3.1.1 Wetland mapping and classification

A total of 1296 wetland polygons covering a combined area of 33.36km^2 were mapped within the ACT study area. The Namadgi and Paddys River HGLs contain the largest number of wetlands, with 186 and 155 respectively, while Jeir Hill and Bruce HGLs contain the lowest number of wetlands, with 1 and 3 wetlands respectively (Table 5). There are 6 riverine and 1 lacustrine wetland that intersect multiple HGL Units. These wetlands and the remaining riverine wetlands were removed from the dataset for the remaining wetland assessment. There are no mapped wetlands in the Boboyan and Brindabella HGLs. The MA5 lower slopes have the highest number of allocated wetlands, closely followed by MA4 mid-slopes, with 418 and 308 wetlands respectively. The lowest number of wetlands was allocated MA6 rises, MA2 upper slope (colluvial) and MA1 ridge top or crests, with 3, 7 and 8 respectively. There are 158 wetlands allocated to MA5/9/10, as they are positioned at the break in slope of a confined valley, where the MA5 lower slope joins the narrow MA9 alluvial plain. The distribution of wetland classification types across the ACT are shown in Figure 1.

Table 5 Number of wetlands allocated to each HGL Unit and Management Area.

HGL UNIT/MA	COUNT
Bimberi	**77**
2/3	12
3	21
4	23
5	7
5/9/10	14
Bruce	**3**
4	1
5	2
Bullen Range	**4**
2/3	3
3	1
Clear Range	**11**
1	1
2	1
2/3	2
3	3
4	3
5/9/10	1
Gungahlin	**138**
2/3	7
4	28
5	66
6	1
9/10	36
Hall	**39**
1	1
4	8
5	20
9/10	10
Hoskinstown	**16**
4	4
5	9
9/10	3
Jeir Hill	**1**
4	1
Kambah Pools	**42**
1	1
2/3	1
4	15
5	20
9/10	5
Kowen	**76**
2/3	2
4	8
5	36
9/10	30
Lanyon	**36**
2/3	1
4	7
5	14
9/10	14
Majura Road	**60**
4	18
5	26
6	2
9/10	14
Namadgi	**186**
1	1
2	1
2/3	22
3	10
4	31
5	28
5/9/10	68
9/10	25
Orroral	**40**
2/3	1
4	6
5	1
5/9/10	30
9/10	2
Paddys River	**155**
2	5
2/3	10
3	21
4	50
5	23
5/9/10	31
9/10	15
Picadilly	**13**
4	1
5/9/10	8
9/10	4
Reedy Creek	**79**
1	2
2/3	3
4	21
5	44
9/10	9
Royalla	**11**
2/3	1
4	2
5	4
9/10	4
South Canberra	**37**
2/3	4
4	5
5	12
9/10	16
Sullivans Creek	**70**
1	1
4	12
5	30
9/10	27
Symonston	**42**
4	4
5	11
9/10	27
Uriarra Road	**153**
1	1
2/3	11
4	60
5	65
5/9/10	1
9/10	15
***Multiple**	**7**
5/9/10	5
9/10	2

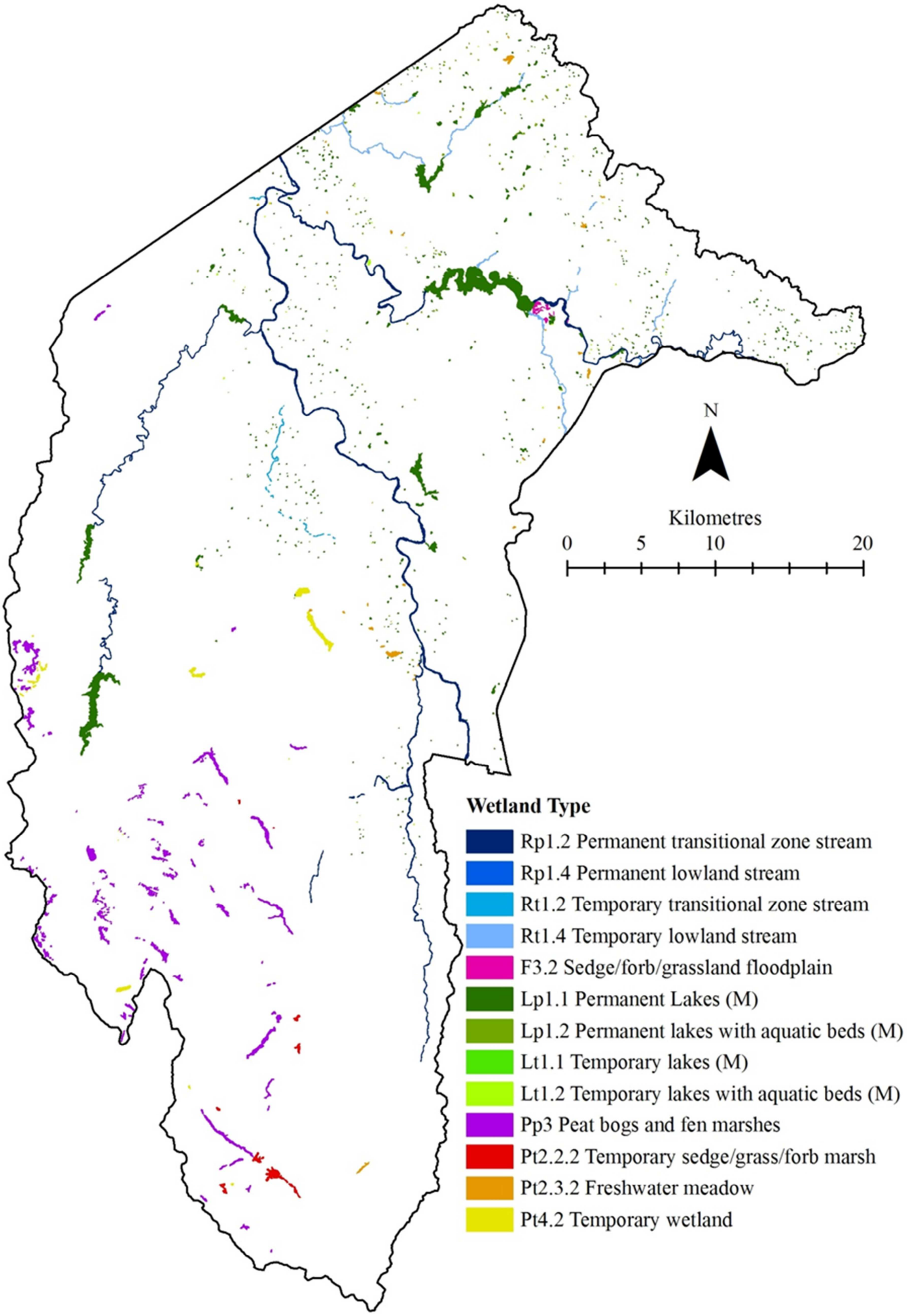

Figure 1 Distribution of mapped wetlands across the ACT, showing ANAE wetland type (Aquatic Ecosystems Task Group 2012a; Brooks *et al*. 2014). M denotes that the wetland is modified.

3.1.2 FLAG outputs

For both the 30m and 10m resolution FLAG outputs, training set 1 (all mapped wetlands) yielded the highest predictive power to map waterlogged areas (Table 6). The associated alpha-cut threshold value was used to scale the FLAG output to derive predicted wetland locations for the study area. The predicted wetland locations totalled 22.843 and 55.498km^2 for the 30m and 10m DEMs respectively (Figure 2). As with the results of McKergow *et al.* (2007), FLAG outputs predicted larger wetlands on the stream network accurately, but omitted smaller seepage wetlands and perched systems, such as the Ginini Flats Wetland Complex which is captured in the National Atlas of Groundwater Dependent Ecosystems (Sinclair Knight Merz 2012). This can be partially linked to large elevation differences in the Australian Alps overwhelming the UPNESS index and influencing FLAG outputs in the lower elevation Werriwa Tablelands (T. Dowling 2016, personal communication). Similarly, where the training set occurs across diverse environments, wetlands that occur lower down the landscape can be confounded by perched wetlands occurring at higher elevations due to factors other than the topographic attributes captured in the DEM. Further research is planned to refine and validate the FLAG outputs for the ACT, including stratification of the landscape using ancillary information relevant to the training set and adjustment of alpha-cut values. It should also be noted that the FLAG analysis is critically dependent on training set accuracy and completeness, and there are still many wetlands in the ACT which are unmapped and therefore not included in the training sets.

Table 6 Quantitative measure values to evaluate the FLAG outputs from comparison of the 30m and 10m total predicted waterlogged area versus actual mapped wetland area.

DEM/TRAINING SET		ALPHA-CUT	DISCRIMINATION	ACCURACY	EFFICIENCY	POWER
30m	1	0.15	0.026	0.990	0.057	0.135*
	2	0.10	0.004	0.974	0.085	0.060
	3	0.10	0.004	0.974	0.099	0.058
10m	1	0.10	0.034	0.976	0.086	0.159*
	2	0.15	0.014	0.991	0.038	0.102
	3	0.15	0.014	0.992	0.045	0.103

3.1.3 Wetland water balance equations

Water balance equations ranged from the default precipitation and surface runoff sources and evapotranspiration loss, to the full combination of water sources and losses from a river or stream connection and groundwater. A summary of the different water balance equations identified are shown in Table 7, categorised with regard to the HGL Unit the wetland was allocated to.

