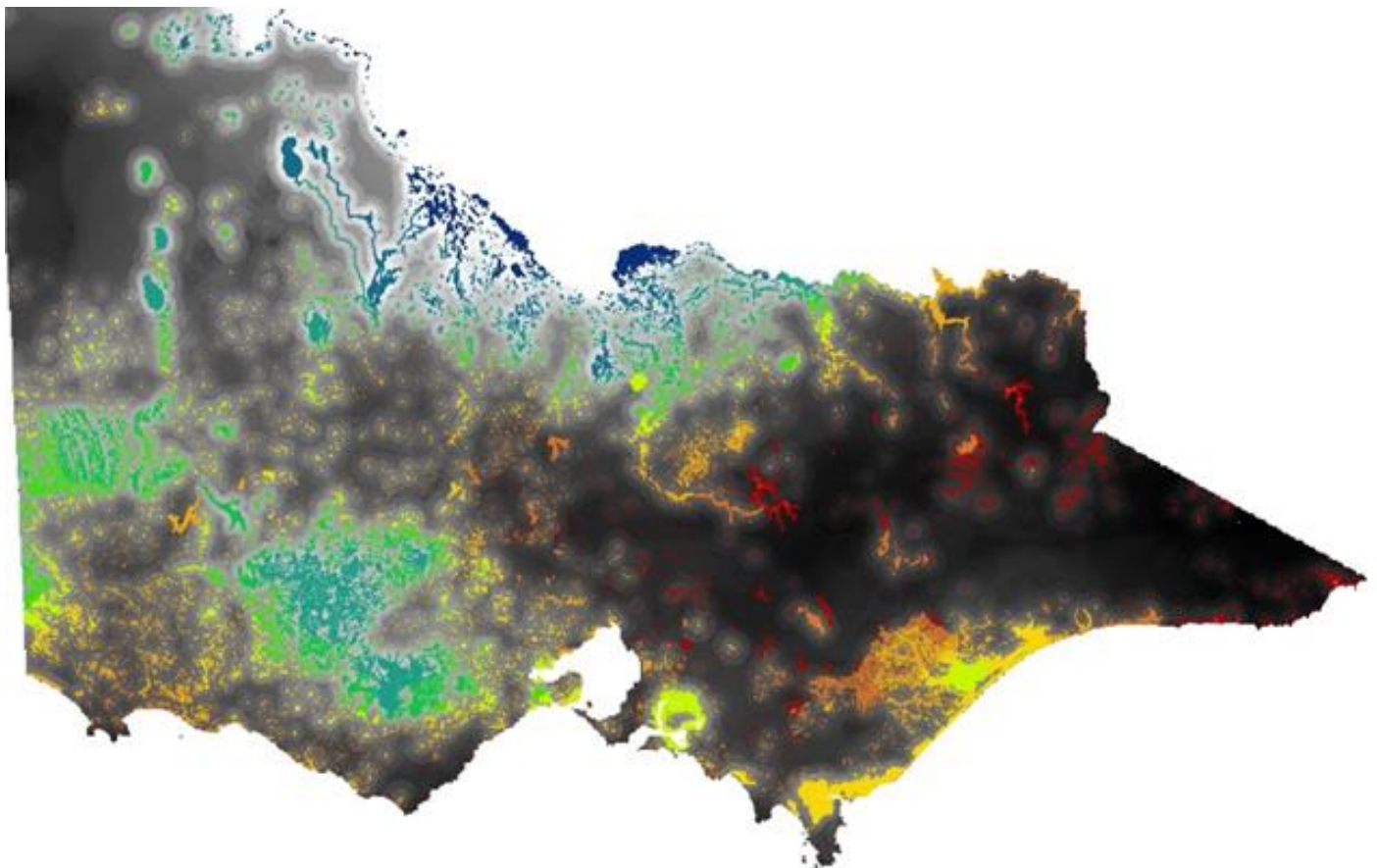


Wetland Connectivity Spatial Data: User's Guide. Version 1

July 2015

Arthur Rylah Institute for Environmental Research

Client Report for the Water and Catchments Group, Department of Environment, Land, Water and Planning



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July 2015

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Citation: DELWP (2015). Wetland connectivity spatial data: user's guide. Version 1. Arthur Rylah Institute for Environmental Research Client Report for the Water and Catchments Group, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

ISBN 978-1-74146-823-6 (pdf)

