Department of Sustainability and Environment

Wetland connectivity models

K. Morris, F. Ferwerda and P. Papas

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Kay Morris, Fiona Ferwerda and Phil Papas

Arthur Rylah Institute for Environmental Research
123 Brown Street, Heidelberg, Victoria 3084

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Arthur Rylah Institute for Environmental Research
Department of Sustainability and Environment
Heidelberg, Victoria

Report produced by: Arthur Rylah Institute for Environmental Research
Department of Sustainability and Environment
PO Box 137
Heidelberg, Victoria 3084
Phone (03) 9450 8600
Website: www.dse.vic.gov.au/ari

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Front cover photo: Wetland of the Moolort Plains, central Victoria (Kay Morris).

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- waterbirds — Richard Loyn (Department of Sustainability and Environment)
- amphibians — Dr Michael Scroggie, Nick Clemann and Katie Howard (Department of Sustainability and Environment)
- wind dispersed plant — Dr Elisa Raulings (Monash University), Dr Merel Soons (Utrecht University, Netherlands).

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Summary

Increasing recognition of the role dispersal plays in explaining community assembly has highlighted the need to consider connectivity in conservation planning. The objective of this project was to develop statewide maps of wetland connectivity to inform wetland risk assessment and prioritisation. To represent the diverse biota of wetland systems, the project aimed to develop models of wetland connectivity for waterbirds, amphibians, wind-dispersed plant propagules and water. Understanding patterns of connectivity for waterbirds also provides insight into the dispersal patterns of plant and invertebrate propagules which they carry. Water acts as both a conduit for the movement of actively dispersing taxa and a dispersal vector for taxa which disperse passively, such as plant and invertebrate propagules.

Assessments of wetland connectivity were informed by a review of the dispersal biology of aquatic taxa as well as consultation with experts. Modelling approaches within a GIS framework were used to develop wetland connectivity models as these approaches currently provide the best method for assessing connectivity at a statewide scale.

The project has produced preliminary models of wetland connectivity for amphibians and waterbirds. New wetland mapping is currently being undertaken and will result in an updated Victorian wetland inventory and spatial layer in 2012. It is recommended that our models of connectivity are re-run when the new wetland spatial layer is available. An evaluation of the amphibian model by experts has highlighted areas for model improvement and these should be incorporated when the models are re-run.

Due to the complexity of modelling hydrological connectivity and the limitations of current datasets, the project has focussed only on floodplain wetlands. Floodplain wetlands identified in this project were validated using known floodplains but this approach requires further validation and development to more thoroughly delineate active floodplains in Victoria. In addition several approaches were used to identify floodplain wetlands that are likely to have reduced connectivity with their source rivers.

Models of wetland connectivity for wind dispersed plant propagules required the development of novel, spatially explicit approaches. Unfortunately there were insufficient resources to fully develop these models. This report provides examples of connectivity maps produced from the modelling approach developed, along with discussion of their limitations.

Assessing connectivity at an ecosystem level remains one of the challenges of landscape ecology. This project has provided insight into the processes that connect wetland systems and has made a major advance towards the development of maps of wetland connectivity for a broad range of wetland taxa.

Connectivity models are based on our current understanding of the habitat requirements, dispersal distances and landscape permeability of representative taxa. In many cases these have been informed from expert opinion as data is lacking. As our understanding of these attributes improves through further research, and our spatial knowledge refined and mapped, it will be possible to develop more refined models. Testing model outputs against actual dispersal data or genetic studies will be required before the validity of connectivity models can be judged. Testing the sensitivity of the results to the assumptions in the model will identify management activities that are most influential. These are critical tasks for the future.

Once individual models of representative wetland biota are completed and validated it may be possible to combine them to provide a system-based map of wetland connectivity. An integrated map of wetland connectivity will provide a tool for guiding policy, strategic investment, planning and policy development. However, an understanding of the patterns of connectivity at a group or species level will still be required to inform targeted management interventions for specific taxa.

1 Introduction

Biological connectivity broadly refers to the ability of plants and animals to move among habitat patches in the landscape and is fundamental to all currently accepted paradigms of community assemblage (Leibold et al. 2004). Increasing recognition of the role dispersal plays in explaining community assembly has highlighted the need to consider connectivity in conservation planning. The broad objective of this project was to develop an understanding of connectivity for wetland ecosystems to inform wetland risk assessment and prioritisation. Specifically the project aimed to develop statewide maps of potential wetland connectivity and to assign connectivity scores to individual wetlands. These tools will assist the landscape-scale management of aquatic habitats in the following ways (Morris 2012):

- identify wetlands that are biologically linked and form functional mosaics;
- identify bottlenecks in the movement of wetland taxa among core habitats;
- identify wetlands that act as stepping stones and enable species to move to refuges during a disturbance and to re-colonise sites when conditions are again suitable;
- assess if a loss in connectivity could be contributing to poor wetland condition;
- identify sites for habitat restoration and/or creation that will have flow on benefits to other habitats by enhancing connectivity; and
- identify likely pathways for the spread of invasive species.

1.1 Overview of approach

Developing a realistic representation of landscape connectivity is a complex task and requires a sound understanding of the habitat requirements and dispersal characteristics of the organism(s) of interest, along with detailed spatial information of the landscape. The types of information needed to develop realistic models of connectivity include the following:

- identification and delineation of habitat patches in the landscape;
- the mode(s) of dispersal (e.g. wind, water, waterbirds, overland);
- an estimate of the distance an organism may move;
- features of the landscape that can impede or facilitate dispersal; and
- the direction(s) of dispersal and when dispersal is constrained in a particular direction(s).

The dispersal characteristics of wetland biota are varied and will result in diverse temporal and spatial patterns of connectivity in the landscape. To capture this diversity in modelling wetland connectivity a multispecies approach is needed. To inform this approach a literature review was undertaken to identify the modes, distances and barriers to movement for key groups for aquatic taxa including: waterbirds, amphibians, fish, plants and invertebrates. The findings from this review are provided in a separate report (see Morris 2012). In addition to the literature review the modelling approach was also guided by consultation with experts who provided advice on the dispersal parameters used in modelling, and commented on completed models.

In developing an approach for assessing wetland connectivity we distinguish wetland biota as either active or passive dispersers. Active dispersers are able to govern their own movement and have a behavioural response to the environment which can influence patterns of movement (e.g. predator avoidance, or avoidance of unfavourable habitats). Active dispersers move among habitat patches either in water (fish and aquatic invertebrates), air (waterbirds and winged invertebrates) or overland (amphibians, turtles, reptiles). Passive dispersers include plants and invertebrates that rely on wind, water and waterbirds to disperse their propagules. For passively dispersed organisms the availability and behaviour of dispersal vectors influence patterns of connectivity in the landscape.

To represent these diverse dispersal mechanisms the project aimed to model patterns of connectivity for waterbirds, amphibians, wind and water. Modelling of connectivity for waterbirds was undertaken to represent patterns of connectivity not only for waterbirds but the plant and invertebrate propagules they carry (Charalambidou and Santamaría 2002, Figuerola and Green 2002). Wind dispersal models focused on plant propagule movement. Models of hydrological connectivity represent potential patterns of connectivity for fish, aquatic invertebrates (adults and/or propagules) and plant propagules.

Although water is perhaps the most important dispersal pathway for aquatic biota, models that capture the complexity of hydrological connectivity proved to be beyond the scope of this project. Instead, the project aimed to identify floodplain wetlands that are likely to have a hydrological connection to rivers.

1.2 Modelling approaches

Assessments of landscape connectivity for amphibians, waterbirds and wind-mediated dispersal of plant propagules requires the application of landscape modelling approaches that can be applied at a statewide scale and are capable of producing a realist representation of connectivity. An appraisal of landscape connectivity models reported in the literature found that only a few are capable of incorporating rules around landscape permeability and the direction and scale of movement (see Morris 2012). Circuit theory (McRae and Beier 2007) is a landscape connectivity modelling approach that accommodates most of these requirements but is computationally demanding and this currently limits its application at a statewide scale. At present, other approaches within a GIS framework provide the best option for modelling connectivity of Victoria's wetlands as they can be carried out with more modest computing requirements and processing times.

Neighbourhood analysis and cost-distance analyses are two approaches available within a GIS framework that can be applied to assess connectivity (VEAC 2010). These approaches are able to incorporate rules around landscape permeability and the direction and scale of movement for the organism(s) of interest to produce a realist representation of connectivity. Both neighbourhood and cost-distance analysis represent the landscape as grids, and cells are assigned a permeability score based on the dispersal constraints for the organism of interest. Habitat cells are assigned the highest permeability. Neighbourhood analysis assigns each cell in the landscape a value that represents the mean permeability of all the cells within a specified circular neighbourhood. This gives the relative amount of habitat, and the degree of permeability in the neighbourhood of each cell anywhere in the landscape. The size of the circular neighbourhood used in the analysis is selected to reflect the distance that the organism of interest is capable of moving. To represent different scales of movement among species with otherwise similar dispersal constraints a series of neighbourhood analyses can be performed. For example, amphibians vary in their mobility but share similar constraints in terms of landscape permeability. A series of neighbourhood analyses can be carried out to represent the range of distances different species within a group of organisms may move and the results combined.

Cost-distance analysis assesses the permeability of cells surrounding habitat patches that lie within the dispersal range of the organism of interest. Permeability is scored based on the distance a cell is to habitat which is then adjusted based on the cost of moving through the intervening landscape. For example, for two cells that are equidistant from a habitat, the cost-distance for the cell where the intervening landscape offers high resistance to movement, such as urban development, will be markedly greater than for the cell where the intervening landscape offers little resistance to movement, such as a seasonally inundated floodplain.

Neighbourhood analysis and cost-distance analysis represent connectivity in slightly different ways. Cost-distance analysis only assesses the permeability of cells surrounding habitats that are within the dispersal range of the organism of interest. This approach provides a detailed representation of connectivity among habitats but provides no information on the permeability of the landscape beyond the specified dispersal distance. In contrast, neighbourhood analysis assesses the permeability of the landscape surrounding each cell in the landscape. This approach identifies permeable corridors that are not revealed using cost-distance analyses. Combining outputs from both analyses give a more comprehensive representation of connectivity than the outputs of the individual analyses.

2 Connectivity model: Amphibians

2.1 Background

Many amphibian species depend on permanent or ephemeral wetlands to complete their life cycle. Although reproductive strategies vary, with some species laying their eggs on land or in water-filled burrows, the majority (86%) of species that occur in Victoria are pond breeders, indicating a strong dependence on wetland habitats (Appendix 1). Amphibian connectivity models have been developed to represent patterns of landscape connectivity for pond breeding amphibians that are also generalist in their habitat use and are likely to occupy most wetland types. Amphibians that breed in ponds that are also habitat generalists represent approximately 65% of the 37 amphibian species that occur in Victoria (Appendix 1). Patterns of landscape connectivity for stream-dwelling species, species with specific habitat requirements or land-breeding species are not represented in the current models. At present, wetlands are not adequately described to allow habitat for specialist amphibians to be identified at a statewide scale, and species that are restricted to streams or are able to breed on land are not as strongly associated with wetland habitats.

Models developed for generalist amphibians may be broadly transferable to the Common Long-necked Turtle *Chelodina longicollis* which occupies both permanent and ephemeral wetlands, and is capable of moving up to 1.4 km overland to reach other wetlands (Roe and Georges 2007), similar to amphibian species with high mobility. The Broad-shelled Turtle *Chelodina expansa* and Murray River Turtle *Emydura macquarii* are more closely associated with both permanent waterways and wetland habitats, and models developed for amphibians, for which habitat has been limited to wetlands, will not represent patterns of connectivity for these species. Several other vertebrates including rodents (e.g. Water-rat), snakes (e.g. Tiger Snake) and lizards (e.g. Lace Monitor) also use wetland habitats but were not included in model development as they were not considered wetland dependent (except in arid regions).

2.2 Method

Patterns of landscape connectivity for amphibians were modelled using neighbourhood and cost-distance analysis within a GIS framework. This approach required the identification and delineation of suitable habitat and features of the landscapes that determine permeability for amphibian movement, as well as an estimate of dispersal distance(s).

Habitat

The Wetlands 1994 spatial layer (DSE 2007a) was used to delineate natural freshwater wetlands that are potentially suitable habitat for generalist amphibians. This required the exclusion of saline wetlands and impoundments from the layer. Saline wetlands represented in the Wetlands 1994 spatial layer are those in which salinities exceed 3,000 mgL^{-1} throughout the whole year (Corrick and Norman 1980, Corrick 1981, 1982). Saline wetlands were not considered habitat as the probability of amphibian occupancy is likely to be low. This is supported by surveys in north-western Victoria that found that there was a low likelihood of frogs occupying wetlands with salinities in excess of 2,400 mgL^{-1} (Smith et al. 2009). Similarly, tadpoles are not found in wetlands with salinities in excess of 3,600 mgL^{-1} (Smith et al. 2007). Impoundments were not treated as habitat, but informed the assessment of permeability, as the objective was to assess the connectivity of natural wetland habitats.

Amphibian habitat was constrained to a 25 m band (based on grid cell size) around the perimeter of wetlands, and the remaining internal area was treated as a highly permeable surface. This avoided over representing the availability of habitat for amphibians, particularly for large deep wetlands for which most of the wetland area is not used by Victorian frogs. However, it is likely that habitat availability will be underestimated in large shallow, well-vegetated wetlands for which much of the wetland area may provide suitable habitat.

Permeability

The ability of frogs to move through the landscape is strongly influenced by precipitation, temperature and breeding season (Pechmann and Semlitsch 1986, Richter et al. 2001, Rothermel and Semlitsch 2002, Parris 2006, Vasconcelos and Calhoun 2004, Wassens et al. 2008). The influence of most land cover types on amphibian movement is not well established and evidence for assigning permeability ratings to different land cover types is limited. At present we can only infer that urban development (housing, commercial, industrial) and multi-lane paved roads with high vehicular traffic represent significant impediments to movement, whereas wet areas of the landscape are highly permeable. Overseas studies demonstrate that migrating amphibians will use streams to disperse, with distances varying from 2.5 km to 10 km (Sinsch 2006). Although some features of the landscape will deter movement, amphibians that are motivated to reach breeding sites on a wet, warm night may move across areas that would normally be avoided (N. Clemann, Department of Sustainability and Environment, pers. comm.).

Several datasets were used to inform landscape permeability. Built-up areas were delineated from the landuse spatial layer (VICMAP Built-up Area) (DSE 2012a) and road and rail networks were identified using the VICMAP Transport spatial layers (DSE 2012a). Wet permeable surfaces included watercourses, waterbodies and flat areas subject to inundation based on the VICMAP Hydrology spatial layers (DSE 2012a). Watercourses identified in the VICMAP Hydrology spatial layers are classified based on stream hierarchy as low, medium and high order streams. Low order streams are those at the top of the catchment, and were not used to inform landscape permeability.

Distance

The distances that amphibians are capable of dispersing overland is highly variable, with some species being very sedentary and moving less than 0.5 km, whereas other species disperse several to many kilometres. The maximum dispersal distances reported for amphibians in Australia are for the Green and Golden Bell frog *Litoria aurea*. Mark-recapture studies of this species revealed dispersal distances of up to 3 km (Pyke and White 2001), although sightings up to *c.* 10 km from the nearest breeding pond have been made (White and Pyke 2008). Overseas studies report similar maximum dispersal distances that range from 3 to 15 km (Sinsch 1990).