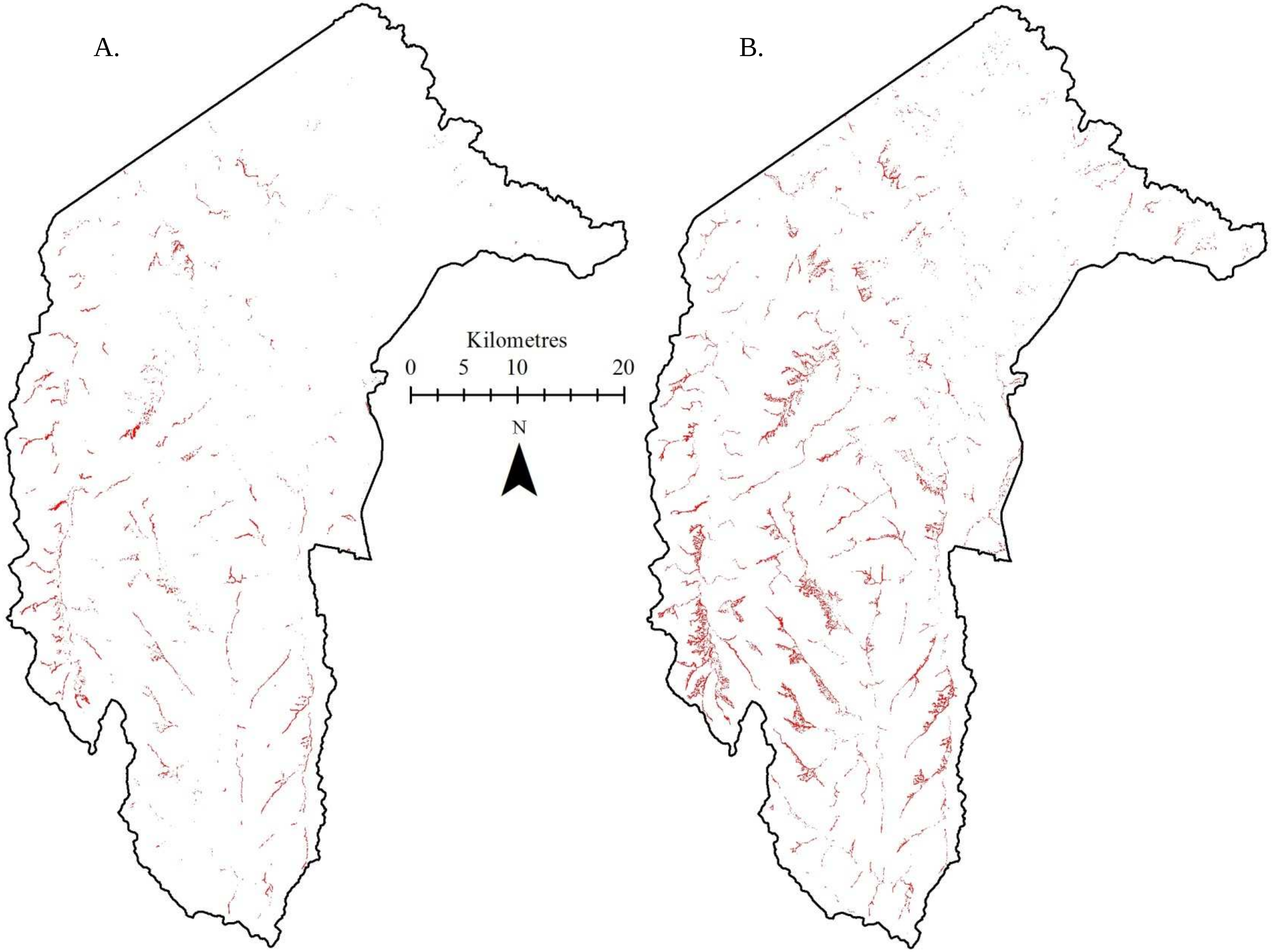

Figure 2 FLAG outputs of total predicted waterlogged area for the ACT, for a. the 30m DEM and training set 1, and b. the 10m DEM and training set 1.

Table 7 Wetland water balance equations categorised with regard to the HGL Unit, where P denotes precipitation, SR surface runoff, SF flow from a river or stream connection and GW groundwater recharge and discharge.

HGL UNIT/EQUATION	COUNT
Bimberi	**77**
S = P + SR - ET	38
S = P + SR - ET - SF	1
S = P + SR - ET - SR	17
S = P + SR + GW - ET - GW	4
S = P + SR + GW - ET - SF - GW	5
S = P + SR + GW - ET - SR - GW	4
S = P + SR + SF - ET - SF	2
S = P + SR + SF + GW - ET - SF - GW	6
Bruce	**3**
S = P + SR - ET - SR	3
Bullen Range	**4**
S = P + SR - ET - SR	3
S = P + SR + GW - ET - SR - GW	1
Clear Range	**11**
S = P + SR - ET	5
S = P + SR - ET - SR	5
S = P + SR + SF + GW - ET - SF - GW	1
Gungahlin	**136**
S = P + SR - ET	48
S = P + SR - ET - SR	71
S = P + SR + GW - ET - GW	1
S = P + SR + GW - ET - SR - GW	13
S = P + SR + SF - ET - SF	1
S = P + SR + SF + GW - ET - SF - GW	2
Hall	**38**
S = P + SR - ET	21
S = P + SR - ET - SR	10
S = P + SR + GW - ET - GW	2
S = P + SR + GW - ET - SR - GW	5
Hoskinstown	**16**
S = P + SR - ET	2
S = P + SR - ET - SR	11
S = P + SR + GW - ET - SR - GW	3
Jeir Hill	**1**
S = P + SR - ET - SR	1
Kambah Pools	**42**
S = P + SR - ET	16
S = P + SR - ET - SR	21
S = P + SR + GW - ET - GW	1
S = P + SR + GW - ET - SR - GW	4
Kowen	**76**
S = P + SR - ET	21
S = P + SR - ET - SR	50
S = P + SR + GW - ET - SR - GW	5
Lanyon	**36**
S = P + SR - ET	10
S = P + SR - ET - SR	20
S = P + SR + GW - ET - SR - GW	6
Majura Road	**59**
S = P + SR - ET	24
S = P + SR - ET - SR	31
S = P + SR + GW - ET - GW	2
S = P + SR + GW - ET - SR - GW	2
Namadgi	**186**
S = P + SR - ET	19
S = P + SR - ET - SF	6
S = P + SR - ET - SR	25
S = P + SR + GW - ET - GW	34
S = P + SR + GW - ET - SF - GW	8
S = P + SR + GW - ET - SR - GW	57
S = P + SR + SF - ET - SF	5
S = P + SR + SF + GW - ET - SF - GW	32
Orroral	**40**
S = P + SR - ET	1
S = P + SR - ET - SR	5
S = P + SR + GW - ET - GW	2
S = P + SR + GW - ET - SR - GW	4
S = P + SR + SF + GW - ET - SF - GW	28
Paddys River	**154**
S = P + SR - ET	44
S = P + SR - ET - SR	84
S = P + SR + GW - ET - GW	11
S = P + SR + GW - ET - SR - GW	11
S = P + SR + SF + GW - ET - SF - GW	4
Picadilly	**13**
S = P + SR - ET - SR	1
S = P + SR + GW - ET - GW	3
S = P + SR + GW - ET - SF - GW	2
S = P + SR + GW - ET - SR - GW	3
S = P + SR + SF - ET - SF	1
S = P + SR + SF + GW - ET - SF - GW	3
Reedy Creek	**77**
S = P + SR - ET	17
S = P + SR - ET - SR	59
S = P + SR + GW - ET - SR - GW	1
Royalla	**11**
S = P + SR - ET - SR	6
S = P + SR + GW - ET - SR - GW	5
South Canberra	**37**
S = P + SR - ET	28
S = P + SR - ET - SR	2
S = P + SR + GW - ET - SR - GW	3
S = P + SR + SF - ET	2
S = P + SR + SF + GW - ET - GW	1
S = P + SR + SF + GW - ET - SF - GW	1
Sullivans Creek	**69**
S = P + SR - ET	29
S = P + SR - ET - SR	34
S = P + SR + GW - ET - SR - GW	6
Symonston	**42**
S = P + SR - ET	19
S = P + SR - ET - SR	18
S = P + SR + GW - ET - GW	3
S = P + SR + GW - ET - SR - GW	2
Uriarra Road	**152**
S = P + SR - ET	57
S = P + SR - ET - SR	86
S = P + SR + GW - ET - GW	2
S = P + SR + GW - ET - SR - GW	6
S = P + SR + SF - ET - SF	1

3.2 Identification and characterisation of wetland clusters

3.2.1 Consensus scenario

Cluster analysis of the 16 variables for the consensus scenario allocated wetlands into 3 clusters (Figure 3). All clusters were significantly different ($p < 0.05$) regarding 11 of the 16 variables, with 2 clusters statistically similar ($p \geq 0.05$) for the 5 remaining variables (Table 8). Table 8 provides a summary of the mean values for the 16 variables for each cluster, calculated from the allocated wetlands (n = 1280). The means are presented colour coordinated according to their ranking from low to high for levels of current anthropogenic pressure and projected future ecological and hydrological change. Of the 16 variables, 11 were present in principle component 1 or 2 (PC1/PC2) across all clusters (Table 8). The 11 variables are: immediate and subcatchment land use pressure, ecological change index for amphibians, absolute change in annual precipitation, evapotranspiration and surface flow, absolute change in summer/winter seasonality of precipitation, evapotranspiration and surface flow and absolute change in spring/autumn seasonality of precipitation and evapotranspiration. Each cluster is described below.

Cluster 1 contains 831 wetland polygons (Table 9), the majority (783) classified as modified permanent or temporary lakes and includes all 13 floodplain wetlands. The wetlands are located in the tableland and upland areas of the ACT within the Werriwa Tablelands physiographic region (Figure 3). This cluster has the lowest climate change vulnerability in the ACT for the consensus scenario. This is despite having the highest immediate and subcatchment anthropogenic pressures and highest levels of ecological change for both amphibians and vascular plants. For the 12 hydrological change variables, this cluster ranked the highest change for 2 variables, moderate change for 2 variables and lowest change for the remaining 8 variables (Table 8). Annual precipitation is projected to reduce, with stronger summer seasonality and weaker autumn seasonality. Both annual evapotranspiration and surface flow are projected to reduce, with weaker summer and autumn seasonality. Annual groundwater recharge is projected to reduce, with weaker summer seasonality and stronger autumn seasonality. Principle component analysis for cluster 1 determined 4 principle components (Eigenvalues: 5.797, 2.616, 2.222, 2.139) that explained a total variance of 79.839% (36.233%, 16.348%, 13.888% and 13.371% each). Of the 16 variables, 12 were present in PC1 and PC2, with only 1 variable additional to PC1/PC2 for this cluster: absolute change in spring/autumn seasonality of surface flow.