Front cover image: Patterns of Waterbird Connectivity

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Acknowledgements

This work was commissioned by the Water and Catchment Group, Department of Environment, Land, Water and Planning (DELWP). Wetland connectivity modelling approaches were developed by Dr Kay Morris (Arthur Rylah Institute for Environmental Research (ARI), DELWP) and Fiona Ferwerda (Environment and Landscape Performance Division, DELWP); modelling products were produced by Adrian Kitchingman (ARI, DELWP). Assoc. Prof. Merel Soons (Utrecht University, Netherlands) provided valuable assistance in developing approaches to represent patterns of seed dispersal by wind. Guidance on the application of connectivity to wetland management was developed by Dr Kay Morris (ARI) and Dr Elisa Raulings (Greening Australia). Janet Holmes, Dr Andrea White (WCG, DELWP) and Phil Papas (ARI, DELWP) provided valuable comments on draft versions of the guide.

1 Wetland connectivity models

1.1 What is connectivity?

Connectivity represents the ability of plants and animals to move between habitat patches in the landscape. A distinction can be made between structural and biological connectivity. Structural connectivity often infers connectivity from the geographical arrangement of habitats in the landscape. In contrast, biological connectivity also considers how a species' mobility and responses to the landscape may influence patterns of movement between habitats.

Connectivity is an important consideration in the management of wetlands as it:

- Provides opportunities for both native and introduced species to expand their range and migrate in response to local and regional changes in habitat conditions,
- Facilitates recolonisation following local extinction events, and
- Promotes gene flow among populations, which prevents populations becoming reproductively isolated, thus increasing genetic diversity.

Understanding landscape-scale patterns of biological connectivity requires knowledge of:

- The geographical arrangement of suitable habitats in the landscape,
- How a species' mobility and responses to features of the landscape influence movement between habitats, and
- Spatial representation of the landscape features that influence species' movements.

1.1.1 Application of connectivity to wetland management

An understanding of biological connectivity has important applications to the management of wetlands. It can help to guide the spatial prioritisation of on-ground activities that aim to protect high-value wetlands, restore degraded wetlands, and protect wetlands from the spread of weeds and/or pathogens. It may also be useful in deciding where best to locate new wetlands (i.e. artificial wetlands) so that they will be colonised by plants and animal from other wetlands. The significance of connectivity to wetland management is discussed in more detail below.

Connectivity and high-quality sites

The values and resilience of high-quality wetlands may depend on biological connections to other wetland habitats that can facilitate the exchange of plants and animals. Adequately protecting high-value sites may therefore also require the protection or enhancement of the wetlands with which they are closely linked and the pathways that facilitate movement between them.

Wetland restoration

An understanding of biological connectivity can be used to guide the selection of wetlands for restoration actions. Where sites selected for these activities are biologically connected to other wetlands, there is a greater likelihood that natural recolonisation of plants and animals will occur, once threatening processes are managed. Undertaking management interventions in highly connected wetlands will have greater flow-on benefits to connected wetlands, compared with undertaking interventions in wetlands that are less connected.

An understanding of connectivity can also be used to identify where the ability of plants and animals to move through the landscape to reach other wetlands has been restricted. Movement may be restricted by the following:

- Wetland loss, which increases the distances between wetlands, and may exceed the maximum distance that wetland species can move; and
- Changes to the landscape between wetlands, which can reduce the ability of some organisms to reach other wetlands; it could include:
 - Loss of wet areas (e.g. land drainage);
 - Altered land use (e.g. urbanisation); or
 - Increased salinisation.

This knowledge may help managers to target interventions to restore connectivity, such as protecting drainage lines through which amphibians may move between wetlands.

Protecting wetlands from the spread of weeds and/or pathogens

Although connectivity can play an important role in maintaining the resilience of wetland systems, connectivity also provides opportunities for the spread of invasive species and pathogens such as Chytrid fungus. Identifying wetlands that represent potential sources of weeds and pathogens, along with an understanding of patterns of connectivity relevant to the target weed species and/or pathogens can help to target surveillance and to identify interventions for preventing their spread.

Wetlands that have low connectivity may be less vulnerable to weed invasion or diseases such as Chytrid fungus and may provide important remnant habitats. As such, protecting and/or restoring these isolated wetlands and maintaining their isolation would be a management priority.