To develop a clearer understanding of the distances Victorian amphibian’s are able to disperse, experts were asked to assign a likely dispersal range to each species. Dispersal ranges were classified as unknown, low (dispersal distance less than 0.5 km), medium (dispersal distance between 0.5 km and 1 km) and high (able to disperse at least 1 km). In this project we considered 3 km to represent the upper dispersal distance for amphibians. For two thirds of the species that occur in Victoria, the experts felt that there was insufficient knowledge of dispersal to assign a dispersal range. For the remaining 12 species, 25% were ranked as having a low dispersal capacity, 20% as moderate and 12% as high (Table 1).

Even for the few vagile species that are capable of moving more than 1 km, most movements will occur over shorter distances. As such, mapping connectivity based on different scales of dispersal can also be viewed as representing different probabilities of movement. For example, the three dispersal ranges (low, medium, high) can also be viewed as representing movements that occur with a high, moderate and low frequency, respectively. To accommodate the variation and uncertainty in dispersal distances, a series of neighbourhood analyses were performed for each of the three dispersal ranges and averaged.

Table 1. Mobility classes and neighbourhood radii used to model amphibian connectivity along with the proportion of species assigned to each mobility class.

Mobility class	Dispersal range (km)	Probability of movement	Radii used in neighbourhood analyses (km)	Number of species in each mobility class
Unknown				24
Low	<0.5	High	0.2, 0.3	6
Medium	> 0.5 and < 1	Medium	0.5 0.7, 1	4
High	> 1	Low	2, 3	2

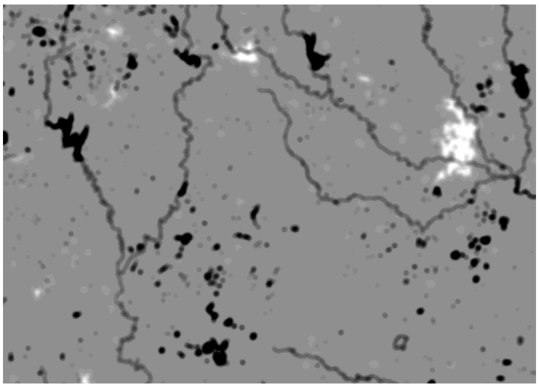
Neighbourhood analysis

Wetland habitat for amphibians was described spatially as the perimeter (the first 25 m inside the wetland boundary) of freshwater wetlands, excluding impoundments. A generic approach to landscape permeability for amphibians was applied resulting in five permeability classes ranging from zero (ocean) to four (habitat, i.e. freshwater wetlands) (Table 2). To improve the discrimination of the analysis, the permeability classes were reclassified using a scale of one to ten (Table 2). For the analyses, the permeability dataset including habitat was converted to raster data, i.e., cells or pixels (25 m x 25 m). For each cell, the mean value of all cells within a specified circular neighbourhood was calculated. This gives a relative amount of wetland habitat and the degree of permeability in the neighbourhood of each cell anywhere in the landscape. Seven neighbourhood scenarios were run, and results were grouped together to provide results for high, medium and low dispersal probabilities/distances (Figure 1A-C). The three probability surfaces were combined into a single surface based on neighbourhood permeability (Figure 1D).

Table 2. List of landscape elements used to inform landscape permeability along with their ranked permeability and the permeability and resistance scores assigned in the modelling to improve discrimination. The spatial data sets used to delineate each landscape element are also listed.

Landscape element	Permeability ranking	Modelled permeability score	Modelled resistance scores	Spatial data
Habitat - perimeter of wetlands (25m cells)	4 (High)	10	0	Wetlands 1994 (with impoundments and saline wetlands removed)
Internal area of habitat wetlands	3	7	2	Wetlands 1994 (with impoundments and saline wetlands removed)
Wet areas	3	7	2	VICMAP Hydrology spatial layers
Stream network	3	7	2	VICMAP Hydrology spatial layers
Terrestrial	2	2	7	
Saline wetlands	1	1	10	Wetlands 1994: wetlands attributed as permanent and semipermanent saline
Urban Areas	1	1	10	VICMAP Built-up Area
Roads and rail	1	1	10	VICMAP Transport spatial layers
Ocean	0 (Low)	No Data	No Data	

A.



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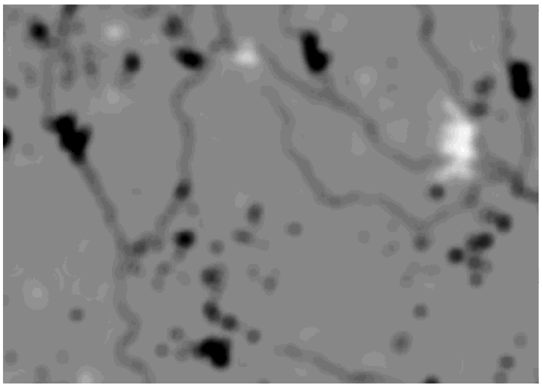

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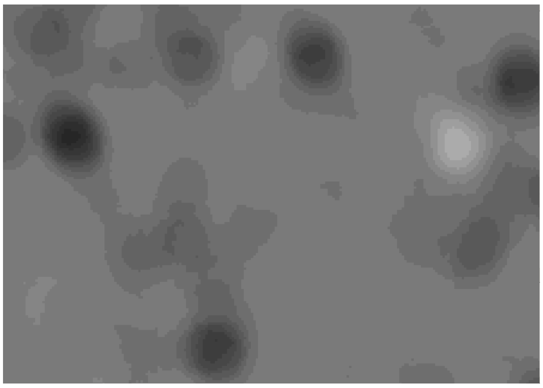

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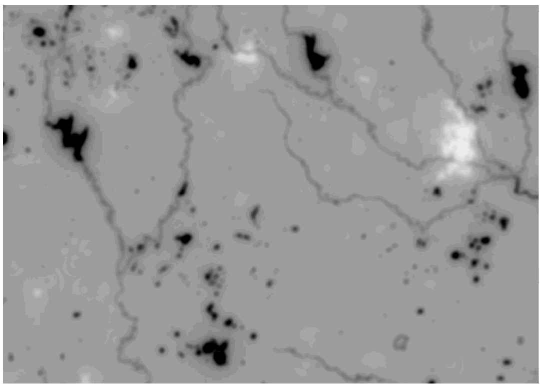

Figure 1. Neighbourhood analysis results are shown for an area (60 km x 40 km) north-west of Melbourne, (the white area on the right is the township of Bacchus Marsh),: (A) high probability of movement (less than 0.5 km), (B) medium probability of movements (> 0.5 km but < 1km), (C) low probability of movement (> 1 km) and (D) values for low, medium and high averaged. For all scenarios, the darker the colour, the more permeable the landscape, and therefore the higher the connectivity.

Cost-distance

A single cost-distance analysis was performed. This analysis assessed the distance of a particular cell in the landscape to “habitat”, assigned it a score and then adjusted the score using the cost of moving through the intervening landscape (i.e., landscape resistance). The landscape resistance was classified as the inverse of the landscape permeability (see Table 2). The results of this analysis are limited to 5 km from any area of habitat. This distance was chosen so that all areas within a 3 km Euclidean distance would receive scores whether they were highly resistant to movement or not. The cell values were partitioned into 100 classes using a geometric interval classification (see Appendix 2).

Combined connectivity score

A single connectivity score (C_s) was calculated by combining the results of the neighbourhood analysis (NA) and cost-distance analyses (CD) using the formula below. The different weighting in the formula were applied to optimise model discrimination.

$$C_s = [3 \times (\mathrm{NA}) + (\mathrm{CD})] / 4$$

Assignment of a connectivity score to wetlands

A single connectivity score was assigned to each wetland in the Wetland 1994 spatial layer based on the mean connectivity value of all cells in each wetland polygon.

Caveats

A number of caveats are associated with this modelling approach, and need to be considered in interpreting the outputs of the modelling:

- Patterns of amphibian connectivity only apply to pond-breeding generalist species that are able to occupy most wetland types. Connectivity estimates are not applicable to species that occupy streams, have specialised habitat requirements or are not dependant on wetlands for breeding,
- Incomplete wetland mapping at a statewide level will produce inaccuracies in the model output. Key deficiencies in the current wetland mapping include the absence of alpine wetlands, some wetlands smaller than 1 ha, and open irrigation channels that may provide important habitat. Some of these deficiencies will be rectified when the updated wetland inventory is available in late 2012. We recommend that the models are re-run when this revised wetland inventory is available.
- Patterns of connectivity have been modelled under a wet scenario, i.e., we assumed that all wetlands and wet areas in the landscape will provide habitat and will be permeable.
- The classification of wetland salinity was undertaken in the early 1980s (Corrick and Norman 1980, Corrick 1981, 1982). The salinity of some wetlands may have changed (increased or decreased) since this time, leading to an incorrect assessment of connectivity.
- Ephemeral waterbodies may be sufficient for some species to breed and some frog species show active preferences for either permanent or ephemeral wetlands. As such, distinguishing between wet areas of the landscape that facilitate movement and those that represent habitat is problematic. Incorrect assignment of permeable areas versus habitat will influence the accuracy of model outputs.
- Wet areas of the landscape are likely to be poorly represented by the Vic-Hydro spatial layers, as the spatial resolution is coarse. In addition, the Vic-Hydro spatial layer is based on topographical maps and changed land use that alters natural drainage patterns, and therefore areas of the landscape subject to inundation are not represented.

2.3 Results and discussion

Examples of the wetland connectivity surfaces produced using neighbourhood, cost-distance and the combined neighbourhood-cost-distance analysis are shown in Figure 2. The combined neighbourhood-cost-distance analysis was applied to produce the wetland connectivity surface for amphibians and individual wetland amphibian connectivity ratings for all of Victoria are shown in Figure 3. The connectivity surface is represented by shading that ranges from black (large amount of habitat in close proximity) to white (small patches of habitat far away from each other). Similarly connectivity scores for individual wetlands are divided into five classes, each represented by different colours.

A comparison of the connectivity surfaces produced by the neighbourhood and cost-distance methods shows that these analyses bring different perspectives to an assessment of wetland connectivity. Neighbourhood analysis identifies permeable areas of the landscape that lie beyond the assigned dispersal distance that are not shown in the cost-distance analysis.

These permeable areas of the landscape represent potential dispersal corridors, provided dispersal is not constrained by distance. The upper conservative dispersal distance of 3 km is shown as a black line around the perimeter of wetlands in Figure 2. This highlights that the limited mobility of this group may prevent movement between patches of habitat despite the availability of permeable corridors. Greater dispersal distances may be achieved when dispersal occurs in a “stepping stone” fashion over generations (e.g. when each successive generation disperses). At present the significance of these corridors for amphibian movement is uncertain and will depend on the mobility of the species, the motivation to disperse (e.g. breeding, avoiding unsuitable habitat) and how closely these areas approximate suitable habitat. For some species, habitat may only need to be inundated briefly to become suitable; in these cases the distinction between habitat and highly permeable areas of the landscape can be unclear. Considering this ambiguity, along with the lack of fine-scale mapping, highly permeable areas of the landscape should be considered potentially important for maintaining amphibian populations. Corridors with high permeability could be targeted for habitat creation and/or enhancement to improve dispersal between habitats.

A comparison of the connectivity surface produced using cost-distance analysis and neighbourhood analysis can help to identify different constraints on connectivity. For example, the surface produced by the neighbourhood analysis identifies a number of small wetlands in the south east corner of Figure 2A in which the land surrounding each wetland has lower connectivity compared with cost-distance analysis (2B). Cost-distance analysis assigns connectivity scores only to cells surrounding wetlands based on distance from wetland habitat, modified by permeability. In this example, the wetlands are very close to each other producing high connectivity scores despite the low permeability of the land (Figure 2B). In contrast, neighbourhood analysis represents connectivity from a broader perspective, as it is based on the mean permeability of all cells within a series of circular neighbourhoods. In this example, the amount of wetland habitat in the area is relative small and fragmented and the permeability of landscape is low, producing low connectivity (Figure 2A).

This information can aid in the management of amphibians in Victoria by showing where movement among habitats is likely to be constrained by the distance wetlands are apart, the permeability of the landscape or the amount of habitat. Where movement among habitats is constrained by distance, the connectivity surface can be used to identify sites that lie within permeable corridors, where habitat can be created or enhanced to improve connectivity. Identifying permeable corridors in the landscape will enable land managers to better protect them from land uses (e.g. roads, urban development) that could reduce their permeability for amphibian movement and lead to lower connectivity. It is also possible to re-run models under different management scenarios such as wetland loss or creation to assess how these actions will alter connectivity.

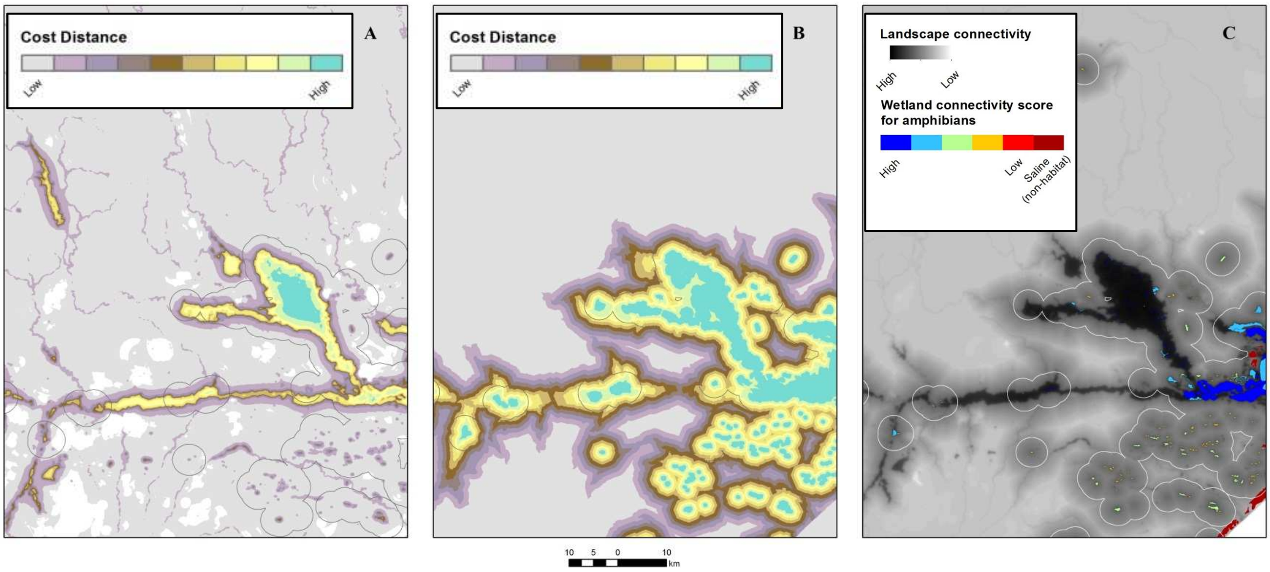

Figure 2. Examples of connectivity surfaces are shown for an area to the west of Lake Wellington in Gippsland, Victoria (including the Thomson and LaTrobe River floodplains). The connectivity surfaces shown were produced by (A) neighbourhood analysis, (B) cost-distance analysis and (C) combined neighbourhood and cost-distance analysis. Permeability is represented in (A) and (B) by colours from grey (low permeability) to green (high permeability) and in (C) by shading from black (high permeability) to light grey (low permeability). The upper conservative dispersal distance of 3 km is shown as a black or white line around the perimeter of wetlands. Amphibian connectivity scores for individual wetlands in (C) are indicated by colours. Saline (non-habitat) wetlands are shown in maroon.