Cluster 2 contains 237 wetland polygons (Table 9), the majority (184) classified as peat bogs and fen marshes. This cluster also contains the largest number of wetlands with a groundwater connection in the water balance equation. The wetlands are located in the upland, subalpine and alpine area of the ACT within the Australian Alps physiographic region (Figure 3). This cluster has the highest climate change vulnerability in the ACT for the consensus scenario. This is despite having the lowest immediate and subcatchment anthropogenic pressures and lowest levels of potential degree of ecological change. For the 12 hydrological change variables, this cluster ranked the highest change for 9 variables and ranked moderate for 2 of the remaining 3 variables (Table 8). Both annual precipitation and surface flow are projected to reduce, with weaker summer and autumn seasonality, changing to weakly winter dominant surface flow. Annual groundwater recharge is projected to reduce, with stronger winter seasonality and weaker autumn seasonality. Annual evapotranspiration is projected to increase, with stronger summer and weaker autumn seasonality. Principle component analysis for cluster 2 determined 3 principle components (Eigenvalues: 7.506, 4.856, 1.819) which explained a total variance of 88.629% (46.915%, 30.348% and 11.367%

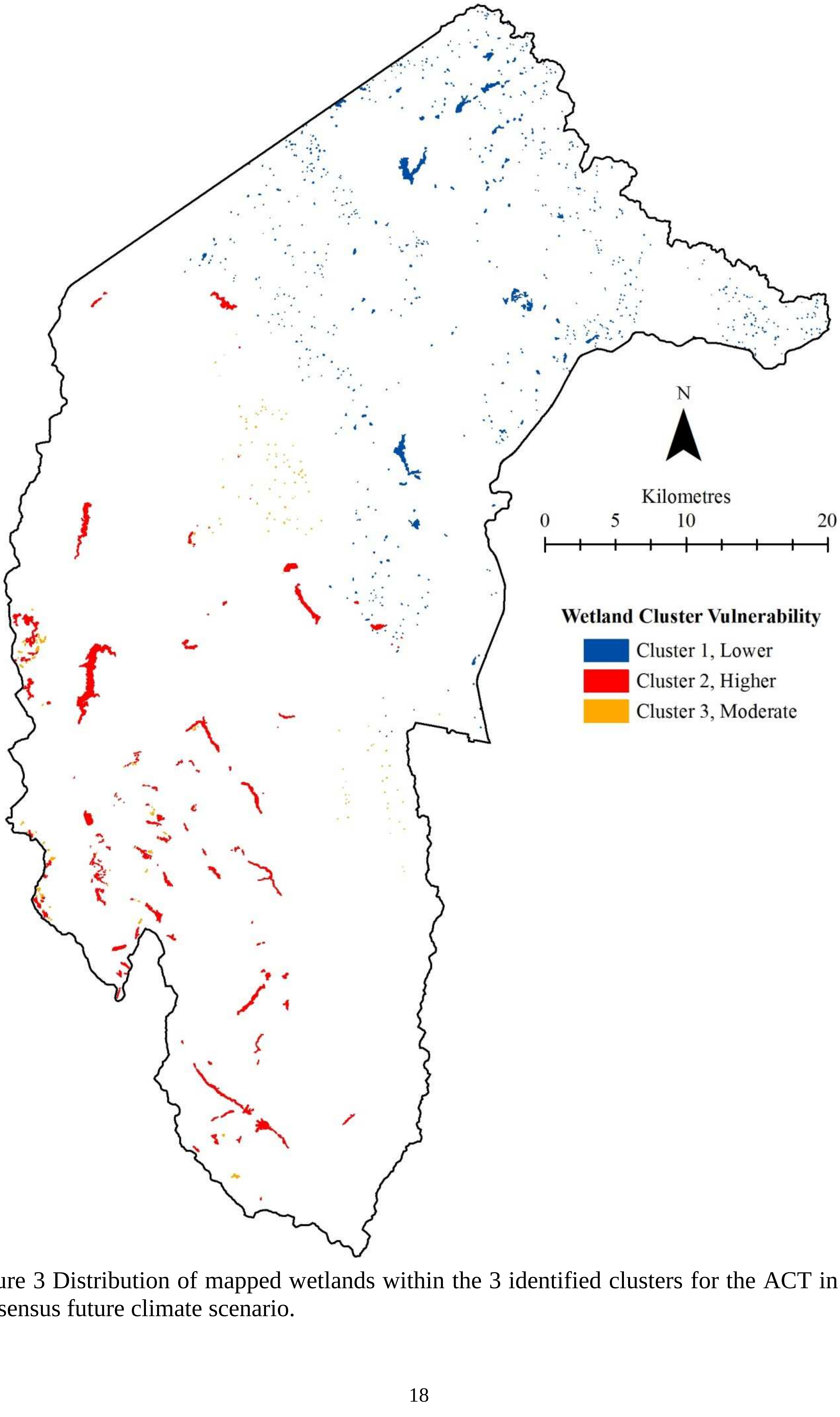

Figure 3 Distribution of mapped wetlands within the 3 identified clusters for the ACT in the consensus future climate scenario.

Table 8 Consensus scenario wetland cluster mean values for each variable, showing ranking by colour, and assignment to identified principle components with loading values. Colour shade and rank: blue – low, yellow – moderate and red – high, * denotes clusters that were not significantly different ($p \geq 0.05$).

VARIABLE	**CLUSTER MEAN**			**PRINCIPLE COMPONENT**					
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**		**Cluster 2**		**Cluster 3**	
Immediate land use pressure	0.431	0.14	0.259	2	0.413	2	0.739	1	0.839
Subcatchment land use pressure	37.696	12.677	14.768	2	0.872	2	0.782	1	0.831
Ecological change index for amphibians	0.728	0.767*	0.756*	1	0.547	2	-0.879	1	-0.96
Ecological change index for vascular plants	0.666	0.679*	0.678*	3	0.897	1	0.92	2	0.908
Absolute change in annual evapotranspiration	-0.702	12.836	10.731	1	-0.899	2	-0.963	1	-0.966
Absolute change in annual groundwater recharge	-2.266	-38.24	-0.074	4	0.897	1	0.846	3	0.986
Absolute change in annual precipitation	-26.818	-37.011	-36.734	1	0.878	1	0.982	2	0.892
Absolute change in annual surface flow	-7.893	-15.011*	-15.071*	1	0.873	1	0.727	2	0.608
Absolute change in summer/winter seasonality of evapotranspiration	-0.017	0.006	-0.001	2	0.749	1	0.83	2	0.926
Absolute change in spring/autumn seasonality of evapotranspiration	0.076	0.032	0.041	1	0.883	2	0.931	1	0.954
Absolute change in summer/winter seasonality of groundwater recharge	-0.036	-0.418	-0.002	4	0.967	1	0.93	3	0.986
Absolute change in spring/autumn seasonality of groundwater recharge	-0.012*	0.264	0*	4	0.61	3	0.89	3	-0.986
Absolute change in summer/winter seasonality of precipitation	0.008	-0.026	-0.018	1	0.707	1	0.663	2	0.714
Absolute change in spring/autumn seasonality of precipitation	0.141	0.148	0.148	2	-0.664	1	-0.976	2	-0.801
Absolute change in summer/winter seasonality of surface flow	-0.066	-0.221	-0.28	1	0.754	1	0.949	2	0.905
Absolute change in spring/autumn seasonality of surface flow	0.114	0.31*	0.308*	1	-0.89	3	0.784	1	-0.688

Table 9 Summary of wetland number, types and water balance equations assigned to each cluster for the consensus future climate scenario. M denotes that the wetland is modified, P precipitation, SR surface runoff, SF flow from a river or stream connection and GW groundwater recharge and discharge.

WETLAND TYPE/WATER BALANCE	COUNT	WETLAND TYPE/WATER BALANCE	COUNT	WETLAND TYPE/WATER BALANCE	COUNT
CLUSTER 1	**831**	**CLUSTER 2**	**237**	**CLUSTER 3**	**212**
F3.2 Sedge/forb/grassland floodplain	**13**	**Lp1.1 Permanent Lakes (M)**	**20**	**Lp1.1 Permanent Lakes (M)**	**102**
S = P + SR - ET	10	S = P + SR + GW - ET - GW	7	S = P + SR - ET	33
S = P + SR + SF - ET	2	S = P + SR + GW - ET - SR - GW	13	S = P + SR - ET - SR	68
S = P + SR + SF + GW - ET - GW	1	**Lp1.2 Permanent lakes with aquatic beds (M)**	**2**	S = P + SR + GW - ET - SR - GW	1
Lp1.1 Permanent Lakes (M)	**632**	S = P + SR + GW - ET - GW	1	**Lp1.2 Permanent lakes with aquatic beds (M)**	**7**
S = P + SR - ET	221	S = P + SR + GW - ET - SR - GW	1	S = P + SR - ET	2
S = P + SR - ET - SR	355	**Pp3 Peat bogs and fen marshes**	**184**	S = P + SR - ET - SR	5
S = P + SR + GW - ET - GW	8	S = P + SR - ET - SF	6	**Lt1.2 Temporary lakes with aquatic beds (M)**	**4**
S = P + SR + GW - ET - SR - GW	48	S = P + SR + GW - ET - GW	38	S = P + SR - ET	4
Lp1.2 Permanent lakes with aquatic beds (M)	**103**	S = P + SR + GW - ET - SF - GW	15	**Pp3 Peat bogs and fen marshes**	**78**
S = P + SR - ET	40	S = P + SR + GW - ET - SR - GW	59	S = P + SR - ET	44
S = P + SR - ET - SR	53	S = P + SR + SF - ET - SF	8	S = P + SR - ET - SR	34
S = P + SR + GW - ET - GW	1	S = P + SR + SF + GW - ET - SF - GW	58	**Pt4.2 Temporary wetland**	**21**
S = P + SR + GW - ET - SR - GW	9	**Pt2.2.2 Temporary sedge/grass/forb marsh**	**9**	S = P + SR - ET	10
Lt1.1 Temporary lakes (M)	**1**	S = P + SR + GW - ET - SR - GW	3	S = P + SR - ET - SR	11
S = P + SR - ET	1	S = P + SR + SF + GW - ET - SF - GW	6		
Lt1.2 Temporary lakes with aquatic beds (M)	**47**	**Pt2.3.2 Freshwater meadow**	**6**		
S = P + SR - ET	24	S = P + SR + GW - ET - GW	2		
S = P + SR - ET - SR	23	S = P + SR + GW - ET - SR - GW	2		
Pt2.3.2 Freshwater meadow	**32**	S = P + SR + SF + GW - ET - SF - GW	2		
S = P + SR - ET	10	**Pt4.2 Temporary wetland**	**16**		
S = P + SR - ET - SR	11	S = P + SR - ET - SF	1		
S = P + SR + GW - ET - GW	3	S = P + SR + GW - ET - GW	5		
S = P + SR + GW - ET - SR - GW	3	S = P + SR + GW - ET - SR - GW	2		
S = P + SR + SF - ET - SF	2	S = P + SR + SF + GW - ET - SF - GW	8		
S = P + SR + SF + GW - ET - SF - GW	3				
Pt4.2 Temporary wetland	**3**				
S = P + SR - ET - SR	3				