2 DELWP wetland connectivity data layers

DELWP has developed statewide spatial layers that represent modelled patterns of wetland connectivity for waterbirds, amphibians and wind-dispersed plant seed. Although hydrological connectivity is of particular significance to maintaining biological connections between wetlands, the limitations of current statewide datasets, and the highly managed nature of water delivery to many wetlands present significant challenges to modelling hydrological connectivity at a statewide scale. Due to these limitations, work on hydrological connectivity has been limited to identifying floodplain wetlands that are likely to experience reduced connectivity with their source rivers (see Morris et al. 2012). The Index of Wetland Condition hydrology subindex also provides some guidance on evaluating whether or not the hydrological connectivity of individual wetlands has been altered (DEPI 2013).

2.1 Application of connectivity to wetland management

It is intended that the connectivity model outputs provided in the spatial data layers described here are used to better target management interventions to wetlands. Applying the connectivity spatial data layers to the management of wetlands requires an understanding of the methods, assumptions and limitations of each of the models underlying the spatial data layers.

Waterbirds and amphibian models have been developed under a wet scenario, in which all wetlands are assumed to be full and terrestrial areas that are prone to waterlogging or inundation are assumed to be wet. The models may, however, be re-run to assess patterns of connectivity under different scenarios, such as drier conditions, or if wetlands become saline. The models could also be re-run if more detailed information becomes available on habitat suitability or landscape features (i.e. drainage channels) that are expected to influence the movement of wetland biota. It may also be possible to tailor the models to provide species-specific models.

The following section describes the key principles of each model and some examples of how the layers derived from the models may be applied in a management context.

3 Waterbird connectivity

Waterbirds are a diverse group of species that utilise wetland habitats. They include waterfowl (e.g. ducks, swans and geese), herons, ibises, spoonbills, rails and coots. Also included are birds associated with estuarine and marine habitats that frequent inland wetlands, including Australian pelicans, darters, cormorants and shorebirds (also known as waders) (Morris 2012).

3.1 Model development

Landscape patterns of wetland connectivity for waterbirds as a group were assessed within a GIS framework using neighbourhood analysis and inverse weighted distance analysis. This approach requires spatial information on suitable waterbird habitat and estimates of dispersal distances as described below. The spatial dataset used to inform model variables is detailed in Appendix A.

3.1.1 Habitat

Waterbirds are characterised by their frequent utilisation of diverse habitats, including wetlands, rivers, estuaries and mudflats to moult, roost, breed and forage (Haig et al. 1998, Kingsford and Norman 2002). As such, all natural wetlands were treated as potential waterbird habitat.

Although the habitat value of human-made wetlands (e.g. Western Treatment Plant, Werribee, Victoria) may often be lower than that of natural wetlands, they can provide important waterbird habitat, particularly when they support aquatic vegetation (Froneman et al. 2001). Moreover, some waterbirds such as Maned Duck (*Chenonetta jubata*, also called Wood Duck) have been reported to breed in dams (Kingsford 1992). As the habitat value of human-made wetlands for waterbirds is uncertain, two models were developed with different assumptions about their habitat value, as described in Table 1.

Table 1. Waterbird connectivity: model scenarios, model outputs and filenames.

Modelled scenarios	Model output type	File name (field)
Only naturally occurring wetlands are treated as habitat	Connectivity surface	wetbird_out_hnodam_pnodam.gdb
	Wetland connectivity score*	wetland2014_connectivity.shp field: bird_nodam
Both naturally occurring wetlands and human-made wetlands are treated as habitat	Connectivity surface	wetbird_out_hdam_pnodam.gdb
	Wetland connectivity score*	wetland2014_connectivity.shp field: bird_dam

*located in attribute table of output shape file: Wetland2014_connectivity.shp

Naturally occurring wetlands

The entire surface of all naturally occurring Victorian wetlands identified in the Wetland inventory spatial layer (WETLAND_CURRENT, DELWP 2015) was treated as waterbird habitat. Due to the large distances waterbirds are capable of moving, wetlands in bordering jurisdictions will exert some influence on patterns of connectivity. To address this, wetlands within 300 km of the Victorian

border were identified from wetland inventories from New South Wales, South Australia and Tasmania, and their entire surface was treated as habitat.

Human-made wetlands

Human-made wetlands were delineated by merging all categories of human-made wetlands in the wetland inventory with those included in the FARM_DAM_BOUNDARIES spatial layer (DEWLP 2015). The entire surface of human-made wetlands of ≤ 8 ha were treated as habitat, but only the perimeter (25 m) of human-made wetlands >8 ha was treated as habitat. This was done because it is unlikely that the entire surface of these large and deep impoundments represent waterbird habitat.