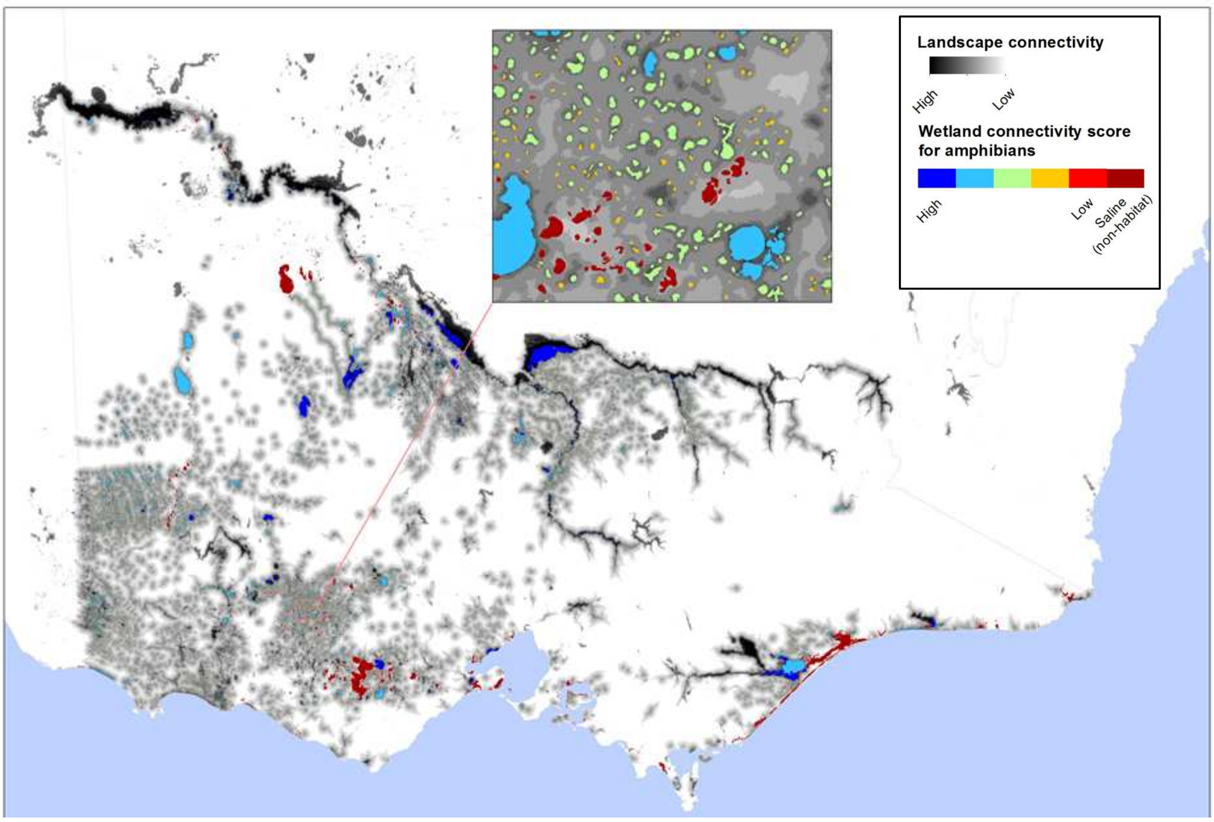

Figure 3. Wetland connectivity surface for amphibians and amphibian connectivity ratings for individual wetlands in Victoria*. The connectivity surface is represented by shading from black (high connectivity) to white (low connectivity) as indicated in the legend. Amphibian connectivity ratings for individual wetlands are represented by different colours ranging from blue (high connectivity) to red (low connectivity) as indicated in the legend. Saline (non-habitat wetlands) are coloured maroon. Saline wetlands are attributed based on the Wetland 1994 inventory and in some wetlands salinities may have change since the development of this inventory

*Only represents amphibian species that are pond breeders and generalists in their habitat use.

Recommendations

Limitations of the model and areas for future improvement associated with the rules used to derive the model were discussed with amphibian experts (Dr M. Scroggie and N. Clemann, Department of Sustainability and Environment). The recommendations are outlined below.

- The models should be re-run when wetland mapping has been completed as many wetlands that would be classed as amphibian habitats are not represented by the Wetland 1994 spatial inventory.
- The Vic-Hydro spatial layer is unlikely to provide sufficient spatial resolution to adequately detect all of the wet areas in the landscape that improve permeability for amphibians or that persist long enough to allow some species to breed. Roadside ditches, irrigation drains and channels represent permeable areas for movement, and in many cases habitat. These, however are not adequately captured by the spatial data currently available. It is recommended that a landscape wetness spatial layer be developed to improve the detection of wet permeable areas and ephemeral waterbodies in the landscape. Species' distributions could then be overlain to identify a relationship between wetness and amphibian habitat. Species occurrence records should be treated cautiously due to biases such as sampling effort. It is likely that the current model under represents wet areas in the landscape particularly in low relief areas of Victoria with high rainfall. If so, the model will also under represent levels of connectivity.
- Although the focus has been to assess connectivity for natural wetlands listed on the Victorian Wetland 1994 spatial inventory, the treatment of wet areas as habitat or as permeable areas of the landscape will alter the connectivity surface and wetland connectivity scores. The sensitivity of model results to attributing ephemeral waterbodies as either habitat or permeable areas should be assessed in the future work.
- Low order streams should be included when the models are re-run as they represent a permeable corridor for movement, can occur proximal to wetlands, and in some cases provide suitable habitat.
- In some instances impoundments should be treated as habitat in the model rather than as a permeable surface. The suitability of impoundments for amphibian habitat is highly variable, Impoundments that have steep sides, concrete embankments or predatory fish will have low habitat suitability and permeability values. The current assignment of impoundments as a permeable surface rather than habitat is likely to underestimate connectivity, while treating impoundments as habitat may overestimate permeability. Future revision of the model should attempt to classify impoundments as either habitat or permeable areas based on their individual attributes, although this is likely to be difficult.
- Farm dams should be incorporated into future models as these are abundant in the landscape, represent permeable areas for amphibian movement and in many case serve as suitable amphibian habitat. During the development of this work a statewide inventory of farm dams was not available but will be in the future.
- To distinguish areas in the landscape where connectivity has been lost from those where low connectivity is naturally occurring, it would be valuable to compare patterns of connectivity produced using the Wetland 1788 spatial layer (DSE 2007b) (which estimates the extent of wetlands at the time of European settlement) to that produced using the Wetland 1994 spatial layer. This could not be performed in the current study as both spatial layers are undergoing revision.

3 Connectivity model: Waterbirds

3.1 Background

Waterbirds are a diverse group of bird species that utilise wetland habitats. They include waterfowl (e.g. ducks, swans and geese), herons, ibises, spoonbills, rails and coots. They also include birds associated with estuarine and marine habitats that also frequent inland wetlands, including species such as Australian Pelican, Darter, cormorants and shorebirds (also known as waders). The significance of connectivity for waterbird populations is likely to be expressed during breeding and moulting when dispersal, which usually occurs over large distances, is restricted (Morris 2012).

During breeding, the need to forage and protect flightless juveniles imposes reliance on nearby wetlands for foraging and the distances between nests and foraging grounds can influence breeding success (Bryan and Coulter 1987). For example, in several ciconiiform wading birds (e.g. egrets and herons), breeding success declined as distance between nests and foraging grounds increased (Smith 1995). Breeding can also limit movement patterns if juveniles have more specific habitat requirements than adults. For example, nasal glands that secrete salts and help maintain salt regulation are not fully developed in juvenile ducks (Riggert 1977), so access to freshwater is required and this can restrict habitat utilisation (Halse 1987).

These examples illustrate that it is during these critical life stages that the connectivity of wetlands exerts the greatest influence on waterbird populations and therefore should be used to inform wetland management. Patterns of connectivity for waterbirds also provide insights into patterns of connectivity for aquatic plants and invertebrate propagules carried by waterbirds (Raulings et al. 2011, van Leeuwen et al. 2012).

3.2 Method

Patterns of landscape connectivity for waterbirds were modelled using neighbourhood analysis within a GIS framework. This approach required the identification and delineation of suitable wetland habitat and a conservative estimate of dispersal distances. As waterbird movement was not considered to be constrained by the nature of intervening landscape, modelling did not include an assessment of landscape permeability.

Habitat

Waterbirds are characterised by their frequent utilisation of multiple habitats including wetlands, rivers, estuaries and mudflats over varying spatial scales to moult, roost, breed and forage (Haig et al. 1998, Kingsford and Norman 2002). Given the broad habitats potentially occupied by waterbirds, all natural wetlands were considered as potential habitat and were delineated spatially using the Wetland 1994 spatial layer, excluding impoundments. Impoundments were excluded as this project aimed to assess the connectivity of natural wetland habitats.

Due to the large distances waterbirds are capable of moving, the availability of wetland habitats in bordering states will exert some influence on patterns of connectivity. To improve model accuracy, wetland spatial data was obtained for New South Wales (NSW Department of Environment Climate Change and Water) and South Australia (Department of Environment and Natural Resources SA). Data from NSW was modified by excluding reservoirs to make the dataset more comparable with the Wetland 1994 dataset. The SA data was not modified as it was unlikely to include dams (Department of Environment and Natural Resources SA). However, among these three datasets the criteria distinguishing wetlands from wet areas of the landscape are not described and it is likely that there are inconsistencies in the definition and attribution of wetlands.

Distances

Waterbirds vary considerably in their habitat requirements and the scale, pattern and frequency of movement among habitat patches (Appendix 3). Waterbirds that are endemic to Australia are typically nomadic (Roshier et al. 2001, Chambers and Loyn 2005). A few species may be classed as somewhat sedentary (e.g. Australian Wood Duck, Chestnut Teal, Australian Shelduck and Purple Swamphen) (Pringle 1985, Ramsey et al. 2010), but even they will sometimes move long distances in response to changes in habitat availability.

Differences in mobility among species are reflected in the results of bird banding studies by Norman (1971) and Frith (1959), summarised in Table 3. These studies recovered 30% of banded Grey Teal at sites more than 300 km from the banding location (Frith 1959). In contrast, only 10% of banded Wood Duck and Black Duck were recovered farther than 300 km from the banding sites. The data also demonstrate that the probability of dispersal declines with increasing distance (Table 3).

Patterns of waterbird movement also represent the dispersal of plants and invertebrate propagules. The distance propagules will be carried by waterbirds will vary depending on wether they are carried internally or externally. The distances propagules are dispersed when they are carried internally will vary depending on gut retention time, flight speeds and dispersal distances of waterbirds. Based on these factors the dispersal of propagules via internal transport is likely to influence plant community structure over distances of 10s-100s of km (Raulings et al. 2011). To reflect different scales and/or probabilities of movement as well as the dispersal of plants and invertebrate propagules, waterbird connectivity was modelled using a range of potential distances.

Table 3. Results of bird banding studies of Norman (1971) and Frith (1959) showing the percentage of banded birds recovered at various distances from the banding location.

Distance (km)	Wood Duck*	Black Duck	Mountain Duck	Grey Teal
0	56%	1.3%	0.6%	1.5%
1-100	19%	67%	57%	38%
101-300	17%	20%	21%	26%
300-500	6%	7%;	17%	24%
>500	2%	4%	3%	10%

*Note that distance ranges for Wood Duck have been approximated from Frith (1959)

Neighbourhood Analysis

For the neighbourhood analysis wetland waterbird habitat was described as habitat (assigned a value of one) or not habitat (assigned a value of zero) according to the wetland spatial datasets. The habitat dataset was converted to raster data (i.e. cells or pixels, 25 m x 25 m). For each cell, the mean value of all cells within a specified circular neighbourhood was calculated. This gives a relative amount of wetland habitat in the neighbourhood of each cell or point in the landscape. Five neighbourhood scenarios were run: 5 km, 10 km, 50 km, 100 km and 300 km. For each cell, the mean values derived for each of the five neighbourhoods were multiplied by one hundred and then averaged. This was done for every cell across the whole landscape to produced the representing the connectivity surface (Figure 4).

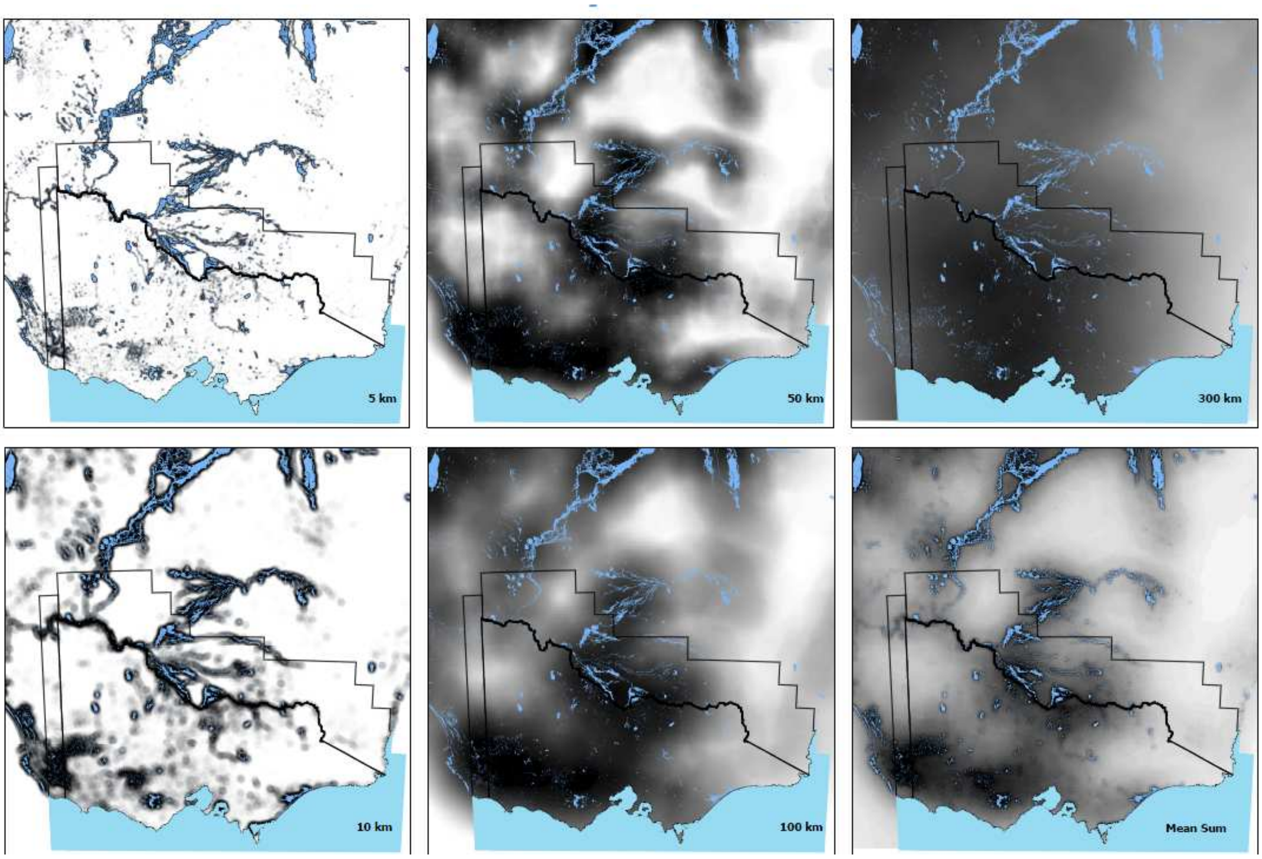

Figure 4. Models of wetland connectivity for waterbirds in south eastern Australia based on each of the five neighbourhood analyses (5 km, 10 km, 50 km, 100 km and 300 km) and their mean sum. The connectivity surface is represented by shading from black (high connectivity) through to white (low connectivity).