each). Of the 16 variables, 14 were present in PC1 and PC2, with 3 variables additional to PC1/PC2 for this cluster: potential degree of ecological change in vascular plants, annual and summer/winter groundwater recharge. The annual and seasonal groundwater recharge variables are not present in PC1/PC2 for any other cluster. These unique PC1/PC2 variables show the link to the high number of wetlands present in this cluster with a groundwater connection in their water balance equation.

Cluster 3 contains 212 wetland polygons (Table 9), the majority classified as modified permanent lakes and peat bogs and fen marshes (109 and 78 respectively). The wetlands are also located in the upland, subalpine and alpine area of the ACT within the Australian Alps physiographic region (Figure 3). However most wetlands in this cluster (all except 1) did not intersect any of the 4 groundwater spatial layers, and are therefore do not have a groundwater connection in their water balance equation. This cluster has moderate climate change vulnerability in the ACT for the consensus scenario. This is despite also having the lowest levels of ecological change for both amphibians and vascular plants. Immediate and subcatchment anthropogenic pressures were moderate for this cluster, due to peri-urban and rural land use and encroaching urban development. For the 12 hydrological change variables, this cluster ranked the highest change for 4 variables, moderate change for 4 variables and lowest change for the remaining 4 variables (Table 8). Both annual precipitation and surface flow are projected to reduce, with weaker summer and autumn seasonality. Annual groundwater recharge is projected to reduce, with stronger winter seasonality and weaker autumn seasonality. Annual evapotranspiration is projected to increase but with weaker summer and autumn seasonality. Principle component analysis for cluster 3 determined 3 principle components (Eigenvalues: 5.615, 5.183, 3.305) that explained a total variance of 88.145% (35.092%, 32.396% and 20.657% each). Of the 16 variables, 13 were present in PC1 and PC2, with 2 additional variables to PC1/PC2 for this cluster: potential degree of ecological change in vascular plants and absolute change in spring/autumn seasonality of surface flow.

3.2.2 Wet-cool extreme scenario

Cluster analysis of the 16 variables for the wet-cool extreme scenario allocated wetlands into 3 clusters (Figure 4). All clusters were significantly different ($p < 0.05$) regarding 11 of the 16 variables, with 2 clusters statistically similar ($p \geq 0.05$) for the 5 remaining variables (Table 10). Table 10 provides a summary of the mean values for the 16 variables for each cluster, calculated from the allocated wetlands ($n = 1280$). Of the 16 variables, 7 were present in PC1/PC2 across all clusters (Table 10). The 7 variables are: subcatchment land use pressure, absolute change in annual evapotranspiration, absolute change in summer/winter seasonality of precipitation and evapotranspiration and absolute change in spring/autumn seasonality of precipitation, evapotranspiration and surface flow. Each cluster is described below.

Cluster 1 contains 494 wetland polygons (Table 11), the majority (457) classified as modified permanent or temporary lakes and includes all 13 floodplain wetlands. The wetlands are located in the urban and peri-urban tableland area of the ACT within the Werriwa Tablelands physiographic region (Figure 4). This cluster has the highest climate change vulnerability within the ACT for the wet-cool extreme scenario. This cluster has the highest immediate and subcatchment anthropogenic pressures and highest levels of ecological change for both amphibians and vascular plants. For the 12 hydrological change variables, this cluster ranked the highest change for 7 variables, moderate change for 2 variables and lowest change for the

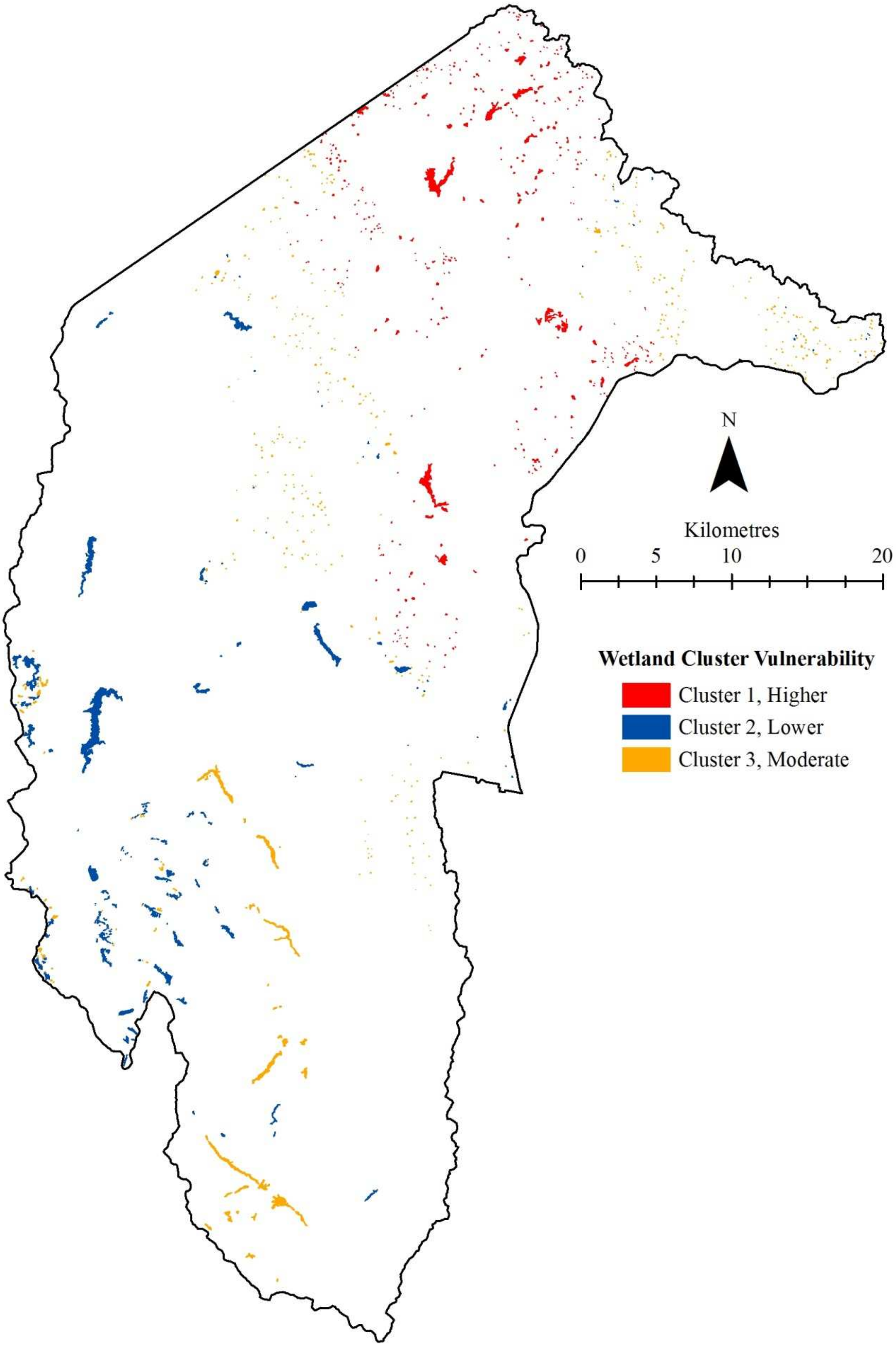

Figure 4 Distribution of mapped wetlands within the 3 identified clusters for the ACT in the wet-cool extreme future climate scenario.

Table 10 Wet-cool extreme scenario wetland cluster mean values for each variable, showing ranking by colour, and assignment to identified principle components with loading values. Colour shade and rank: blue – low, yellow – moderate and red – high, * denotes clusters that were not significantly different (p ≥ 0.05).