3.1.2 Dispersal distances

Waterbirds vary considerably in the scale and frequency of movement between habitat patches. For example, bird-banding studies by Norman (1971) and Frith (1959) found that 30% of banded Grey Teal (*Anas gracilis*) were recovered at sites >300 km from the banding location, but only 10% of banded Australian Wood Duck (*Chenonetta jubata*) and Pacific Black Duck (*Anas superciliosa*) were recovered farther than 300 km from the banding sites.

Patterns of waterbird movement also indicate potential patterns of dispersal of plant and invertebrate propagules (Figuerola and Green 2002, Raulings et al. 2011). Waterbirds carry seed and vegetative fragments of plants and resting egg stages of invertebrates externally when they attach to their feathers, feet and bill, and internally when they are ingested and survive gut passage. The distance propagules are carried by waterbirds will vary depending on whether they are carried internally or externally. The distances propagules are dispersed when they are carried internally will vary with 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 to 100s of kilometres (Raulings et al. 2011).

To reflect different scales of movement, as well as the dispersal of plants and invertebrate propagules, waterbird connectivity was modelled using a range of potential distances, including: 5 km, 10 km, 50 km, 100 km and 300 km.

3.2 Spatial analysis

The spatial datasets for each of the two model scenarios (i.e. (i) natural wetlands and (ii) natural wetlands plus human-made wetlands) were converted to raster data, i.e. cells or pixels (25 m x 25 m), and analysed separately.

Patterns of landscape connectivity for amphibians were modelled within a GIS framework using two analytical approaches: (i) Neighbourhood analysis and (ii) Inverse weighted distance analysis, as described below. The outputs of these two approaches were combined to produce the connectivity surface. This is considered to be a more representative view of connectivity.

3.2.1 Neighbourhood analysis

For each cell, the mean habitat value of all cells within a specified radius (i.e. neighbourhood) was calculated. This gave the relative amount of wetland habitat in the neighbourhood of each cell anywhere in the landscape. Five neighbourhood scenarios were run based on the range of potential dispersal distances (5, 10, 50, 100, 300 km, described in section 3.1.2) and combined into a single surface.

3.2.2 Inverse weighted distance score

A single inverse weighted distance analysis was performed. This analysis assigned a score to each cell in the landscape, based on its distance to habitat. The results of the analysis were limited to 300 km from any habitat.

3.2.3 Connectivity surface

The geometric mean of the neighbourhood score and the inverse weighted distance score was calculated and recalibrated to produce connectivity values between 1 and 100, presented as a raster file at 100-m resolution (i.e. cell size 100 m x 100 m).

3.3 Model outputs

Two types of model outputs are provided to inform potential landscape-scale patterns of waterbird connectivity and are described below.

3.3.1 Waterbird connectivity surface

A waterbird connectivity surface is provided for each of the two modelled scenarios (Table 1). The waterbird connectivity surface gives the model predictions as raster data (25 m x 25 m grid). Each cell of the grid has been assigned a value that reflects the proximity and availability of wetland habitat within the range of distances that waterbirds may move.

Connectivity surfaces are also available for each of the distances used in generating the overall waterbird connectivity surface. Patterns of connectivity for each of these distances (5, 10, 50, 100, 300 km) could be used to evaluate wetlands connectivity for a specific waterbird species, provided its mobility corresponds with one of the distances examined in the modelling.

3.3.2 Wetland waterbird connectivity scores

The wetland connectivity score uses the connectivity surface to calculate the mean connectivity value of all cells (25 m x 25 m) that make up each wetland polygon. Connectivity scores have been assigned to all naturally occurring wetlands in the WETLAND_CURRENT spatial layer for each of the two modelled scenarios, as detailed in Table 1.

3.4 Model assumptions

The following assumptions were made when developing the connectivity model for waterbirds, and need to be considered in interpreting model outputs:

- Wetlands in Victoria, New South Wales, South Australia and Tasmania are accurately mapped.
- All wetlands are fully inundated.
- The range of potential dispersal distances used in the model are representative of the spectrum of dispersal distances for waterbirds as a group.
- All naturally occurring wetlands are suitable habitat for waterbirds.
- The attribution of wetlands as naturally occurring and human-made is correct.
- The movement patterns of waterbirds are not influenced by behavioural preferences toward any particular landscape feature other than the amount and proximity of water bodies.