Assignment of a connectivity score to wetlands

A single connectivity score was calculated for each Victorian wetland polygon representing habitat for waterbirds based on the mean connectivity surface score of all cells in each wetland polygon.

3.3 Results and discussion

The waterbird connectivity surface and connectivity scores for individual wetlands across Victoria are shown in Figure 5. The connectivity surface is represented by shading which ranges from black (large amount of habitat in close proximity), through to white (small amounts of habitat far away from each other). Connectivity scores for individual wetlands are divided into five classes, each represented by different colours. Wetland with the highest connectivity scores are dark blue and those with the lowest scores are yellow. The highest waterbird connectivity score in the study area was 63. A score of 100 is only achievable where 100% cover of suitable wetland habitat occurs within a neighbourhood. This only occurred within the 5 and 10 km neighbourhoods.

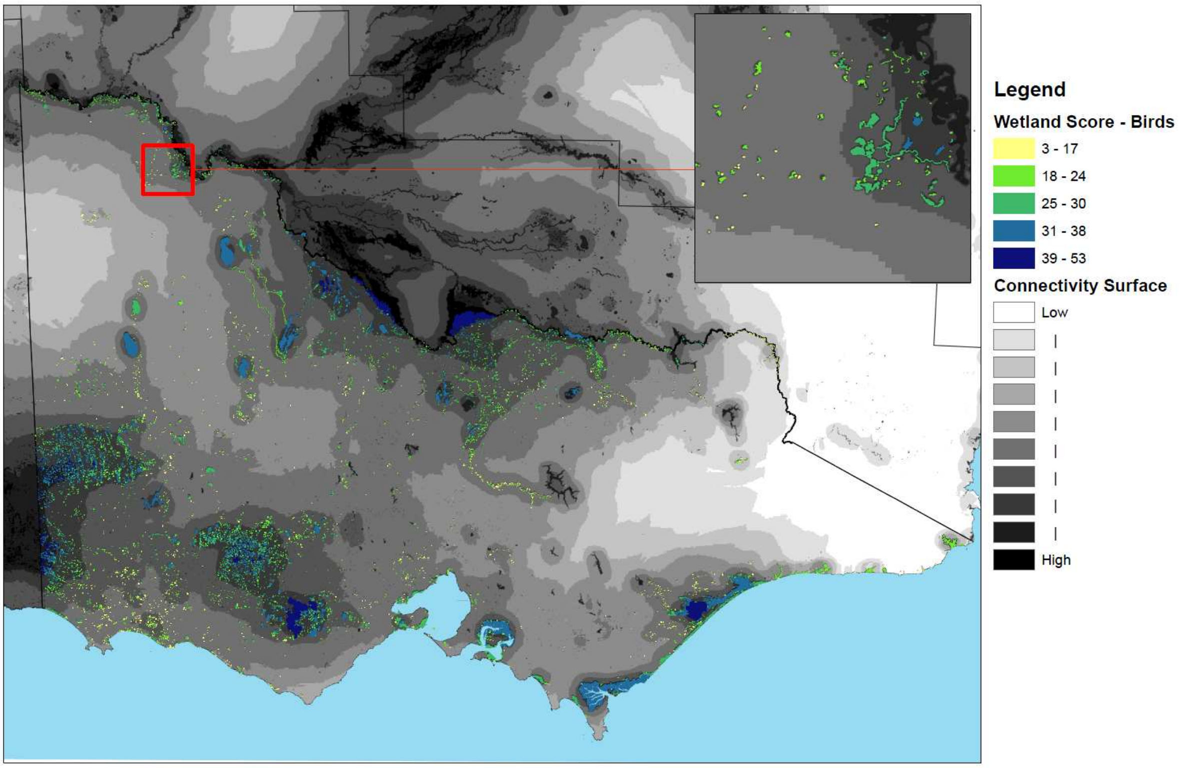

Figure 5. Connectivity scores assigned to wetlands in Victoria. The connectivity surface is represented by shading from black (high connectivity) through to white (low connectivity). The connectivity scores for individual wetlands are divided into five classes, each represented by different colours ranging from blue (high connectivity) to yellow (low connectivity) as indicated in the legend.

Regions of very high connectivity (i.e. black shading) represent areas of the landscape that are connected for waterbirds with low mobility but can also be viewed as areas for which waterbird movement occurs at a high frequency as, even for very mobile birds, more frequent movements occur over smaller distances. Similarly, areas of low connectivity (i.e. light grey shading) represents the connectivity surface for waterbirds with the highest level of mobility but also can be viewed as representing areas of the landscape for which waterbird movement occurs with low frequency.

Evaluation of model and recommendations

To identify limitations of the model and areas for future improvement input was sought from waterbird expert R. Loyn (Department of Sustainability and Environment). Issues raised are outlined below.

- The connectivity surface appears to under-represent wetland connectivity for some coastal wetlands. This is likely to be because habitat availability is reduced by their proximity to the ocean. This may be appropriate for some species but not others.
- Larger wetlands generally have higher connectivity scores than smaller wetlands as the amount of habitat influences wetland connectivity scores in the model. Using wetland size to inform connectivity for waterbirds was considered appropriate as much of the wetland area is probably utilised by many waterbird species. This differs to the case for amphibians, where only the perimeter was considered as habitat.
- Current wetland mapping is incomplete and is likely to result in inaccuracies in model outputs. It is recommended that the models are re-run when an updated inventory is available.

- The significance of wetland connectivity for waterbird persistence could be evaluated further by mapping the distribution of colonial waterbird breeding sites and assessing if these sites are highly connected to other wetlands. This would be useful because waterbird breeding colonies necessarily attract waterbirds from widely distributed parts of their range, making connectivity a potentially important issue.

4 Connectivity model: Wind

4.1 Background

Wind is an important dispersal pathway for wetland plants. Wind and or convective currents also facilitate the active dispersal of a number of winged invertebrates as well as the passive dispersal of invertebrate propagules (see Morris 2012). Although wind plays a role in the dispersal of invertebrates, modelling approaches in this study are limited to the dispersal of plants.

Wind has the potential to transport seeds to hydrologically isolated sites, and to upstream wetlands over long distances (Soons 2006). A high proportion of wetland plant species have adaptations for wind dispersal, particularly species that occur in rainwater- or groundwater-fed wetlands that lack connections to other aquatic habitats via surface water flows (Soons 2006). Adaptations for wind dispersal were found in 37–46% of plant species occurring in rainwater or groundwater fed wetlands in the Netherlands (Soons 2006). Similar analyses of wetland plant communities in Australia were not found in the published literature, but there is no reason why similar patterns would not be expected.

An understanding of how wetlands are connected through the dispersal of plant seeds can help assess if species that become locally extinct are able to re-colonise through the dispersal of propagules from adjacent sites. Models of wind dispersal can also help to identify potential source populations of invasive plant species in order to assess the risk of incursions.

Plants can be grouped into three broad wind-dispersal categories based on seed terminal velocities, i.e. the falling speed (ms^{-1}) in still air once a constant speed is reached (Soons 2006). The first group are seeds that fall very slowly, with terminal velocities below 0.3 ms^{-1}. This group has the greatest potential for long-distance dispersal in wind because their seeds can be lifted by convective currents or wind turbulence, extending their dispersal range to many kilometres (Tackenberg 2003, Soons 2006). The widely distributed tall emergent wetland plants, *Typha* spp. and *Phragmites* spp., which occur in Victoria, have seeds with terminal velocities in this range (Soons 2006, van Diggelen 2006). The second dispersal category contains plants with terminal velocities of 0.3–2 ms^{-1}. These seeds are too heavy to be lifted by convective currents but may be carried long distances by turbulent winds during storms. The dispersal distance varies from tens of metres to several kilometres, depending on the terminal velocity, seed release height and wind speed. In the third dispersal category are plants having heavy seeds with terminal velocities above 2 ms^{-1}. These plants are not adapted for wind dispersal, and seed is commonly deposited close the parent plant.

4.2 Method

To inform the development of wetland connectivity models of wind dispersed plants requires an understanding of the relationships between wind speed and dispersal distance as well as the frequency, speed and direction of wind across the landscape. Seed dispersal models that produce realistic estimates of dispersal distances are available, but are location specific, computationally complex and beyond the scope of this project. However, relationships between wind strength and dispersal distances using these models have been described for several species with terminal velocities near 0.3 ms^{-1} and these provided a reference for model development (Table 4, Soons 2003, Dr M. Soons, University of Utrecht, pers. comm.). Dispersal models based on these relationships provide only a conservative estimate of the dispersal distances of seeds with terminal velocities < 0.3 ms^{-1} which are likely to disperse considerably further.

Table 4. Relationship between seed dispersal and wind strength for some seeds with terminal velocities around 0.3 ms^{-1}.

Wind speed (ms^{-1})	Wind speed (kmh^{-1})	Distance (km)
10-15	36 -54	Up to 1
15-20	54 -72	Up to 2
20-25	72-90	Up to 4
25-30	90-108	Up to 6

Habitat

Due to the diversity of plant species associated with wetlands and the lack of detailed information on wetland environment attributes at a statewide scale, all wetlands were considered as potential habitat for wind dispersed plants.

Wind data

To develop statewide patterns of wetland connectivity for wind dispersed seed, wind data from the Australian Bureau of Meteorology was obtained for 119 monitoring stations with at least 15 years of data. For each wind station the frequency over each season that wind speeds occurred in each of four categories (10-15, 15-20, 20-25 ms^{-1}), for each of four wind directions (N, S, W, E) was assessed. Wind speed categories of 10-15, 15-20, 20-25 and 25-30 ms^{-1} may disperse seeds up to 1, 2, 4, and 6 km, respectively. The wind direction was split up into four categories (N, S, W or E) which included ± 45° from each cardinal direction (e.g. the north category included wind from the NE, NNE, N, NNW, NW). To improve model discrimination the frequency of time winds occurs in each wind speed category and direction were placed into four groups as described in Table 5.

Table 5. Description of the four wind frequency categories used to assess wind patterns.

Frequency Category	Proportion of observations over a season	Days per season
Very low	0.1 - 0.5%	< 0.5 days over the season
Low	0.6 - 1%	0.5 to 1 days over the season
Medium	> 1 - 5%	1 to 5 days over the season
High	> 5%	> 5 days over the season

Visual display of wind data

To visually display wind speeds and frequencies associated with seed dispersal each wetland was assigned wind data from one of the 119 wind stations using Thiessen polygons. Thiessen polygons, identify regions based on their proximity to a set of unevenly positioned points, in this case weather stations in the landscape (Brassel and Reif 1979). To avoid wetlands crossing the boundary of more than one area of influence the centroid (rather than a polygon) was used to spatially represent wetlands in the model. A customised tool was developed to apply the distance and direction values for each of the four wind frequencies for each season. This tool allows the area of potential seed dispersal (from the wetland edge) to be mapped, based on information provided on wind speed and direction for each frequency group. For example, for a season, the tool identifies for each wetland, the wind strength and direction category at each of the four frequencies and applies the area of potential seed dispersal based on direction (N, E, S, W) and distance (where distance is distance from wetland edge). A value of one is applied to any area in the landscape that may potentially receive wind dispersed seeds from a wetland (seed source), based on the direction and strength of winds. The tool produces four rasters – one for each wind frequency and this is then overlaid visually to give a picture of the seasonal pattern of wind influence that includes all wind frequencies. Wind frequencies can be interpreted as representing the likelihood of seed dispersal, assuming that winds that occur with greater frequency disperse more seed. This analysis is of most value as a visual tool to assess wind dispersal of seed from one wetland to another.

4.3 Results and discussion

As an example of the visual display of wind patterns produced by the analyses, the pattern of wind influence on wetlands in shown for the south-west region of Victoria in spring (Figure 6). In this region, the pattern of wind influence reveals that the highest level of connectivity among wetlands is produced by winds that occur with very low frequency. These winds tend to be of high velocity and are likely to carry seeds the farthest. In contrast, the most frequent winds produce a very limited connectivity because winds tend to be of low velocity and carry seeds only a short distance. The pattern of wind influence on wetlands also reveals that the direction of wind varies with wind frequency and location (i.e. in some locations, medium frequency winds do not blow to the east whereas high frequency winds blow in all directions) resulting in a complex pattern of seed dispersal. The hard boundary of the area of influence may be a poor representation of actual conditions, which we would expect to diminish gradually.

Recommendations

A methodology to represent potential spatial patterns of seed dispersal from wetlands by wind has been developed using data on wind strength, direction and frequency. It is recommended that patterns of wind dispersal across the state be produced for each season. A statewide map representing wind dispersal potential across the state in spring was developed but time constraints prevented maps for other seasons being produced. It is necessary to produce maps of potential wind dispersed seed for each season because seeds are released in different seasons, and the direction, strength and frequency of winds also change seasonally.

The approach developed to assess patterns of wind dispersed seed produced is of most value as a visual tool to assess wind likely dispersal from one wetland to another. However, further work is needed to assess the level of connectivity for individual wetlands.

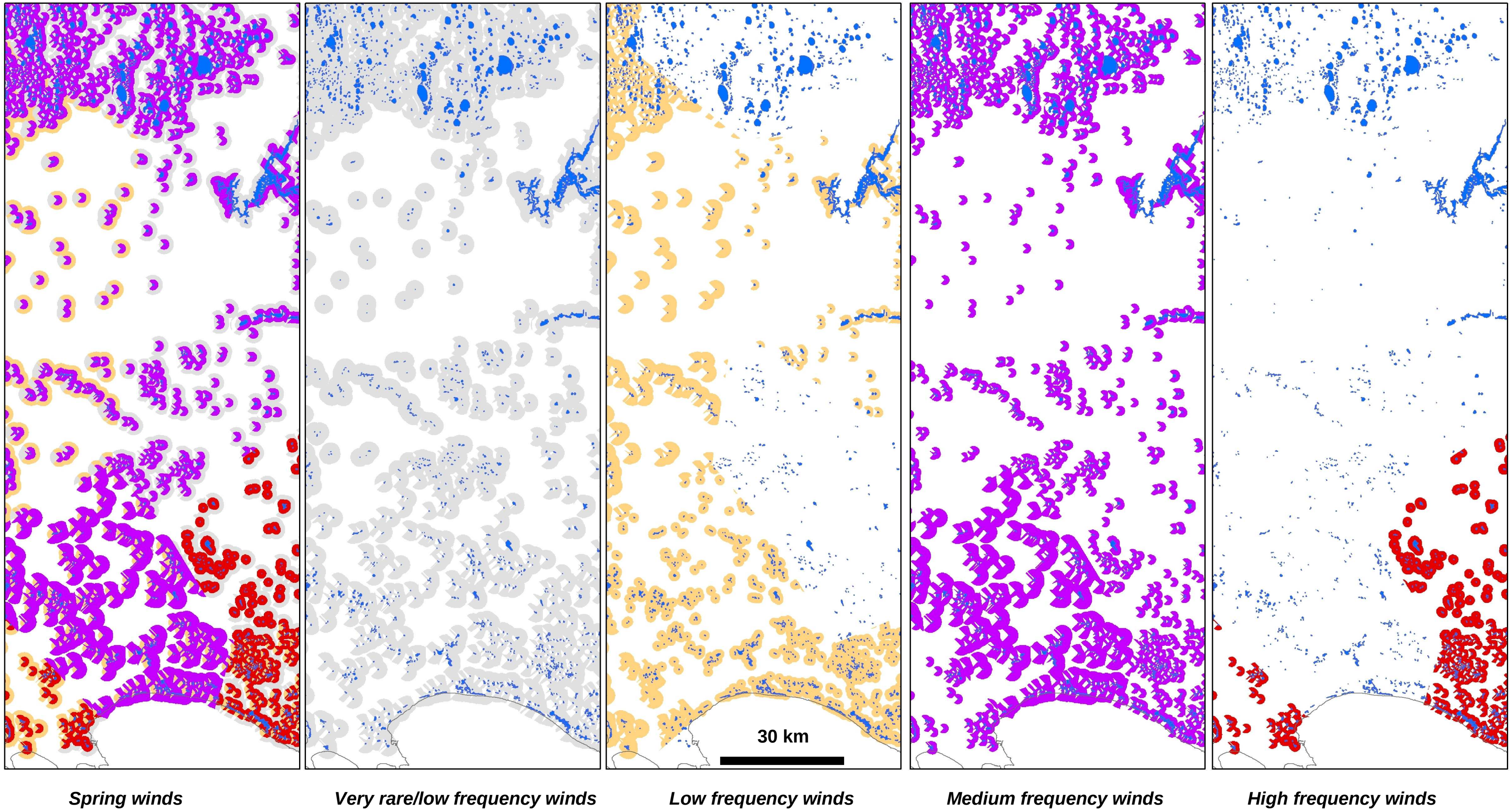

Figure 6. Patterns of potential wind dispersal across wetlands (blue) in south west Victoria showing the distance and direction that winds occurring at very low (grey), low (yellow), medium (purple) and high (red) frequency are likely to transport seed in spring. Spring winds (first panel) show the pattern of wind influence on wetlands for all wind frequencies. The extent and shape of the coloured regions around the perimeter of wetlands represent the distance and direction of wind influence, respectively.