VARIABLE	**CLUSTER MEAN**			**PRINCIPLE COMPONENT**					
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**		**Cluster 2**		**Cluster 3**	
Immediate land use pressure	0.455	0.174	0.327			1	0.818	1	0.664
Subcatchment land use pressure	45.17	14.068	21.409	1	0.803	1	0.861	1	0.804
Ecological change index for amphibians	0.725	0.761	0.744	4	0.942	1	-0.925	1	-0.857
Ecological change index for vascular plants	0.666	0.675*	0.672*	4	0.815	4	0.713	1	-0.727
Absolute change in annual evapotranspiration	32.352	30.063	30.286	2	0.884	2	0.618	2	0.747
Absolute change in annual groundwater recharge	-2.606	-19.633	-0.444	5	0.945	1	-0.74	3	-0.881
Absolute change in annual precipitation	1.794	1.435	0.756	3	0.656	4	0.835	3	0.706
Absolute change in annual surface flow	-9.167	-11.415*	-10.281*	3	0.797	4	0.677	4	0.941
Absolute change in summer/winter seasonality of evapotranspiration	0.195	0.136	0.17	2	0.906	1	0.817	2	0.635
Absolute change in spring/autumn seasonality of evapotranspiration	0.019	0.001*	0.004*	1	0.716	2	0.829	2	0.903
Absolute change in summer/winter seasonality of groundwater recharge	-0.02	0.043	0.003	5	0.948	3	0.897	3	0.709
Absolute change in spring/autumn seasonality of groundwater recharge	-0.001*	0.199	0.021*	2	-0.464	2	-0.934	3	0.923
Absolute change in summer/winter seasonality of precipitation	0.233	0.12	0.177	1	0.704	1	0.846	1	0.622
Absolute change in spring/autumn seasonality of precipitation	0.023	0.068	0.05	1	-0.926	1	-0.876	1	-0.668
Absolute change in summer/winter seasonality of surface flow	0.108*	0.062	0.289*	3	0.741	3	0.927	4	0.953
Absolute change in spring/autumn seasonality of surface flow	-0.187	0.146	-0.002	1	-0.762	1	-0.735	2	-0.79

Table 11 Summary of wetland number, types and water balance equations assigned to each cluster for the wet-cool extreme future climate scenario. M denotes that the wetland is modified, P precipitation, SR surface runoff, SF flow from a river or stream connection and GW groundwater recharge and discharge.

WETLAND TYPE/WATER BALANCE	COUNT	WETLAND TYPE/WATER BALANCE	COUNT	WETLAND TYPE/WATER BALANCE	COUNT
CLUSTER 1	**494**	**CLUSTER 2**	**229**	**CLUSTER 3**	**557**
F3.2 Sedge/forb/grassland floodplain	**13**	**Lp1.1 Permanent Lakes (M)**	**44**	**Lp1.1 Permanent Lakes (M)**	**373**
S = P + SR - ET	10	S = P + SR + GW - ET - GW	8	S = P + SR - ET	112
S = P + SR + SF - ET	2	S = P + SR + GW - ET - SR - GW	36	S = P + SR - ET - SR	260
S = P + SR + SF + GW - ET - GW	1	**Lp1.2 Permanent lakes with aquatic beds (M)**	**3**	S = P + SR + GW - ET - SR - GW	1
Lp1.1 Permanent Lakes (M)	**337**	S = P + SR + GW - ET - GW	2	**Lp1.2 Permanent lakes with aquatic beds (M)**	**24**
S = P + SR - ET	142	S = P + SR + GW - ET - SR - GW	1	S = P + SR - ET	5
S = P + SR - ET - SR	163	**Pp3 Peat bogs and fen marshes**	**158**	S = P + SR - ET - SR	19
S = P + SR + GW - ET - GW	7	S = P + SR - ET - SF	6	**Lt1.1 Temporary lakes (Modified)**	**1**
S = P + SR + GW - ET - SR - GW	25	S = P + SR + GW - ET - GW	36	S = P + SR - ET	1
Lp1.2 Permanent lakes with aquatic beds (M)	**85**	S = P + SR + GW - ET - SF - GW	15	**Lt1.2 Temporary lakes with aquatic beds (M)**	**16**
S = P + SR - ET	37	S = P + SR + GW - ET - SR - GW	57	S = P + SR - ET	6
S = P + SR - ET - SR	39	S = P + SR + SF - ET - SF	8	S = P + SR - ET - SR	10
S = P + SR + GW - ET - SR - GW	9	S = P + SR + SF + GW - ET - SF - GW	36	**Pp3 Peat bogs and fen marshes**	**104**
Lt1.2 Temporary lakes with aquatic beds (M)	**35**	**Pt2.2.2 Temporary sedge/grass/forb marsh**	**1**	S = P + SR - ET	44
S = P + SR - ET	22	S = P + SR + GW - ET - SR - GW	1	S = P + SR - ET - SR	34
S = P + SR - ET - SR	13	**Pt2.3.2 Freshwater meadow**	**7**	S = P + SR + GW - ET - GW	2
Pt2.3.2 Freshwater meadow	**23**	S = P + SR + GW - ET - GW	3	S = P + SR + GW - ET - SR - GW	2
S = P + SR - ET	7	S = P + SR + GW - ET - SR - GW	2	S = P + SR + SF + GW - ET - SF - GW	22
S = P + SR - ET - SR	6	S = P + SR + SF + GW - ET - SF - GW	2	**Pt2.2.2 Temporary sedge/grass/forb marsh**	**8**
S = P + SR + GW - ET - GW	2	**Pt4.2 Temporary wetland**	**16**	S = P + SR + GW - ET - SR - GW	2
S = P + SR + GW - ET - SR - GW	3	S = P + SR - ET - SF	1	S = P + SR + SF + GW - ET - SF - GW	6
S = P + SR + SF - ET - SF	2	S = P + SR + GW - ET - GW	5	**Pt2.3.2 Freshwater meadow**	**8**
S = P + SR + SF + GW - ET - SF - GW	3	S = P + SR + GW - ET - SR - GW	2	S = P + SR - ET	3
Pt4.2 Temporary wetland	**1**	S = P + SR + SF + GW - ET - SF - GW	8	S = P + SR - ET - SR	5
S = P + SR - ET - SR	1			**Pt4.2 Temporary wetland**	**23**
				S = P + SR - ET	10
				S = P + SR - ET - SR	13

remaining 3 variables (Table 10). Both annual precipitation and evapotranspiration are projected to increase, with stronger summer seasonality and weaker autumn seasonality. Annual surface flow is projected to reduce, with stronger summer and autumn seasonality. Annual groundwater recharge is projected to reduce, with stronger winter and autumn seasonality. Principle component analysis for cluster 1 determined 5 principle components (Eigenvalues: 3.360, 2.774, 2.201, 2.068, 2.030) that explained a total variance of 77.707% (21.001%, 17.335%, 13.759%, 12.923 and 12.689% each). Of the 16 variables, 8 were present in PC1 and PC2, with only 1 variable additional to PC1/PC2 for this cluster: absolute change in spring/autumn seasonality of groundwater recharge. Immediate land use pressure was not associated with any principle component for this cluster.

Cluster 2 contains 229 wetland polygons (Table 11), the majority (158) classified as peat bogs and fen marshes. This cluster contains the largest number of wetlands with a groundwater connection in their water balance equation, located in the upland, subalpine and alpine area of the ACT within the Australian Alps physiographic region (Figure 4). This cluster was determined to have the lowest climate change vulnerability within the ACT for the wet-cool scenario. This cluster has the lowest immediate and subcatchment anthropogenic pressures and lowest levels of ecological change for both amphibians and vascular plants. For the 12 hydrological change variables, this cluster ranked the highest change for 5 variables, moderate change for 2 variables and lowest change for the remaining 5 variables (Table 10). Again, both annual precipitation and evapotranspiration are projected to increase, with stronger summer seasonality and weaker autumn seasonality. Annual surface flow and groundwater recharge are projected to reduce, with stronger summer and weaker autumn seasonality for surface flow and stronger winter and weaker autumn seasonality for groundwater recharge. Principle component analysis for cluster 2 determined 4 principle components (Eigenvalues: 6.092, 3.044, 2.551, 2.425) that explained a total variance of 88.198% (38.078%, 19.022%, 15.944% and 15.155% each). Of the 16 variables, 11 were present in PC1 and PC2, with 4 variables additional to PC1/PC2 for this cluster: potential degree of ecological change in amphibians, immediate land use pressure and absolute change in annual and spring/autumn groundwater recharge. The annual groundwater recharge variable is unique to PC1/PC2 for this cluster, again reflecting the importance of groundwater interaction to the wetlands in this cluster.

Cluster 3 contains 557 wetland polygons (Table 11), the majority classified as modified permanent lakes and peat bogs and fen marshes (397 and 104 respectively). The wetlands are located in 2 principle areas of the ACT: the upland area of the Werriwa Tablelands associated with the Cullarin Uplift; and also upland and subalpine areas of the Australian Alps physiographic region (Figure 4). As with cluster 3 in the consensus scenario, most wetlands in this cluster (all except 35) did not intersect any of the 4 groundwater spatial layers, and are therefore not considered to have a groundwater connection in their water balance equation. This cluster has moderate climate change vulnerability within the ACT for the wet-cool extreme scenario. Immediate and subcatchment anthropogenic pressures were moderate for this cluster as was a moderate rank for ecological change for both amphibians and vascular plants. For the 12 hydrological change variables, this cluster ranked the highest change for 2 variables, moderate change for 4 variables and lowest change for the remaining 6 variables (Table 10). As with cluster 2, both annual precipitation and evapotranspiration are projected to increase, with stronger summer seasonality and weaker autumn seasonality. Again, annual surface flow and groundwater recharge are projected to reduce, with stronger summer and autumn seasonality for surface flow and stronger winter and autumn seasonality for groundwater recharge. Principle component analysis for cluster 3 determined 4 principle components (Eigenvalues: 3.872, 3.495, 3.203, 2.670) that explained a total variance of 82.750% (24.200%, 21.845%, 20.016 and 16.689% each). Of the 16 variables, 10 were present in PC1 and PC2, with 3 variables additional to PC1/PC2 for this cluster: immediate land use pressure and the potential degree of ecological change in vascular plants and amphibians. The potential degree of ecological change in vascular plants variable is unique to this cluster.