5 Connectivity model: Water

5.1 Background

Water provides both a conduit for movement of actively dispersing taxa (such as fish) and a dispersal vector for passively dispersed plant and invertebrate propagules. Hydrological connections may occur in several ways: (1) between rivers and floodplain wetlands with overbank flows; (2) among non-floodplain wetlands via surface flows from one wetland to another when they overflow, or via natural or artificial channels; (3) across catchments during large floods; (4) between lakes and fringing wetlands; and (5) between wetlands and fringing embayments.

Hydrological connectivity among wetlands can be impaired by a variety of mechanisms. For example, river regulation alters the timing, frequency and magnitude of floodplain inundation. Levees, weirs and regulators can restrict flows to wetlands and create barriers to dispersal for some species.

Hydrological connectivity is perhaps the most important dispersal pathway for wetland biota. Developing an accurate assessment of hydrological connectivity at a statewide level is currently limited by the poor resolution and coverage of flood inundation mapping across the state, and by the lack of information on the nature, location and operation of water control structures (e.g. levels, weirs, channels). Given these constraints, this project has primarily focused on identifying the location of floodplain wetlands and where there is altered connectivity with their source rivers.

The storage and extraction for water for human use has altered the nature of connectivity between rivers and floodplain wetlands. Floodplain connectivity can be altered by changes in lateral connectivity and/or longitudinal connectivity. Longitudinal connectivity refers the ability of organisms to move up and down river channels. Lateral connectivity refers to the ability of organisms to move between the river and floodplain.

The presence of instream levees, weirs and dams represent a physical barrier to the movement of aquatic biota within the stream network, resulting in a loss in longitudinal connectivity. Reductions in longitudinal connectivity in turn reduce access to floodplain wetlands, contributing indirectly to a loss in lateral connectivity. Water storage structures such as dams and reservoirs can either artificially increase or decrease lateral connectivity. Where floodplain wetlands are used as water storages, or where water is stored instream, floodplain wetlands will experience more frequent or even permanent inundation. This will artificially increase lateral connectivity. In contrast, the filling of dams reduces the frequency and magnitude of river flows and this can reduce the frequency of wetland inundation or prevent inundation completely. This will reduce lateral connectivity. Kingsford (2000) states that in Australia 50% of floodplain wetlands on developed rivers are isolated from their source river. Dams not only reduce the frequency of wetland inundation, they can also alter the timing of inundation. In southern Australia, dams can cause wetland inundation to shift from spring to summer (Kingsford 2000). In wetlands that have been isolated due to river regulation, water may be supplied artificially through the use of pumps, or through the installation and operation of gated channels between the wetland and its source river. Mechanisms to deliver water to wetlands may prevent some species from reaching wetlands, or may not be synchronised with natural dispersal events.

The National Catchment and Stream Environment Database version 1.1.1 (NCSED) was used to identify artificial structures within the stream network that may impact on floodplain connectivity. Artificial barriers captured in The NCSED included dams, spillways and large reservoirs. These structures may affect floodplain connectivity in two ways. Firstly, they may form barriers to the movement of some organisms within the stream network, reducing longitudinal connectivity. This in turn will reduce lateral connectivity, as it limits the ability of organisms to reach areas where floodplains occur. Secondly, water storages such as dams and reservoirs can alter the flow regime of the source river and alter lateral connectivity by changing the frequency, extent and magnitude of flooding from overbank flows. This approach however does not distinguish between barriers such as spillways, which primarily reduce movement within the stream network (with secondary impacts on lateral connectivity) from those such as dams that impact lateral connectivity directly by altering patterns of floodplain inundation.

To identify where river-floodplain connections have been disrupted by changes in floodplain inundation, river reaches with altered high flows were identified using the Victorian Index of Stream Condition (ISC) flow stress ranking inventory (FSR_Catchments, DSE 2007c). The ISC high flow index provides a direct measure of changes in river flows that are likely to reduce floodplain inundation and hence lateral connectivity.

5.2 Method

Identification of floodplain wetlands

Two spatial datasets were used to identify floodplains: (1) floodplain geomorphic units (GMU250) (DSE 2011) and (2) flood frequency and extent (Extent_100Y_ARI, DSE 2012b). The ability of these datasets to identify known floodplain wetlands was assessed by overlaying these spatial layers with aerial imagery from 2005-2010 and wetland spatial data (Wetlands 1994 and Vic-Hydro spatial datasets). Both the geomorphic units and food frequency and extent datasets failed to adequately capture known floodplains and several alternative approaches were trialled.

The mean elevation of each wetland was estimated by using a Digital Terrain Model (DTM 20 m resolution 2010, Information Management Service, DSE 2010). This value was then compared against the elevation of proximal river segments defined by the NCSED (version 1.1.1). A wetland was considered to be on a floodplain if the elevation of the wetland was lower than the elevation of the proximal stream segment. The results were tested by visual inspection of known floodplain wetlands and were shown to result in inaccurate floodplain wetland identification.

The second approach used the Environmental Streams Database of Victoria (En Chee 2010). This database provides values of floodplain width based on a metric derived from an index of mean valley bottom flatness. The floodplain width was constrained by the criteria described in the stream network metadata (En Chee 2010): where stream order was ≥ 3 , the floodplain width was limited to 3 km and when the stream order was ≤ 3, it was limited to 0.2 km (stream order was based on the Shreve classification). Floodplains widths generated by this process were then intersected with the Wetlands 1994 spatial layer. Visual examination of the floodplain widths inferred using this approach revealed that it failed to capture adjacent wetlands that were clearly floodplain wetlands.

The final approach was to apply a 3 km buffer to streams represented on the NCSED that were greater than 4th order (using the Strahler classification). Trials using smaller buffer widths failed to capture some known floodplain wetlands. The 3 km buffered stream spatial layer was intersected with the Wetlands 1994 spatial layer. Non-floodplain areas were deleted from the dataset, including impoundments, intertidal flats, mangroves, coastal salt flats, inlets, some coastal lakes, as well as obvious non floodplain wetlands (e.g. around Lake Coranagamite). The data derived from this process appeared to be more representative of actual floodplains; floodplain wetlands identified were validated based on known floodplain wetlands. However, a more thorough validation is needed in the future, ideally by waterway managers with local knowledge of the distribution of floodplain wetlands. In addition, flood inundation mapping for the Murray River (RiM-FIM) has been undertaken by CSIRO and could be used to validate floodplain attribution for this region (Overton 2006).

Altered hydrological connectivity between floodplain wetlands and their source rivers

Two approaches were used to assess altered floodplain connectivity. The NCSED attributes stream segments with a range of connectivity metrics including the presence of artificial barriers upstream (BARRIERUP). Artificial barriers in the NCSED database are derived from AusHydro Version 1.6 (Geosicence Australia) and include dam walls spillways and reservoir outlets. To identify floodplain wetlands that may be affected by barriers, streams greater than 4th order (using the Strahler classification) with a barrier upstream were selected, and wetlands within 3 km of these stream segments were attributed as experiencing some level of altered connectivity with their source rivers. This approach however does not distinguish between barriers such as spillways that primarily reduce movement within the stream network (with secondary impacts on lateral connectivity) from those that directly impact lateral connectivity by altering natural patterns of floodplain inundation.

The second approach aimed to identify where river-floodplain connections have been disrupted due to a reduction in high flows (and therefore a reduction in overbank flows). To do this 4th order river reaches with low high flow indices were identified from the ISC flow stress ranking inventory (FSR_catchments, DSE 2007c). The ISC high flow index provides a direct measure of changes in river flows that are likely to reduce floodplain inundation and hence lateral connectivity. The high flow index represents the extent to which high flows differ to natural conditions, with values varying from 10 (pristine) to zero (highly altered) (SKM 2005). Although low high flow values can represent either an increase or decrease in high flows compared with natural conditions, in the majority of cases low values represent a reduction in high flows as data was collected over a period of drought (Paul Wilson, DSE pers. comm.). As such, we can infer that river reaches with low high flow index scores potentially experience reduced lateral connectivity.

In this study, we consider river reaches with high flow index values of ≤ 6 to potentially have altered patterns of floodplain inundation and hence lateral connectivity. This threshold is somewhat arbitrary but was selected as it distinguishes scores for free-flowing and regulated rivers; free-flowing rivers on the ISC inventory were found to have indices of seven or higher. Fourth order river segments in the ISC inventory were identified using the NCSED database. A 3 km buffer was applied to 4th order river segments with high flow indices ≤ 6. This layer was then intersected with the floodplain wetland layer (generated as a part of this project, see above) to identify floodplain wetlands with reduced lateral connectivity.

5.3 Results and discussion

Wetlands delineated as either floodplain or non-floodplain wetlands are shown in Figure 7; 4,857 potential floodplain wetlands were identified, representing approximately 30% of the 16,318 wetland polygons included in the analysis (Wetlands 1994 spatial layer).

In this report two approaches were used to assess altered floodplain connectivity. In the first approach, the prevalence of instream barriers was used to infer possible changes in connectivity between rivers and areas containing floodplains. The second approach used the ISC reduction in high flow stress ranking to identity floodplain wetlands that are likely to experience reduced flood inundation and hence reduced lateral connectivity.

The first approach found that 91% of floodplain wetlands were potentially fed by streams with an artificial barrier upstream (Figure 8). This assessment probably overestimates losses in connectivity for several reasons. Firstly, the impact that artificial structures have on floodplain connectivity will be determined by: (1) the size and type of structure, (2) its location in the stream network and (3) its operation. Secondly, inputs from tributaries downstream of artificial structures will reduce their impact on flows. Thirdly, the assessment does not discriminate between structures that primarily reduce lateral connectivity through a reduction in overbank flows from those that limit the movement of biota within the stream network, with secondary impacts on lateral connectivity.

The second approach identified where floodplain connectivity has been affected by reduced river flows (and hence reduced overbank flows). There are flow stress rankings for almost all 4th order river segments represented in the NCSED database, indicating that there was good spatial coverage for the purposes of this analysis (Figure A1, Appendix 5). A list of 4th order streams with a high flow stress rating ($\leq$ 6) is provided in Table A4, Appendix 5).

The results indicate that 41% of floodplain wetlands are likely to experience reduced lateral connectivity with their source river due to reductions in high flows (Figure 9). This assessment can only be regarded as an indicator of altered lateral connectivity as the impact of a reduction in high flows will vary depending on the flows required to inundate each floodplain wetland. In some systems losses in lateral connectivity may be mitigated by water control structures such as gated culverts, drains, channels or pumps that deliver environmental water from the river to floodplains. The size, type and operation of these structures will determine the extent to which losses in lateral connectivity are mitigated.

Although this work contributes to our understanding of river-floodplain connectivity, their remains a high level of uncertainty regarding the accuracy of floodplain delineation and the extent to which water extraction and storage for human use have altered hydrological connections between floodplain wetlands and their source rivers and more work in this area is needed.

Recommendations

Our assessment of hydrological connectivity focussed on assessing connectivity between floodplain wetlands and their source rivers, and whether these connections are altered by river regulation. The outputs of this work were limited by the resolution and coverage of statewide flood inundation mapping and the lack of information on the nature, location and operation of water control structures (e.g. levees). Recommendations to improve upon the current assessment of floodplain wetland-river connectivity are described below, as well as areas for further work to improve our understanding of hydrological connectivity.

It is anticipated that statewide flood inundation mapping will be improved in the future through the outputs of Floodzoom, a State government initiative to improve understanding of flood behaviour. The information generated by this project could be used in the future to inform the delineation of floodplain wetlands. Identifying floodplain wetlands based on flood extent will require that floodplain wetlands are defined in terms of the flood interval required to maintain ecological function. This requires an understanding of how the frequency, timing and nature (e.g. overbank flow) of inundation maintains the ecological character of floodplain wetlands and this requires further research.

Current patterns of flood inundation captured in projects such as Floodzoom may not identify floodplain wetlands that have been isolated by human activities. These may be identified by mapping vegetation communities that are characteristic of floodplains.

High flow stress rankings measured by the ISC were used to identity floodplain wetlands that are likely to experience reductions in high flows and hence reduced lateral connectivity. The ISC also identifies river reaches where seasonal flow patterns have been altered. This could be used to identify where flow patterns may no longer be synchronised with seasonal patterns of dispersal of aquatic biota.

Although Flow Stress Rankings (FSR) are useful for inferring change in floodplain connectivity, an understanding of the mechanisms that underlie their estimation are needed to inform appropriate management interventions to restore connectivity. These are not yet comprehensively identified in the ISC. Possible causal mechanisms for flow stress include changed climate patterns (e.g. increased drought severity), altered catchment processes (i.e. deforestation, urbanisation), instream barriers, water storages or diversions, and changes in river flow management. An inventory of instream barriers is currently being compiled to help identify the causes of flow stress. However, only structures visible on aerial imagery (1:25 000) will be detected, and this will be inadequate to detect all structures that affect flow. A comprehensive inventory of river-floodplain barriers that impact on lateral connectivity will be needed in the future to inform the management of floodplain wetlands.

Further work is required to identify non-floodplain wetlands that are connected by surface flows, or by artificial channels. A better understanding of groundwater depend wetlands at a statewide level is also needed, as groundwater levels will influence water depth and hence the likelihood of overflows connecting wetlands. Information on how water is artificially transferred between wetlands, as well as describing and mapping water control structures and barriers (e.g. levees and weirs) is needed to develop a more accurate representation of hydrological connectivity at a landscape scale for both floodplain and non-floodplain wetlands.

Although developing maps to represent hydrological connections among wetlands will provide a valuable tool for the landscape-scale management of wetlands, an improved understanding of the role and nature of hydrological connectivity of individual wetlands will inform management activities to restore connectivity. For example, enhancing the connectivity of individual wetlands can be achieved by: (1) removing barriers to water movement and/or the dispersal of particular taxa; (2) providing sufficient environmental water to restore flows in the river channel and flood inundation extent of floodplains; (3) delivering water in a way that mimics natural patterns of connectivity; and (4) by restoring connectivity by using modes of water delivery that do not impact on water-mediated dispersal of wetland biota.

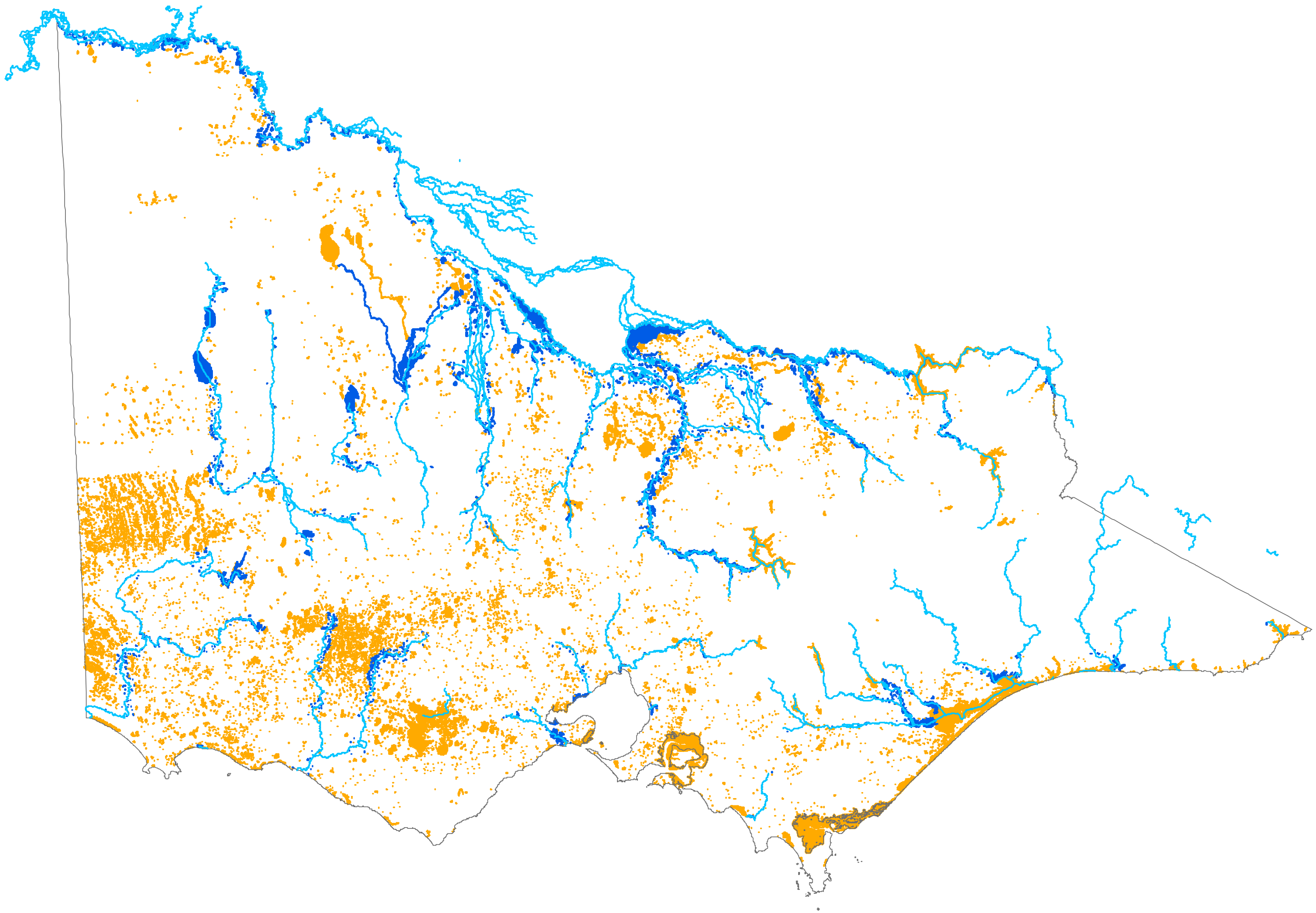

Figure 7. Map of floodplain wetlands (blue), non-floodplain wetlands (yellow) and streams greater than 4th order (light blue). Stream order is based on the Strahler classification system. Stream data was derived from the NCSED database.

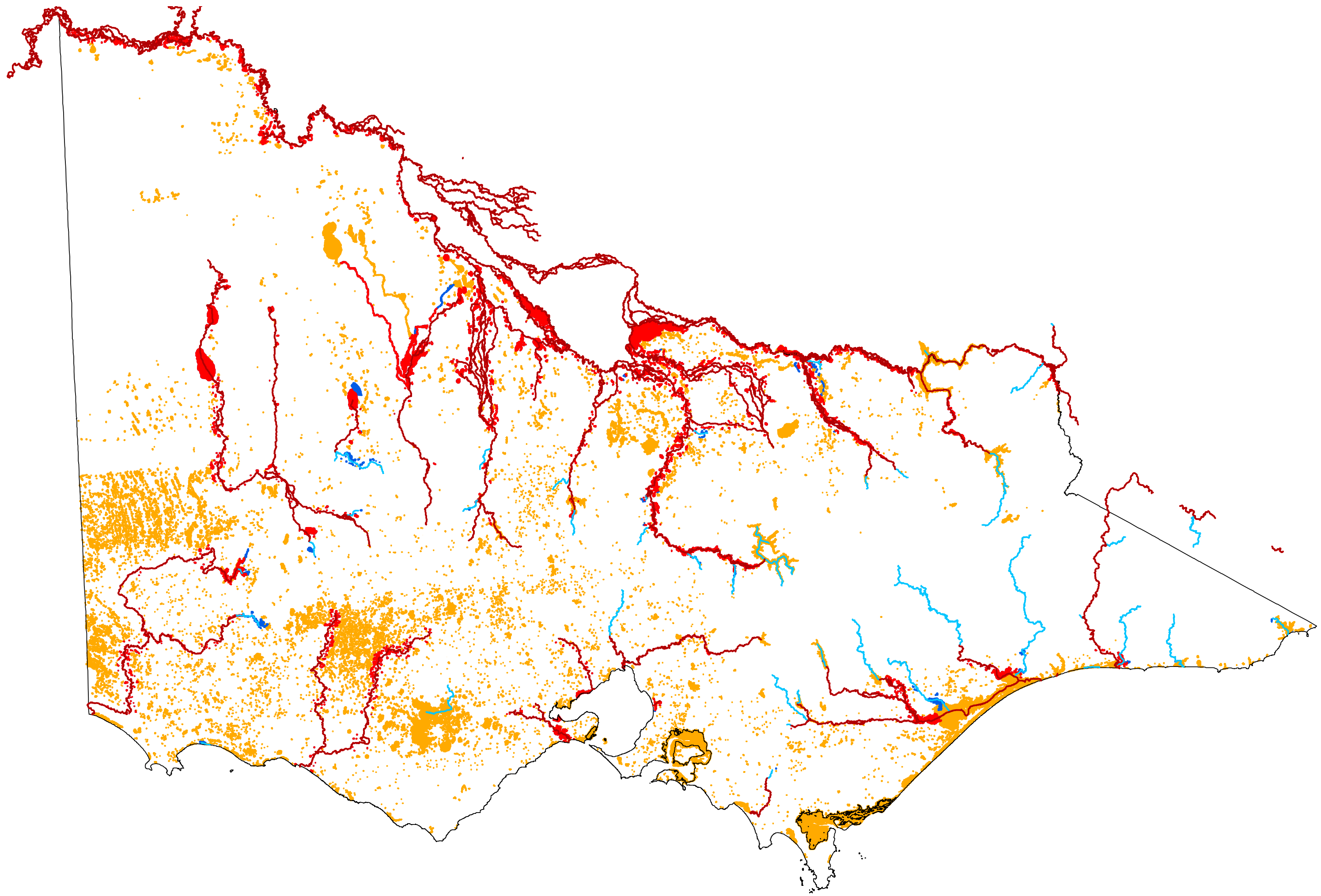

Figure 8. Map of wetlands attributed as: (i) non-floodplain (yellow); (ii) floodplain wetlands potentially fed by streams great than 4th order with no barriers upstream (dark blue); and (iii) floodplain wetlands, potentially fed by streams great than 4th order that have a barrier upstream (red). Stream order is based on the Strahler classification system. Barriers are dam walls, spillways and reservoir outlets. Stream data was derived from the NCSED database.

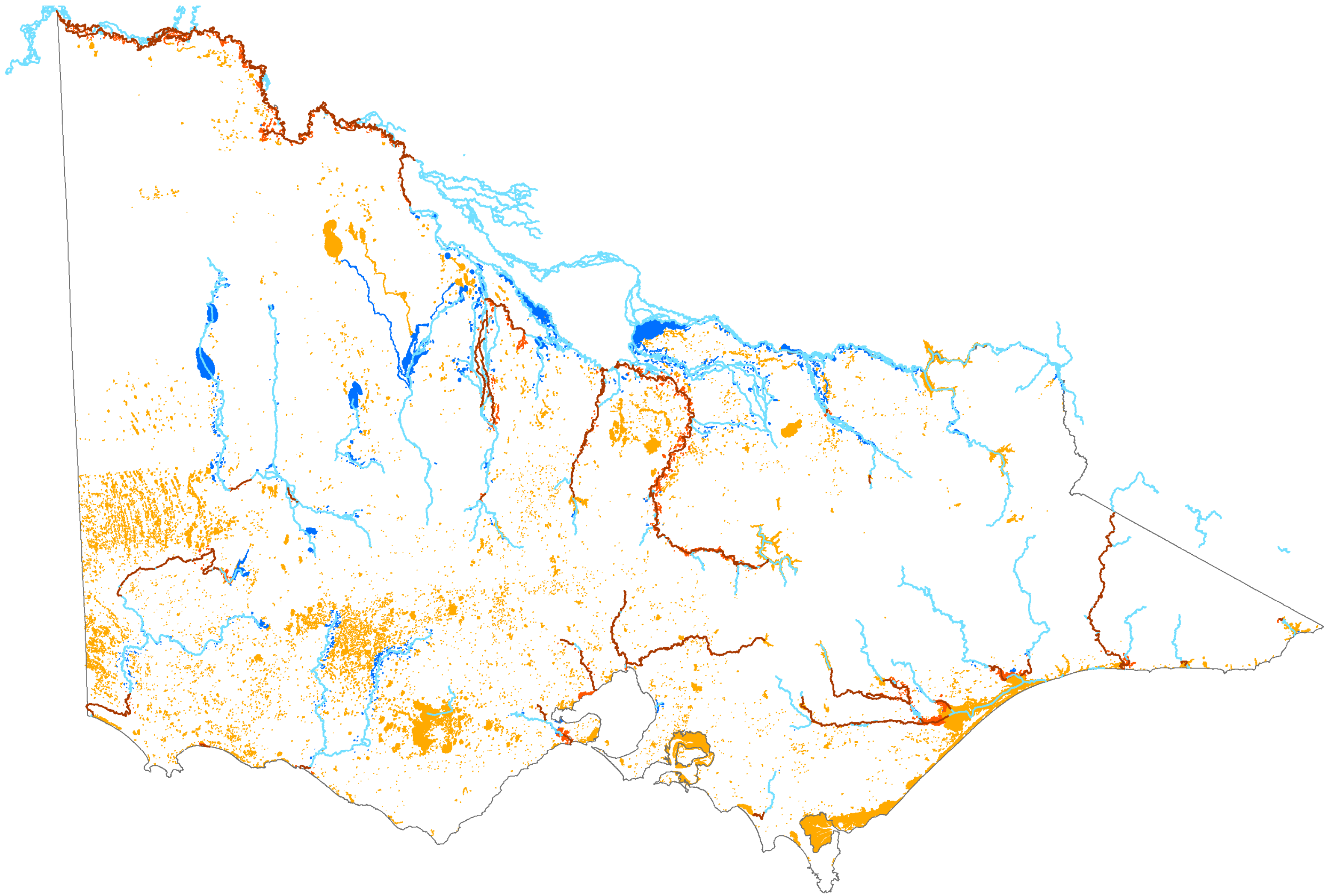

Figure 9. Map of wetlands attributed as: (i) non-floodplain (yellow); (ii) floodplain wetlands potentially fed by streams greater than 4th order, with a high flow stress ranking > 6 (dark blue) and; (iii) floodplain wetlands potentially fed by streams greater than 4th order, with a high flows stress ranking ≤ 6 (red). Stream order is based on the Strahler classification system. The stream network shown was derived from the NCSED database. The high flow index in the ISC reflects the extent to which high flows have been reduced compared to a reference. Values vary from 10, indicating pristine conditions, to 0, indicating completely altered conditions. A list of 4th order streams with a high flow stress rating ≤ 6 is provided in Appendix 4.

6 General discussion

Historically, wetland conservation objectives have primarily focused on maintaining or restoring the condition of individual wetlands and preventing further wetland loss (Amezaga et al. 2002). More recently, the importance of managing wetlands at a landscape scale has gained wider recognition.

This project aimed to improve our understanding of connectivity for wetland ecosystems and develop statewide models of wetland connectivity. The work focused on a range of wetland biota and developed connectivity estimates for waterbirds, amphibians, wind dispersed seeds and water. Patterns of connectivity for waterbirds also provide insight into the dispersal patterns of plant and invertebrate propagules carried by waterbirds.

The project has produced preliminary models of wetland connectivity for amphibians and waterbirds, identified floodplain wetlands where hydrological connectivity may be impaired and made progress in developing a novel approach to assess patterns of connectivity for wind dispersed seeds. The amphibian and waterbird models are considered preliminary as they used incomplete and outdated wetland mapping that will generate inaccuracies in the model outputs. New wetland mapping is currently being undertaken and will result in an updated Victorian wetland inventory in 2012. It is recommended that models are re-run when the new wetland inventory is completed. An evaluation of the amphibian model by experts has highlighted areas for model improvement and these should be incorporated when the models are re-run. The floodplain wetlands delineated in this project require more comprehensive validation by regional waterway managers or by comparison with flood inundation models (e.g. RiMFIM). Models of wetland connectivity for wind dispersed plant propagules required the development of novel approaches within GIS; resources proved insufficient to fully develop these models.

Applications

An understanding of the processes that connect wetlands, in conjunction with information on wetland values and threats, will help assist in the management of aquatic habitats at local and landscape scales. Understanding patterns of connectivity will help identify highly connected wetlands among which plants and animals are able to move. These wetlands are likely to form refuges from which species can disperse when conditions are again suitable. Conversely, it will identify wetlands that are poorly connected and more vulnerable to disturbance and stressful conditions such as drought. For degraded wetlands, understanding landscape connectivity will help to identify if a loss in connectivity could be contributing to the poor condition and how connectivity may be restored. Knowledge of connectivity may also be used to limit weed invasion or the spread of diseases such chytrid fungus in amphibians. Understanding how dispersal connects habitats in the landscape will allow identification of sites for conservation, restoration, or wetland re-creation that will have flow on benefits to other habitats through dispersal. It is also important to note that management strategies aimed at improving connectivity may exert positive effects on some species and negative effects on others. Taylor et al. (2006) recommends that the aim of connectivity management strategies should be to identify the consequences of changing elements of the landscape for the persistence of populations.