3.2.3 Dry-hot extreme scenario

Cluster analysis of the 16 variables for the dry-hot scenario allocated wetlands into 3 clusters (Figure 5). All clusters were significantly different ($p < 0.05$) regarding 14 of the 16 variables, with 2 clusters statistically similar ($p \geq 0.05$) for the 2 remaining variables (Table 12). Table 12 provides a summary of the mean values for the 16 variables for each cluster, calculated from the allocated wetlands ($n = 1280$). Of the 16 variables, 10 were present in PC1/PC2 across all clusters (Table 12). The 10 variables are: immediate and subcatchment land use pressure, ecological change index for vascular plants and amphibians, absolute change in annual precipitation and evapotranspiration, absolute change in summer/winter and spring/autumn seasonality of precipitation and evapotranspiration. Each cluster is described below.

Cluster 1 contains 557 wetland polygons (Table 13), of which the majority (522) were classified as modified permanent or temporary lakes and includes all 13 floodplain wetlands. The wetlands are located in the tableland and eastern upland areas of the ACT within the Werriwa Tablelands physiographic region (Figure 5). This cluster was determined to have moderate climate change vulnerability within the ACT for the dry-hot extreme scenario. This cluster has the highest immediate and subcatchment anthropogenic pressures, moderate level of ecological change for amphibians and the lowest level of ecological change for vascular plants. For the 12 hydrological change variables, this cluster ranked the highest change for 5 variables, moderate change for 3 variables and lowest change for the remaining 4 variables (Table 12). All 4 annual change variables are projecting reductions in precipitation, evapotranspiration, surface flow and groundwater recharge. For precipitation, weak winter dominance is changing to weak summer dominance in seasonality, with weaker autumn seasonality. Evapotranspiration has weaker summer and autumn seasonality. Matching the change in precipitation, surface flow becomes summer dominant, with weaker spring seasonality. Groundwater recharge has weaker winter seasonality and changes to weak spring dominant. Principle component analysis for cluster 1 determined 4 principle components (Eigenvalues: 5.629, 3.171, 2.779, 1.878) which explained a total variance of 84.107% (35.184%, 19.819%, 17.367% and 11.737% each). Of the 16 variables, 12 were present in PC1 and PC2, with 2 additional variables to PC1/PC2 for this cluster: absolute change in summer/winter and spring/autumn seasonality of surface flow. The absolute change in summer/winter seasonality of surface flow is unique to this cluster.

Cluster 2 contains 261 wetland polygons (Table 13), the majority (184) classified as peat bogs and fen marshes. This cluster also contains the largest number of wetlands with a groundwater connection in their water balance equation. The wetlands are located in the upland, subalpine and alpine area of the ACT within the Australian Alps physiographic region (Figure 5). This cluster has the lowest climate change vulnerability within the ACT for the dry-hot extreme scenario. This cluster has the lowest immediate and subcatchment anthropogenic pressures and lowest levels of potential degree of ecological change in amphibians, but moderate change for vascular plants. For the 12 hydrological change

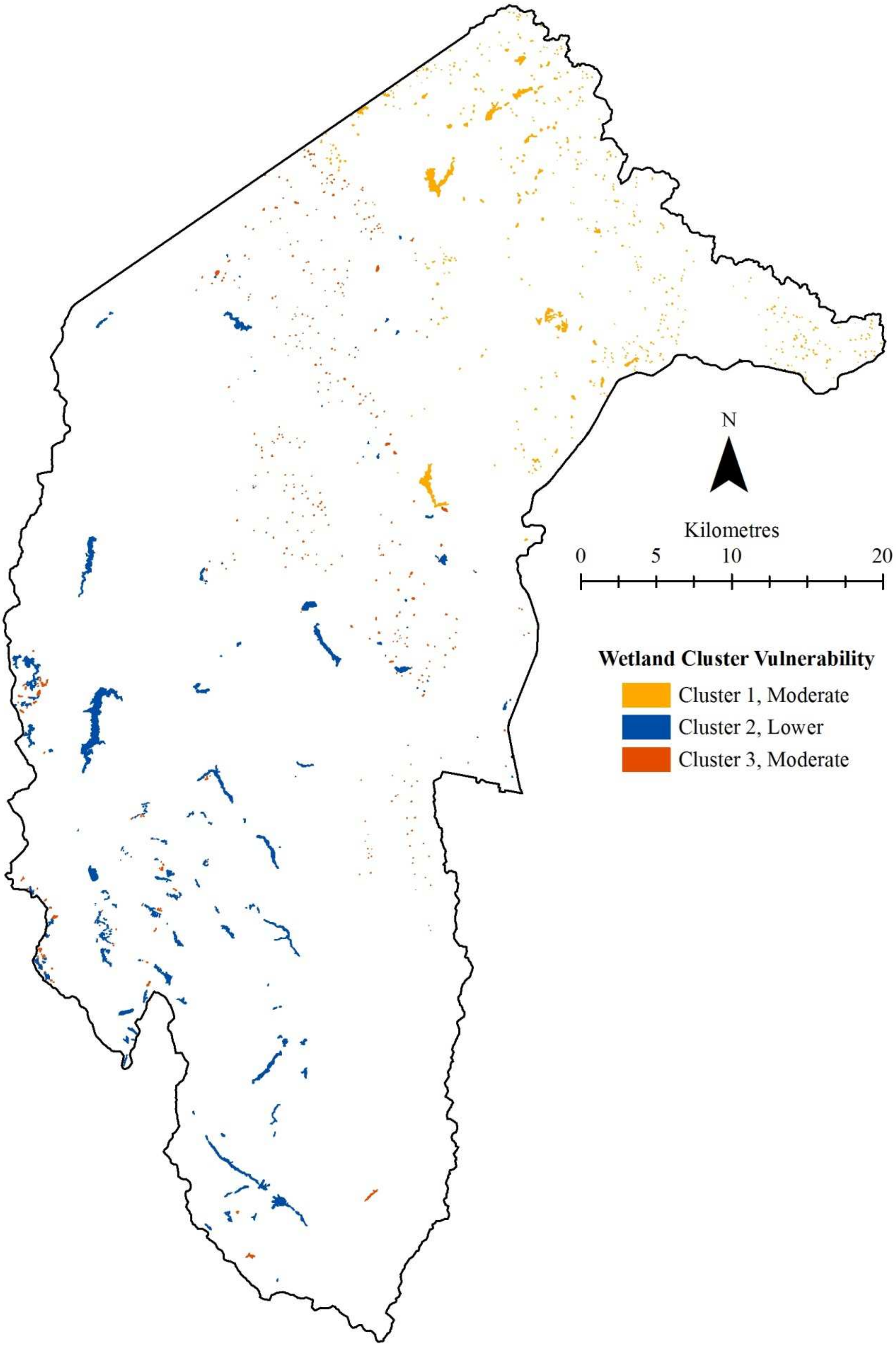

Figure 5 Distribution of mapped wetlands within the 3 identified clusters for the ACT in the dry-hot extreme future climate scenario.

Table 12 Dry-hot extreme scenario wetland cluster mean values for each variable, showing ranking by colour, and assignment to identified principle components with loading values. Colour shade and rank: blue – low, yellow – moderate and red – high, * denotes clusters that were not significantly different ($p \geq 0.05$).

VARIABLE	**CLUSTER MEAN**			**PRINCIPLE COMPONENT**					
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**		**Cluster 2**		**Cluster 3**	
Immediate land use pressure	0.436	0.17	0.345	1	0.32	1	-0.768	1	-0.841
Subcatchment land use pressure	39.875	14.56	24.783	1	0.895	1	-0.86	1	-0.726
Ecological change index for amphibians	0.667	0.673	0.643	1	-0.883	1	0.908	1	0.942
Ecological change index for vascular plants	0.522	0.504	0.468	2	-0.811	1	0.861	1	0.886
Absolute change in annual evapotranspiration	-31.556	-4.804	-9.781	1	0.816	1	0.731	2	0.734
Absolute change in annual groundwater recharge	-1.05	-20.896	-0.035	3	-0.984	1	-0.729	3	-0.991
Absolute change in annual precipitation	-33.007	-14.746	-18.473	2	0.759	2	0.969	2	0.936
Absolute change in annual surface flow	-4.035*	-1.098	-3.222*	4	0.963	2	0.928	2	0.947
Absolute change in summer/winter seasonality of evapotranspiration	-0.221	-0.134	-0.172	1	0.912	1	0.844	1	0.636
Absolute change in spring/autumn seasonality of evapotranspiration	0.321	0.12	0.202	1	-0.965	1	-0.949	1	-0.872
Absolute change in summer/winter seasonality of groundwater recharge	0.148	-4.378	0.006	3	0.936	2	0.798	3	0.998
Absolute change in spring/autumn seasonality of groundwater recharge	0.145	3.178	0.014	3	0.93	3	0.947	3	0.993
Absolute change in summer/winter seasonality of precipitation	0.326	0.491	0.447	2	0.708	1	0.84	1	0.808
Absolute change in spring/autumn seasonality of precipitation	0.216	0.298	0.264	1	-0.68	2	0.792	2	0.799
Absolute change in summer/winter seasonality of surface flow	1.539*	1.617	1.505*	1	0.654	3	-0.879		
Absolute change in spring/autumn seasonality of surface flow	-0.102	1.889	1.232	2	0.793	3	0.71	2	0.69

Table 13 Summary of wetland number, types and water balance equations assigned to each cluster for the dry-hot extreme future climate scenario. M denotes that the wetland is modified, P precipitation, SR surface runoff, SF flow from a river or stream connection and GW groundwater recharge and discharge.