In other studies, the level of uncertainty in assessing connectivity has raised concerns about giving higher priority to connectivity objectives than to those aimed at enhancing the size or quality of habitats, where the effects on biodiversity are more certain (Hodgson et al. 2009). Even where enhancing habitat size and quality are the primary conservation strategies they should be informed by an understanding of connectivity as connections to other wetlands may be important in maintaining the ecological character of the site. Restoring wetlands with multiple connections to other wetlands may enhance diversity and ecosystem resilience to a greater degree than restoring those that lack these connections.

Next Steps

Assessing connectivity at a landscape level remains one of the challenges of landscape ecology. This project has provided insight into the processes that connect wetland systems and has made a major advance towards the development of connectivity maps for a broad range of wetland taxa. The breadth and novelty of the project, coupled with uncertainty around dispersal constraints of wetland taxa and limitations of spatial datasets at a statewide scale has limited the outputs of the project. Although the models remain preliminary (waterbirds and amphibian) or require further development (wind dispersal of plant seeds, water-mediated dispersal) and validation, they represent a significant contribution to our understanding of connectivity and provide a strong basis for further development.

The connectivity models presented are based on our current understanding of the habitat requirements, dispersal distances and landscape permeability for representative taxa. In many cases these have been informed through expert opinion as data is lacking. Further research that improves our understanding of (1) habitat requirements, (2) dispersal distances and (3) features of the landscape that facilitate or inhibit movement for representative taxa is needed to improve connectivity models. A better understanding of habitat requirements and landscape permeability for aquatic taxa will only enable connectivity models to be improved if this knowledge is also known on-the-ground and mapped. Importantly, testing the outputs of connectivity models against actual dispersal data is needed before the validity of the models can be judged. Testing the sensitivity of model results to the assumptions in the model will help identify management activities that exert the most influence on connectivity.

Levels of genetic variation among populations provide insights into spatial patterns of biological connectivity among habitats (Sork et al. 1999, Wang and Smith 2002). Patterns of connectivity inferred from genetic analyses are useful in testing and refining the assumptions of connectivity models (Spear et al. 2005, Stevens et al. 2006). Actual dispersal data or genetic studies of aquatic taxa in Victoria are needed to test the accuracy of connectivity models and this should be a priority for future work.

Comparing model outputs against those produced by other connectivity modelling approaches such as circuit theory and others will also be useful in validating the current approach. Circuit theory provides an assessment of connectivity among multiple habitats by identifying pathways of least resistance in the landscape (McRae and Beier 2007). Models based on circuit theory are computationally demanding when the number of habitats is large and this prevented circuit theory being used in this study where a statewide assessment, encompassing over 16000 wetland polygons, was required. An assessment of connectivity using circuit theory or other approaches would be feasible for smaller areas and could be undertaken in order to compare model outputs against those produced using the current approach. The relative performance of each model could then be evaluated against actual dispersal data or genetic data. These are essential tasks for future work.

Developing a system-based map of wetland connectivity is desirable to guide strategic planning and investment and to improve our understanding of how wetlands interface with other ecosystem types. Once individual models of representative wetland biota are completed it may be possible to combine them to provide a system-based map of wetland connectivity. Wetlands could be scored based on the number of groups/vectors for which they are highly connected. For example, a wetland that is highly connected for waterbirds, amphibians, wind dispersed seed and water would receive a score of four. In contrast, a wetland that was only highly connected for waterbirds would receive a score of one. Different weights for each vector could be developed to increase the level of discrimination among wetlands. Although an integrated map of wetland connectivity will provide a useful tool for guiding wetland management at the landscape level, an understanding of the patterns of connectivity at a taxonomic group or species level is needed to inform more targeted on-ground management interventions to restore connectivity for particular taxa.

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Appendix 1. Description of amphibians recorded in Victoria

Table A1. Description of amphibians recorded in Victoria including: conservation listing (CL) in Victoria (DSE 2007), mobility and habitat use. The genus *Litoria* belongs to the family Hylidae, all the other genera belong to the family Myobatrachidae.

Species name	Common name	CL	Altitudinal range (m)	Habitat use	Mobility
Litoria aurea	Green and Golden Bell Frog	Vu	10–720	Generalist	High
Litoria booroolongensis	Booroolong Tree Frog	CE, FFG	210–260	Stream	Unknown
Litoria citropa	Blue Mountains Tree Frog		10–590	Stream	Unknown
Litoria dentata	Bleating Tree Frog			Generalist	Unknown
Litoria ewingii	Southern Brown Tree Frog		10–1510	Generalist	Unknown
Litoria lesueuri	Lesueur's Frog		10–1460	Stream	Unknown
Litoria littlejohni	Large Brown Tree Frog	DD, FFG	110–1160	Generalist	Medium
Litoria nudidigita	Leaf Green Tree Frog		10–1390	Stream	Unknown
Litoria paraewingi	Plains Brown Tree Frog		20–1730	Generalist	Medium
Litoria peronii	Peron's Tree Frog		10–1030	Generalist	Unknown
Litoria raniformis	Growling Grass Frog	E, FFG	10–1140	Generalist	High
Litoria spenceri	Spotted Tree Frog	CE, FFG	310–1700	Stream	Unknown
Litoria verreauxii alpina	Alpine Tree Frog	CE, FFG	1000–1720	Specialist	Unknown
Litoria verreauxii verreauxii	Verreaux's Tree Frog		10–980	Generalist	Unknown
Crinia parinsignifera	Plains Froglet		20–850	Generalist	Unknown
Crinia signifera	Common Froglet		10–1950	Generalist	Unknown
Crinia sloanei	Sloane's Froglet		80–210	Generalist	Unknown
Geocrinia laevis †	Southern Smooth Froglet		10–720	Specialist	Low
Geocrinia victoriana †	Victorian Smooth Froglet		10–1730	Specialist	Low
Heleioporus australiacus†	Giant Burrowing Frog	Vu, FFG	60–830	Unknown	Unknown
Limnodynastes dumerilii	Pobblebonk Frog		10–1700*****	Generalist	Medium
Limnodynastes fletcheri	Barking Marsh Frog		20–300	Generalist	Unknown
Limnodynastes interioris	Giant Bullfrog	CE, FFG	80–400	Generalist	Medium
Limnodynastes peronii	Striped Marsh Frog		10–1180	Generalist	Unknown
Limnodynastes tasmaniensis	Spotted Marsh Frog		10–1150	Generalist	Unknown
Mixophyes balbus	Southern Barred Frog	CE, FFG	200–970	Stream	Unknown
Neobatrachus pictus	Mallee Spadefoot Toad		30–370	Generalist	Unknown
Neobatrachus sudelli	Common Spadefoot Toad		10–440	Generalist	Unknown
Paracrinia haswelli	Haswell's Froglet		10–910	Generalist	Unknown
Philoria frosti †	Baw Baw Frog	CE, FFG	810– 1570	Specialist	Low
Pseudophryne bibroni †	Brown Toadlet	E, FFG	10–1090	Specialist	Low
Pseudophryne dendyi †	Dendy's Toadlet	DD	10–1710	Specialist	Low
Pseudophryne semimarmorata †	Southern Toadlet	Vu	10–1500	Specialist	Low
Uperoleia laevigata	Smooth Toadlet	DD	190–950	Generalist	Unknown
Uperoleia martini	Martin’s Toadlet	DD	20–210	Generalist	Unknown
Uperoleia rugosa	Rugose Toadlet	Vu, FFG	100–200	Generalist	Unknown
Uperoleia tyleri	Tyler’s Toadlet	DD	20–210	Generalist	Unknown

Habitat use: generalist, species that utilise most wetland types and do not have specialised breeding biology; specialist, species with narrow habitat requirement and/or specialised breeding biology; stream, stream dwelling species. Mobility ratings are based on expert opinion: Unknown, Low, < 0.5 km; Medium, < 1 km; High, > 1 km. Conservation listing in Victoria (DSE 2007): RE, regionally extinct; CE, critically endangered; E, endangered; Vu, vulnerable; DD, data deficient; FFG, listed as threatened under the FFG Act 1988.

†species that do not breed in ponds; *elevation data may encompass multiple subspecies; Tyler’s Toadlet and Martin’s Toadlet may be the same species (taxonomy unresolved).

Sources: Robinson (1998); M. Scroggie, N. Clemann and S. Saddlier, ARI, pers. comm.

Appendix 2. Geometrical interval classification

A geometric series is a pattern where a constant coefficient multiplies each value in the series. For example, a sequence of {0.1, 0.3, 0.9, 2.7, 8.1} is where each value is multiplied by 3. The inverse of 3 would be 0.33333 (or 1/3). Table A2 below is an example of a geometrical interval classification that was produced in ArcMap. The interval (or bin size) of the class is calculated by subtracting the minimum from the maximum. The geometric coefficient is calculated by dividing the previous interval by the current interval. There are two possible geometric coefficients to create this classification structure, 1.539927 and 0.649382, which are inverses of each other.

Table A2. Geometric interval classification produced in ArcMap.

Minimum	Maximum	Interval	Coefficient
0.026539462	0.046593756	0.020054	
0.046593757	0.059616646	0.013023	1.539927
0.059616647	0.068073471	0.008457	1.539927
0.068073472	0.081096361	0.013023	0.649382
0.081096362	0.101150655	0.020054	0.649382
0.101150656	0.132032793	0.030882	0.649382
0.132032794	0.179589017	0.047556	0.649382

Source: ESRI Help, esri.com.au

Appendix 3. Waterbirds recorded in Victoria that are associated with wetlands

Table A3. List of waterbirds associated with wetlands that have been recorded in Victoria, the types of wetlands in which they occur, status of occurrence and conservation listing in Victoria. Movement patterns associated with breeding, feeding and moulting are also listed. Pelagic seabirds, vagrants and land birds using saltmarsh are excluded from this list. Species are grouped by taxon number according to Christidis and Boles (2007). This table was compiled by R. Loyn, Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment.

CL = conservation listing; MB = movements between breeding and non-breeding habitat; MF = movements between feeding, roosting and moulting habitats. See key on page 46.

Common Name	Scientific Name	Habitat	Status	CL	MB	MF
Magpie Goose	*Anseranas semipalmata*	F	RI	NT	L	L
Plumed Whistling-Duck	*Dendrocygna eytoni*	F	RB		A	L
Musk Duck	*Biziura lobata*	FST		Vu	A	L
Freckled Duck	*Stictonetta naevosa*	F		E, FFG	IA	L
Cape Barren Goose	*Cereopsis novaehollandiae*	FS		NT	C	R
Feral Goose	*Anser anser*	F	I		L	L
Black Swan	*Cygnus atratus*	FST			A	M
Australian Shelduck	*Tadorna tadornoides*	FST	G		A	M, F
Australian Wood Duck	*Chenonetta jubata*	F	G		A	L
Pink-eared Duck	*Malacorhynchus membranaceus*	FS	G		IA	L
Australasian Shoveler	*Anas rhynchotis*	FS	G	Vu	A	L
Grey Teal	*Anas gracilis*	FST	G		IA	L
Chestnut Teal	*Anas castanea*	FST	G		A	T
Mallard	*Anas platyrhynchos*	F	I		L	L
Pacific Black Duck	*Anas superciliosa*	F	G		A	L
Hardhead	*Aythya australis*	F	G	Vu	IA	L
Blue-billed Duck	*Oxyura australis*	FS		E, FFG	A	L
Australasian Grebe	*Tachybaptus novaehollandiae*	F			L	L
Hoary-headed Grebe	*Poliocephalus poliocephalus*	FST			IA	L
Great Crested Grebe	*Podiceps cristatus*	FST			A	L
Darter	*Anhinga novaehollandiae*	F			L	L
Little Pied Cormorant	*Microcarbo melanoleucos*	FST			A	T
Great Cormorant	*Phalacrocorax carbo*	FST			A	T
Little Black Cormorant	*Phalacrocorax sulcirostrus*	FST			A	T
Pied Cormorant	*Phalacrocorax varius*	FST		NT	L	T
Black-faced Cormorant	*Phalacrocorax fuscescens*	C		NT	C	T
Australian Pelican	*Pelecanus conspicillatus*	FST			A	F, T
Australasian Bittern	*Botaurus poiciloptilus*	F		E, FFG	A	L
Australian Little Bittern	*Ixobrychus dubius*	F	S		A	L
Black Bittern	*Ixobrychus flavicollis*	FT	RB	Vu, FFG	A	L
White-necked Heron	*Ardea pacifica*	F			IA	F
Eastern Great Egret	*Ardea modesta*	FST		Vu, FFG	IA	F
Intermediate Egret	*Ardea intermedia*	FT		CE, FFG	IA	F
Cattle Egret	*Ardea ibis*	F	W		A	F, R

(continued on next page)

Appendix 3 (continued)

Common Name	Scientific Name	Habitat	Status	CL	MB	MF
White-faced Heron	*Egretta novaehollandiae*	FST			L	F
Little Egret	*Egretta garzetta*	FST		E, FFG	A	F
Eastern Reef Egret	*Egretta sacra*	T	RNB		A	T
Nankeen Night-Heron	*Nycticorax caledonicus*	F		NT	A	F
Glossy Ibis	*Plegadis falcinellus*	F		NT	IA	R
Australian White Ibis	*Threskiornis molucca*	FST			A	R
Straw-necked Ibis	*Threskiornis spinicollis*	F			IA	R
Royal Spoonbill	*Platalea regia*	FST		Vu	A	T
Yellow-billed Spoonbill	*Platalea flavipes*	F			IA	F
Eastern Osprey	*Pandion cristatus*	C	RNB		A	F
White-bellied Sea-Eagle	*Haliaeetus leucogaster*	FST		Vu, FFG	A	F, T
Whistling Kite	*Haliastur sphenurus*	FT			A	L
Swamp Harrier	*Circus approximans*	FS			A	R
Brolga	*Grus rubicundus*	F		Vu, FFG	A	L, M
Purple Swamphen	*Porphyrio porphyrio*	FS			L	L
Lewin's Rail	*Lewinia pectoralis*	FST		Vu, FFG	L	L
Buff-banded Rail	*Gallirallus philippensis*	FST			L	L
Baillon's Crake	*Porzana pusilla*	F	S	Vu, FFG	A	L
Australian Spotted Crake	*Porzana fluminea*	FST			A	L
Spotless Crake	*Porzana tabuensis*	F			A	L
Black-tailed Native-hen	*Tribonyx ventralis*	F			A	L
Dusky Moorhen	*Gallinula tenebrosa*	F			L	L
Eurasian Coot	*Fulica atra*	F			A	L
Pied Oystercatcher	*Haematopus longirostris*	T			C	T
Sooty Oystercatcher	*Haematopus fuliginosus*	T		NT	C	T
Black-winged Stilt	*Himantopus himantopus*	FS			A	L
Red-necked Avocet	*Recurvirostra novahollandiae*	FST			IA	F
Banded Stilt	*Cladorhynchus leucocephalus*	S			IA	F
Pacific Golden Plover	*Pluvialis fulva*	T	S	NT	NH	T
Grey Plover	*Pluvialis squatarola*	T		NT	NH	T
Red-capped Plover	*Charadrius ruficapillus*	FST			A	T
Double-banded Plover	*Charadrius bicinctus*	FST	W		NZ	T
Lesser Sand Plover	*Charadrius mongolus*	T	S	Vu	NH	T
Greater Sand Plover	*Charadrius leschenaultii*	T	S	Vu	NH	T
Oriental Plover	*Charadrius veredus*	FS	RNB		NH	F
Inland Dotterel	*Charadrius australis*	FS		Vu	A	F
Black-fronted Dotterel	*Elseyornis melanops*	F			L	L
Hooded Plover	*Thinornis rubricollis*	T		Vu, FFG	C	L
Red-kneed Dotterel	*Erythrogonys cinctus*	FS			IA	L
Banded Lapwing	*Vanellus tricolor*	FS			L	L
Masked Lapwing	*Vanellus miles*	FST			L	L
Australian Painted Snipe	*Rostratula australis*	FS		CE,FFG	A	L
Latham's Snipe	*Gallinago hardwickii*	F	S	NT	NH	L

(continued on next page)

Appendix 3 (continued)

Common Name	Scientific Name	Habitat	Status	CL	MB	MF
Black-tailed Godwit	*Limosa limosa*	FST	S	Vu	NH	T
Bar-tailed Godwit	*Limosa lapponica*	T	S		NH	T
Little Curlew	*Numenius minutus*	FS	RNB		NH	L
Whimbrel	*Numenius phaeopus*	T	S		NH	T
Eastern Curlew	*Numenius madagascariensis*	T	S	NT	NH	T
Terek Sandpiper	*Xenus cinereus*	T	S	E, FFG	NH	T
Common Sandpiper	*Actitis hypoleucos*	FST	S	Vu	NH	L
Grey-tailed Tattler	*Tringa brevipes*	T	S		NH	T
Common Greenshank	*Tringa nebularia*	FST	S		NH	T
Marsh Sandpiper	*Tringa stagnatilis*	S	S		NH	L
Wood Sandpiper	*Tringa glareola*	F	RNB	Vu	NH	L
Ruddy Turnstone	*Arenaria interpres*	T	S		NH	T
Great Knot	*Calidris tenuirostris*	T	S		NH	T
Red Knot	*Calidris canutus*	T	S	NT	NH	T
Sanderling	*Calidris alba*	T	S	NT	NH	T
Red-necked Stint	*Calidris ruficollis*	FST	S		NH	T
Long-toed Stint	*Calidris subminuta*	F	RNB	NT	NH	L
Pectoral Sandpiper	*Calidris melanotos*	FS	RNB	NT	NH	L
Sharp-tailed Sandpiper	*Calidris acuminata*	FST	S		NH	T
Curlew Sandpiper	*Calidris ferruginea*	FST	S		NH	T
Broad-billed Sandpiper	*Limicola falcinellus*	T	RNB		NH	T
Ruff	*Philomachus pugnax*	F	RNB		NH	L
Oriental Pratincole	*Glareola maldivarum*	FST	RNB		NH	L
Australian Pratincole	*Stiltia isabella*	FS	S	NT	A	L
Little Tern	*Sternula albifrons*	C		Vu, FFG	C, NH	T
Fairy Tern	*Sternula nereis*	C		E, FFG	C	T
Gull-billed Tern	*Gelochelidon nilotica*	FST		E, FFG	A	F
Caspian Tern	*Hydroprogne caspia*	FST			A	T
Whiskered Tern	*Chlidonias hybrida*	FS		NT	A	F
White-winged Black Tern	*Chlidonias leucopterus*	FST	S	NT	NH	F
White-fronted Tern	*Sterna striata*	C	W	NT	NZ	T
Common Tern	*Sterna hirundo*	C	S		NH	T
Crested Tern	*Thalasseus bergii*	C			C	T
Pacific Gull	*Larus pacificus*	C		NT	C	T
Kelp Gull	*Larus dominicanus*	C			C	L
Silver Gull	*Chroicocephalus novaehollandiae*	FST			A	F, T
Azure Kingfisher	*Ceyx azureus*	F		NT	L	L
Australian Reed-Warbler	*Acrocephalus australis*	F	S		A	L
Little Grassbird	*Megalurus gramineus*	FST			L	L

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Key for Appendix 3.

Wetland habitats (main habitats used by each species)	
C	Coastal waters
F	Freshwater wetlands (may be vegetated or open, favoured by different species)
FS	Freshwater or saline wetlands, but rarely tidal
FST	Freshwater, saline or tidal wetlands
FT	Freshwater or tidal wetlands (e.g. among paperbarks and mangroves in tropics, mostly freshwater in Victoria
S	Saline wetlands (may use freshwater or tidal habitats locally or periodically)
ST	Saline or tidal wetlands
T	Tidal mudflats or beaches
Status	
I	Introduced to Australia
RI	Re-introduced to Victoria after extinction in early 20th century
RB	Rare breeding species
RNB	Rare non-breeding visitor to Victoria
G	Classed as a game species (in some years not all these species are allowed to be taken)
S	Mainly summer visitor
W	Mainly winter visitor
Note that vagrants (recorded on rare occasions, presumably as lost individuals) are not included in this table.	
Victorian Conservation Status (Source: DSE 2007)	
CE	Critically Endangered
E	Endangered
Vu	Vulnerable
NT	Near Threatened
FFG	Listed under the *Flora and Fauna Guarantee Act 1988*
Movements between breeding and non-breeding habitat	
A	Migratory or nomadic movements in Australia (not including subset below)
IA	Nomad, breeding mainly in inland Australia during floods, and largely vacating coastal habitats in those times
NH	Migrant, breeding in Northern Hemisphere
NZ	Migrant, breeding in New Zealand
C	Mainly coastal, may make movements along coasts or to breed on coastal islands
L	Mainly local movements (< 50 km)
Note, there are some regular seasonal patterns in nomadism in Australia, but they may be over-ridden by major flood events	

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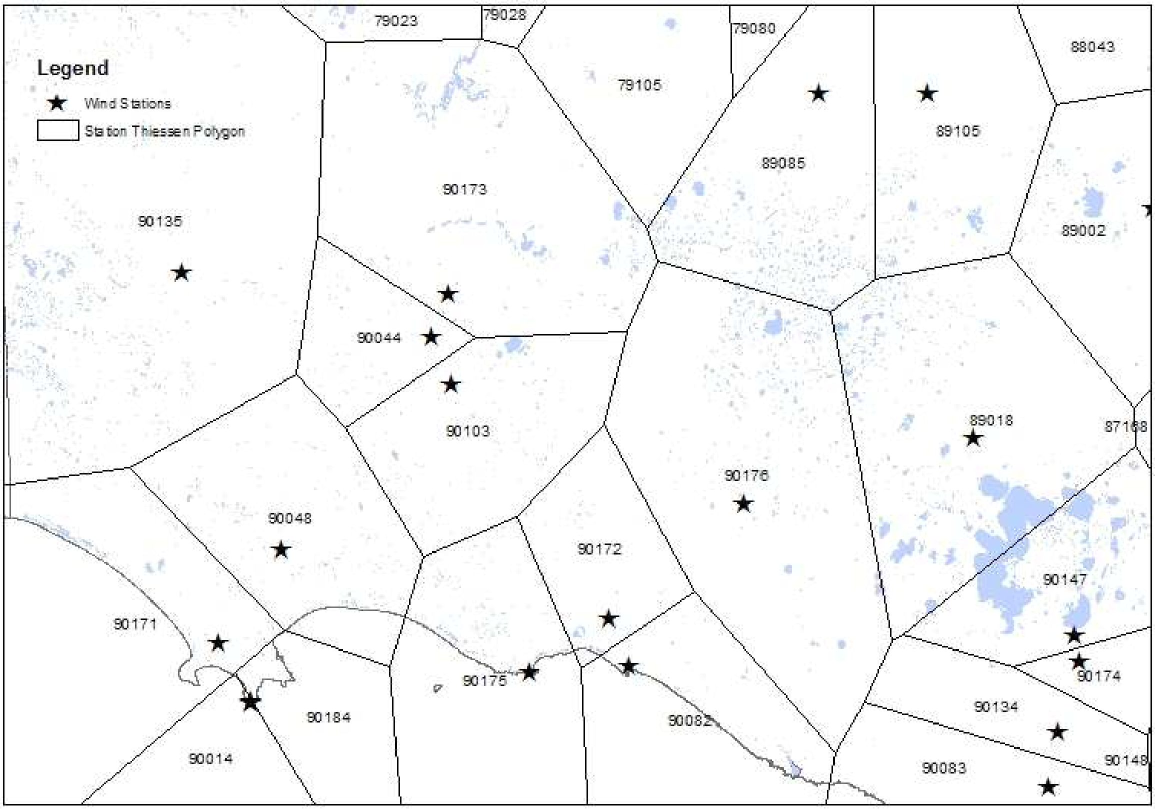
Key for Appendix 3 (continued)

Movements between feeding, roosting and moulting habitats	
T	Regular (twice-daily) movements up to 20 km between feeding areas and high-tide roosts on spits, islands or saltmarsh. (Species that use tidal and non-tidal habitats typically make shorter daily movements when feeding in non-tidal habitats.)
R	Regular daily movements up to 20 km between feeding and roosting habitats
F	Regular movements up to 10 km between alternative feeding habitats
M	Annual movements to suitable moulting habitat
L	Mainly local movements (< 5 km)

Appendix 4 Thiessen polygons representing areas of wind influence.



Appendix 5 Rivers with significant reductions in high flows.

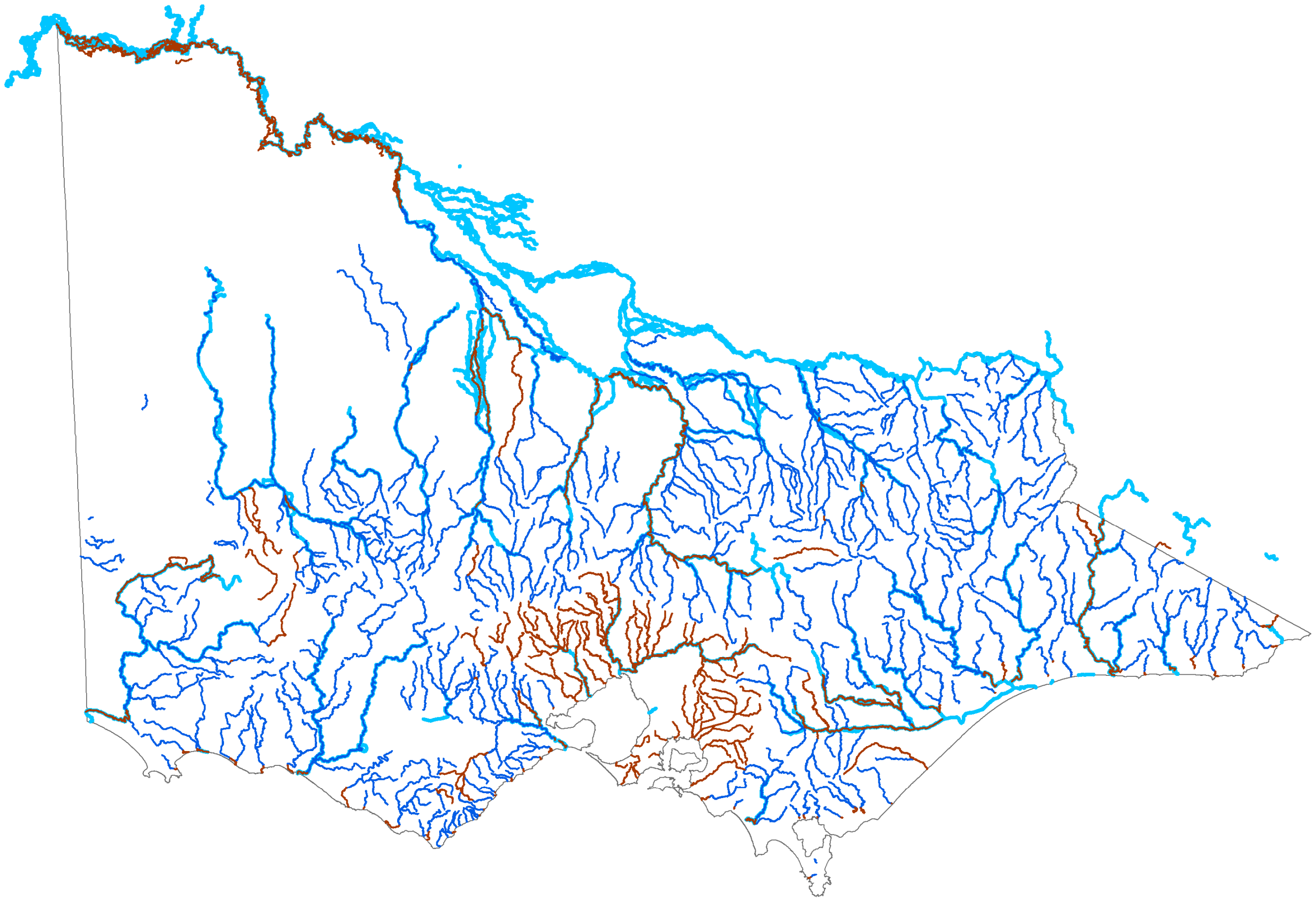


Figure A1. Stream networks represented in the Index of Stream Condition inventory of flow stress rankings showing river segments with a high flow index of >6 in blue and ≤ 6 in red. Fourth order streams (Strahler classification) represented on the NCSED database are shown in light blue beneath other stream layers to illustrate the spatial coverage of ISC stream data.

Table A4 List of 4th order river reaches with reduced high flows as assessed by the Index of Stream Condition (ISC) high flow index. The high flow index in the ISC reflects the extent to which high flows have been reduced compared to a reference. Values vary from 10, indicating pristine conditions, to 0, indicating completely altered conditions. River reaches reported in this table received a high flow index score of ≤ 6. Where high flow indices were reported for multiple segments of the same river, the range of high flow indices are provided. Stream order was based on the Strahler stream classification and assigned using the NCESD database.

River	High flow index	River	High flow index
Avon River	0	Mullaroo Creek	0
Barwon River	0	Murray River	0
Bemm River	0	Narcooyia Creek	0
Bonyaricall Creek	0	O'Shannassy River	0
Bridge Creek	0	Parwan Creek	0
Brodribb River	0	Perry River	0
Buffalo River	0	Plenty River	0
Bumbang Creek	0	Potterwalkagee Creek	0
Burnt Creek	4	Pyramid Creek	4
Burra Creek	0	Rainbow Creek	1
Campaspe River	5-6	Ranka Creek	0
Chalka Creek	0	Reedy Creek	0
Deep Creek	0	Serpentine Creek	5
Emu Creek	0	Sheepwash Creek	4
Finnigans Creek	0	Snowy River	0-2
Fitzroy River	0	Suggan Buggan River	1
Genoa River	0	Tambo River	0
Glenelg River	0-6	Tanjil River	0-6
Goulburn River	0-6	Tarwin River	0
Hopkins River	0	Thompson Creek	0
Jacksons Creek	0	Thomson River	0-2
Latrobe River	0-6	Toupnein Creek	0
Lindsay River	0	Towrie and Outlet Creek	0
Loddon River	0-5	Tyers River	3
Macalister River	6	Unnamed Creek	0
Mackenzie River	1	Wallpolla Creek	0
Maribyrnong River	0	Werribee River	0
Merri Creek	0	Willipanance Creek	0
Milky Creek	0	Yarra River	0
Mitchell River	0	Yarrarabula Creek	0
Moorabool River	5		

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