WETLAND TYPE/WATER BALANCE	COUNT	WETLAND TYPE/WATER BALANCE	COUNT	WETLAND TYPE/WATER BALANCE	COUNT
CLUSTER 1	**557**	**CLUSTER 2**	**261**	**CLUSTER 3**	**462**
F3.2 Sedge/forb/grassland floodplain	**13**	**Lp1.1 Permanent Lakes (M)**	**43**	**Lp1.1 Permanent Lakes (M)**	**301**
S = P + SR - ET	10	S = P + SR + GW - ET - GW	11	S = P + SR - ET	104
S = P + SR + SF - ET	2	S = P + SR + GW - ET - SR - GW	32	S = P + SR - ET - SR	196
S = P + SR + SF + GW - ET - GW	1	**Lp1.2 Permanent lakes with aquatic beds (M)**	**3**	S = P + SR + GW - ET - SR - GW	1
Lp1.1 Permanent Lakes (M)	**410**	S = P + SR + GW - ET - GW	1	**Lp1.2 Permanent lakes with aquatic beds (M)**	**29**
S = P + SR - ET	150	S = P + SR + GW - ET - SR - GW	2	S = P + SR - ET	13
S = P + SR - ET - SR	227	**Pp3 Peat bogs and fen marshes**	**184**	S = P + SR - ET - SR	16
S = P + SR + GW - ET - GW	4	S = P + SR - ET - SF	6	**Lt1.1 Temporary lakes (M)**	**1**
S = P + SR + GW - ET - SR - GW	29	S = P + SR + GW - ET - GW	38	S = P + SR - ET	1
Lp1.2 Permanent lakes with aquatic beds (M)	**80**	S = P + SR + GW - ET - SF - GW	15	**Lt1.2 Temporary lakes with aquatic beds (M)**	**19**
S = P + SR - ET	29	S = P + SR + GW - ET - SR - GW	59	S = P + SR - ET	14
S = P + SR - ET - SR	42	S = P + SR + SF - ET - SF	8	S = P + SR - ET - SR	5
S = P + SR + GW - ET - GW	1	S = P + SR + SF + GW - ET - SF - GW	58	**Pp3 Peat bogs and fen marshes**	**78**
S = P + SR + GW - ET - SR - GW	8	**Pt2.2.2 Temporary sedge/grass/forb marsh**	**9**	S = P + SR - ET	44
Lt1.2 Temporary lakes with aquatic beds (M)	**32**	S = P + SR + GW - ET - SR - GW	3	S = P + SR - ET - SR	34
S = P + SR - ET	14	S = P + SR + SF + GW - ET - SF - GW	6	**Pt2.3.2 Freshwater meadow**	**11**
S = P + SR - ET - SR	18	**Pt2.3.2 Freshwater meadow**	**6**	S = P + SR - ET	3
Pt2.3.2 Freshwater meadow	**21**	S = P + SR + GW - ET - GW	2	S = P + SR - ET - SR	7
S = P + SR - ET	7	S = P + SR + GW - ET - SR - GW	2	S = P + SR + SF + GW - ET - SF - GW	1
S = P + SR - ET - SR	4	S = P + SR + SF - ET - SF	1	**Pt4.2 Temporary wetland**	**23**
S = P + SR + GW - ET - GW	3	S = P + SR + SF + GW - ET - SF - GW	1	S = P + SR - ET	10
S = P + SR + GW - ET - SR - GW	3	**Pt4.2 Temporary wetland**	**16**	S = P + SR - ET - SR	13
S = P + SR + SF - ET - SF	1	S = P + SR - ET - SF	1		
S = P + SR + SF + GW - ET - SF - GW	3	S = P + SR + GW - ET - GW	5		
Pt4.2 Temporary wetland	**1**	S = P + SR + GW - ET - SR - GW	2		
S = P + SR - ET - SR	1	S = P + SR + SF + GW - ET - SF - GW	8		

variables, this cluster ranked the highest change for 7 variables and ranked lowest change for the remaining 5 variables (Table 12). The lowest levels of change were found for 3 annual change variables, experiencing reductions in annual precipitation, evapotranspiration, surface flow and groundwater recharge. Precipitation changes to weak summer and spring dominance in seasonality. Evapotranspiration has weaker summer and autumn seasonality. Surface flow has weaker winter seasonality and changes to weak spring seasonality. Groundwater recharge has stronger winter and weaker autumn seasonality. Principle component analysis for cluster 2 determined 3 principle components (Eigenvalues: 6.719, 4.247, 2.624) that explained a total variance of 84.943% (41.993%, 26.547% and 16.403% each). Of the 16 variables, 13 were present in PC1 and PC2, with 3 variables additional to PC1/PC2 for this cluster: absolute change in annual surface flow and groundwater recharge and summer/winter groundwater recharge. The annual and seasonal groundwater recharge variables unique to PC1/PC2 for this cluster, again reflecting the importance of groundwater interaction to the wetlands in this cluster.

Cluster 3 contains 462 wetland polygons (Table 13), the majority classified as modified permanent lakes and peat bogs and fen marshes (130 and 78 respectively). The wetlands are also located in the western upland areas of the ACT within the Werriwa Tablelands and upland, subalpine and alpine area of the ACT within the Australian Alps physiographic region (Figure 5). Most wetlands in this cluster (all except 2) did not intersect any of the 4 groundwater spatial layers, and are therefore not considered to have a groundwater connection in their water balance equation. This cluster has moderate climate change vulnerability within the ACT for the dry-hot extreme scenario. Immediate and subcatchment anthropogenic pressures were moderate for this cluster, with the highest levels of ecological change for both amphibians and vascular plants. For the 12 hydrological change variables, this cluster ranked the highest change for 1 variable, moderate change for 7 variables and lowest change for the remaining 4 variables (Table 12). Annual change variables are again projecting reductions in precipitation, evapotranspiration, surface flow and groundwater recharge. Precipitation changes to weak summer dominance with weaker autumn seasonality. Evapotranspiration has weaker summer and autumn seasonality. Surface flow has weaker winter seasonality and changes to weak spring seasonality. Groundwater recharge has stronger winter and weaker autumn seasonality. Principle component analysis for cluster 3 determined 4 principle components (Eigenvalues: 5.000, 4.111, 2.990, 2.206) that explained a total variance of 89.417% (31.251%, 25.693%, 18.685 and 13.788% each). Of the 16 variables, 12 were present in PC1 and PC2, with 2 variables additional to PC1/PC2 for this cluster: absolute change in annual and spring/autumn seasonality of surface flow, absolute change in summer/winter seasonality of surface flow was not associated with any principle component for this cluster.

4 DISCUSSION

4.1 Comparison of future change in the ACT between climate futures

Trends in the downscaled hydrological impact assessment near future dataset (Littleboy *et al*. 2015), for each of the 3 climate scenarios, reflect the initial choice to represent a 12 model mean consensus, wet-cool and hot-dry extreme futures from the 10km climate change projections for the ACT (Olson *et al*. 2014; NSW Office of Environment and Heritage 2015b). However this is not directly obvious in the ACT-wide mean absolute change in volume values for annual and seasonal precipitation, evapotranspiration, surface flow and groundwater recharge (Table 14). As previously stated, the individual climate models used in the NARCliM Project will have inherent variability in gridded values for both the current and

Table 14 Summary of variability in ACT-wide mean hydrological change between the 3 future climate scenarios, for absolute change in annual and seasonal volumes (mm) and current and future seasonality ratios.

VARIABLE/ SCENARIO	PRECIPITATION	EVAPO-TRANSPIRATION	SURFACE FLOW	GROUNDWATER RECHARGE
ANNUAL				
Consensus	-32.525	8.016	-14.346	-29.606
Wet-Cool extreme	1.785	30.469	-12.031	-19.044
Dry-hot extreme	-17.112	-11.569	-2.652	-15.173
SPRING				
Consensus	-23.291	-0.549	-5.434	-11.171
Wet-Cool extreme	-20.166	5.487	-9.936	-18.231
Dry-hot extreme	-37.359	-7.130	-3.046	-8.740
SUMMER				
Consensus	-13.820	1.334	-7.973	-15.927
Wet-Cool extreme	29.803	18.774	0.747	-0.609
Dry-hot extreme	32.249	-15.633	0.652	-1.189
AUTUMN				
Consensus	10.322	6.740	0.269	-1.641
Wet-Cool extreme	-1.337	5.283	-2.411	1.534
Dry-hot extreme	12.694	11.862	4.384	2.698
WINTER				
Consensus	-5.737	0.492	-1.209	-0.867
Wet-Cool extreme	-6.514	0.925	-0.432	-1.739
Dry-hot extreme	-24.696	-0.669	-4.641	-7.942
SUMMER/WINTER (current)				
Consensus	0.725 Summer	1.958 Summer	0.831 Summer	0.245 Summer
Wet-Cool extreme	0.508 Summer	2.120 Summer	0.272 Summer	-0.368 Winter
Dry-hot extreme	-0.366 Winter	1.107 Summer	-2.473 Winter	-4.334 Winter
SUMMER/WINTER (near future)				
Consensus	0.715 Summer	1.956 Summer	0.628 Summer	-0.205 Winter
Wet-Cool extreme	0.666 Summer	2.275 Summer	0.357 Summer	-0.358 Winter
Dry-hot extreme	0.091 Summer	0.949 Summer	-0.697 Winter	-5.853 Winter
SPRING/AUTUMN (current)				
Consensus	-0.235 Autumn	-0.279 Autumn	-0.302 Autumn	-0.549 Autumn
Wet-Cool extreme	-0.325 Autumn	-0.262 Autumn	-0.633 Autumn	-1.161 Autumn
Dry-hot extreme	-0.290 Autumn	-0.470 Autumn	-0.838 Autumn	-3.604 Autumn
SPRING/AUTUMN (near future)				
Consensus	-0.090 Autumn	-0.230 Autumn	-0.057 Autumn	-0.416 Autumn
Wet-Cool extreme	-0.264 Autumn	-0.256 Autumn	-0.530 Autumn	-0.968 Autumn
Dry-hot extreme	-0.013 Autumn	-0.299 Autumn	0.738 Spring	-1.182 Autumn

the near future time periods, due to the global climate model and regionalisation methods used (Evans and Ji 2012a, 2012b; Evans *et al*. 2013, 2014; Ji *et al*. 2016). The variability in current values prevents direct comparison of the determined wetland vulnerability between the 3 future climate scenarios. However this analysis allows for the ACT Environment, Planning and Sustainable Development Directorate to undertake natural resource management planning, with consideration of a range of likely futures and possible desired outcomes, as recommended by the CSIRO Climate Adaptation Flagship (Rissik et al. 2014; Timbal 2015).

For the current time period, ACT-wide mean values (Table 14) indicate the consensus scenario is expressing an overall summer seasonality in precipitation, evapotranspiration, surface flow and groundwater recharge. The wet-cool extreme scenario follows suit, but with winter seasonality for groundwater recharge reflecting the lower evapotranspiration in winter. The dry-hot extreme scenario is expressing winter seasonality in precipitation, surface flow and groundwater recharge, with summer seasonality for evapotranspiration. There are only 2 changes in seasonality for the near future time period, with the consensus scenario changing to winter seasonality in groundwater recharge and the dry-hot extreme scenario changing to summer seasonality in precipitation. All 3 of the climate futures are consistent in expressing an overall autumn seasonality in precipitation, evapotranspiration, surface flow and groundwater recharge for the current time period. This pattern remains in the near future, except for surface flow in the dry-hot extreme scenario which has spring seasonality.

In contrast, the Bureau of Meteorology (2010) dataset, using the method of Gaffney (1971), has precipitation classed as uniform year round for the ACT, except for a small area of winter dominant precipitation in the northwest of the ACT. The method of determining seasonality used in this chapter (Williams *et al*. 2010a, 2010b), does not have a uniform category, with values closer to 0 indicating weaker seasonality and larger positive/negative values indicating stronger seasonality. Some of the changes in seasonality for the ACT (or individual clusters) that shift in ratio values close to +/-0 may represent a uniform seasonality and therefore no change. Advice from Williams *et al*. (2010a, 2010b) has been sought, to determine if threshold values for a uniform class can be integrated into the seasonality calculation method. No final decision has been reached as yet, so the original seasonality assignment was used.

Across the ACT, the ecological change in vascular plant communities is much greater for the hot scenario than for the mild scenario. The ACT-wide mean index value for the hot scenario is 0.490 (min = 0.361, max = 0.655) and for the mild scenario is 0.678 (min = 0.564, max = 0.783), the lower the similarity value the greater the potential change in future biodiversity (Williams *et al*. 2014). The same pattern is seen for amphibian communities although with less overall change, mean index value for the hot scenario is 0.666 (min = 0.538, max = 0.797) and for the mild scenario 0.758 (min = 0.649, max = 0.859). Where change is occurring in ecological communities, the further measures of Williams *et al*. (2014) show the potential for disappearing communities is higher than the potential for novel communities. Calculated ACT-wide disappearing index means are 0.661 and 0.803 respectively for vascular plants and amphibians in the hot scenario, and 0.860 and 0.775 in the mild scenario. Calculated ACT-wide novel index means are 0.654 and 0.790 respectively for vascular plants and amphibians in the hot scenario, and 0.767 and 0.846 in the mild scenario. This suggests future loss in biodiversity.

4.2 Comparison of clusters within climate futures

There was a pattern in the distribution of the wetlands clusters across all 3 future climate scenarios (Figures 3 to 5). Cluster 1 of each scenario was typically present across the low elevation undulating tableland areas of the Werriwa Tablelands physiographic region in the ACT. Cluster 2 of each scenario was typically present across the high elevation upland, subalpine and alpine areas of the Australian Alps physiographic region. Cluster 3 of each scenario was typically present in 2 situations: the moderate elevation tableland and upland areas, transitioning between the Werriwa Tablelands and Australian Alps physiographic regions and; the non-groundwater associated wetlands in the Australian Alps physiographic region. The exception is the additional area of cluster 2 on the eastern arm of the ACT associated with the Cullarin Uplift in the wet-cool extreme scenario. This cluster pattern is understandable, considering the underlying variation of climate and landscape controls for different physiographic regions on hydrogeological and hydrological properties and processes, and creation of associated ecological habitat niches and species distribution (e.g. associated IBRA and vegetation distribution in the ACT). It is also reflected in the choice of variables for undertaking wetland classification and defining unique classes (Brinson 1993; Claus *et al*. 2011; Semeniuk and Semeniuk 2011). For example, in the ANAE Classification Framework broad regional divisions are made based on climate, physiographic, hydrological and biological patterns (Aquatic Ecosystems Task Group 2012; Brooks *et al*. 2014).

Further, cluster 1 of each scenario contained the majority of modified permanent or temporary lakes and always included all 13 floodplain wetlands present in the ACT (Tables 9, 11 and 13). In each scenario, cluster 2 contained the majority of peat bog and fen marshes across the ACT and the largest number of wetlands with a groundwater connection in their water balance equation. Cluster 2 of each scenario also showed a higher association with the groundwater recharge variables in the principle component analysis, as additional or unique variables to PC1/PC2 (Tables 8, 10 and 12). For cluster 3 of each scenario, the majority of included wetlands did not intersect any of the 4 groundwater spatial layers, and are therefore not considered to have a groundwater connection in their water balance equation.

However, while all clusters across each of the future climate scenarios show anthropogenic pressure and future hydrological and ecological change, the nature and severity of the pressure and change is different. This is expressed in the variability of principle component analysis results seen in each cluster (Tables 8, 10 and 12). For the consensus scenario, cluster 1 PC1/PC2 contained all variables except vascular plants and the 3 groundwater recharge variables. The PC1 contained the majority of precipitation, evapotranspiration and surface flow, annual and seasonal hydrological variables and ecological change in amphibians, while PC2 contained the anthropogenic pressure variables. Cluster 2 PC1/PC2 contains all variables except spring/autumn change in seasonality for surface flow and groundwater recharge. The ecological change in vascular plants, annual and summer/winter seasonality in groundwater recharge are strongly loaded on PC1, while the ecological change in amphibians is loaded to PC2, again with the anthropogenic pressure variables. Cluster 3 PC1/PC2 also contained all variables except the 3 groundwater recharge variables. Here, both ecological change in amphibians and the anthropogenic pressure variables are highly loaded to PC1, while the majority of the precipitation, evapotranspiration and surface flow annual and seasonal variables are loaded to PC2. The nuances between the principle component analysis results for each cluster within a future climate scenario can play a vital role in determining the factors for consideration during wetland management planning.

4.3 Implications for investment and management

The determined wetland vulnerability levels can be used to prioritise wetlands for investment and management, either through groups of wetlands within a given cluster or a specific wetland from the attributed Management Area values. The statistical analysis can assist in identifying those wetlands that are currently at risk from anthropogenic pressure, as well as those wetlands that will be the most, or the least, affected by future from ecological or hydrological change. The identification of current and future hazards to wetlands from the detailed wetland assessment can be related to the characteristic properties and processes of the wetland and its landform setting, allowing for the targeted investment and management towards improvement or mitigation. The common, additional or unique variables associated with the principle components can customise management to target what is driving hazards across the whole of the ACT (common PC1/PC2 variables) as well as within each individual cluster or wetland (additional and unique PC1/PC2 variables). Mapping of Management Areas will also allow precise identification of suitable locations to implement recommended Management Actions, at the wetland or within the subcatchment, thereby facilitating strategic management.

4.4 Refinement to use hydrological change indices

The use of indices in natural resource assessment and management is common (Parsons *et al*. 2002; Stein *et al*. 2002; Healey *et al*. 2012). The existing methods to determine wetland land use pressure and the projected similarity of future vascular plant and amphibian communities used in this research both produce indices (Williams *et al*. 2014; QLD Department of Science, Information Technology, Innovation and the Arts 2015). As the method for determining hydrological vulnerability was developed within this research, the detailed wetland assessment may benefit from further refinement. In particular, the number of hydrological variables outweighs the anthropogenic pressure and ecological change variables, possibly introducing bias in the statistical analysis outputs. The simplest solution would be to only use the 4 individual absolute change variables for annual precipitation, evapotranspiration, surface flow and groundwater recharge. However, any seasonal change data would be lost from the analysis and there would be no consideration of these implications to the hydrology, habitat and species within the wetlands. Given the time constraints for research, considerations have been made regarding targeted use of hydrological change indices, thus reducing the number of variables and refining the wetland assessment before further publication.

The hydrological change indices approach would need to consider three factors for wetlands: the unique water balance equation; the annual change in water sources and losses; and change in seasonality for water sources and losses. Wetlands have been assigned a unique water balance equation (Sections 2.1.3 and 3.1.3) and this wetland attribute could be used as categorical data for the statistical analysis. Instead of 4 individual absolute change variables for annual precipitation, evapotranspiration, surface flow and groundwater recharge, a single accumulated absolute change variable could be used with careful consideration of the unique water balance and how increases and decreases for the water sources and losses are treated (*sensu* Sections 2.2.3 and 2.4). The accumulated absolute change variable would remain a continuous numerical variable for the statistical analysis. To reduce the 8 individual absolute change variables for summer/winter and spring/autumn seasonality in precipitation, evapotranspiration, surface flow and groundwater recharge, a single variable could be developed to indicate if any seasonal change is occurring. If there is seasonal change occurring, the categorical variable would indicate if the change was for only the summer/winter ratio, the spring/autumn ratio or both ratios. This approach would produce 3 future hydrological change variables, instead of 12, to complement the 2 current anthropogenic pressure and 2 future ecological change variables for a more balanced statistical analysis. If using this approach, statistical clustering methods for mixed datasets would need to be considered (Morales *et al*. 1998; de Leon and Carriere 2005; McCane and Albert 2008; Hunt and Jorgrnsen 2011).

5 SUMMARY

Hydrological and ecological change is projected to occur across all climate futures considered in this research. However the nature and severity of change is different, with the nuances of a range of likely futures and possible desired outcomes needing to be considered for natural resource management planning. Integration with ecological change data and Management Areas further links the understanding of HGL Unit hydrological, physical and biological landscape characteristics with the inherent variability in wetland setting, processes and functions that determine wetland type and water sources. Spatial mapping of Management Areas will also allow precise identification and prioritisation of suitable locations to implement recommended Management Actions to improve or mitigate the identified hazards. On-ground actions may be required at the wetland or across the subcatchment, facilitating strategic management. If wetland mapping is not available for a study area, the detailed wetland assessment can be undertaken using the calculated mean Management Area values, although this would prevent the refinement of the water balance equation to suit the individual wetland.

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