3.5 Application

Two versions of the waterbird connectivity surface and wetland connectivity scores are available based on different assumptions regarding the utility of human-made wetland for waterbirds (Table 1). In selecting which surface is more appropriate for informing management, the value of human-made wetlands in the region should be evaluated. It may also be helpful to compare the connectivity outputs between the two versions in order to understand the potential differences in connectivity values based on differing assumptions about the value of human-made wetlands for waterbirds. It is

likely that the connectivity outputs for naturally occurring wetlands may underrepresent levels of connectivity, while the inclusion of human-made wetlands may over represent levels of connectivity.

The distance waterbirds may move among suitable habitat varies for different waterbird species. Spatial data layers representing waterbird connectivity are also available for each of the distances used in generating the overall waterbird connectivity layer (5, 10, 50, 100 and 300 km). Patterns of connectivity for a particular waterbird species can be evaluated using the distance model that best corresponds to the movement characteristics of the species of interest.

The waterbird connectivity layer will help to identify areas in the landscape where the amount and proximity of habitat is greatest for waterbirds as a group. At sites with high connectivity scores, waterbirds have the greatest amount of habitat in relatively close proximity.

When considering degraded sites, those that are highly connected may be prioritised for management intervention over sites that are less well connected. This approach is based on the assumption that in highly connected sites, waterbirds are likely to have access to a greater range of wetland resources, and this can enhance waterbird diversity and breeding success (Browne and Dinsmore 1986, Smith 1995).

For species that need to provide food to flightless juveniles, breeding sites that are highly connected to wetlands that provide food resources will reduce the energy expended in foraging and in turn lead to higher fledging survival (Smith 1995). This suggests that highly connected wetlands that also have features required for breeding and/or feeding, or where these features could be restored, should be a high priority for protection and/or restoration.

Waterbirds carry plant and invertebrate propagules when they attach to their feathers, feet and bill, and when they are ingested and survive gut passage. Wetlands with high waterbird connectivity are therefore also likely to receive a higher influx of plant and invertebrate propagules through bird visitation, compared with wetlands with low connectivity. The arrival of propagules through waterbird movements can assist with natural recolonisation of wetland species following disturbance events, but may also contribute to the spread of invasive species.

4 Amphibian connectivity

Amphibian connectivity models have been developed to represent patterns of landscape connectivity for pond breeding amphibians that are generalist in their habitat use and are likely to occupy most wetland types. This represents approximately 62% of the 37 amphibian species that occur in Victoria (Table 2). Patterns of landscape connectivity for stream-dwelling species, species with specific habitat requirements or land-breeding species are not represented in the current models.

Table 2. List of Victorian amphibian species that the connectivity models apply to, conservation listing in Victoria (CL), and mobility rating. These amphibian species include those that utilise most wetland types, and do not have specialist habitat requirements and/or specialised breeding biology (adapted from Morris 2012).

Species name	Common name	CL	Altitudinal range (m)	Mobility rating Low <0.5 km; Medium < 1 km; High > 1 km
<i>Litoria aurea</i>	Green and Golden Bell Frog	Vu	10–720	High
<i>Litoria dentata</i>	Bleating Tree Frog			Unknown
<i>Litoria ewingii</i>	Southern Brown Tree Frog		10–1510	Unknown
<i>Litoria littlejohni</i>	Large Brown Tree Frog	DD, FFG	110–1160	Medium
<i>Litoria paraewingii</i>	Plains Brown Tree Frog		20–1730	Medium
<i>Litoria peronii</i>	Peron's Tree Frog		10–1030	Unknown
<i>Litoria raniformis</i>	Growling Grass Frog	E, FFG	10–1140	High
<i>Litoria verreauxii verreauxii</i>	Verreaux's Tree Frog		10–980	Unknown
<i>Crinia parinsignifera</i>	Plains Froglet		20–850	Unknown
<i>Crinia signifera</i>	Common Froglet		10–1950	Unknown
<i>Crinia sloanei</i>	Sloane's Froglet		80–210	Unknown
<i>Limnodynastes dumerilii</i>	Pobblebonk Frog		10–1700 ^a	Medium
<i>Limnodynastes fletcheri</i>	Barking Marsh Frog		20–300	Unknown
<i>Limnodynastes interioris</i>	Giant Bullfrog	CE, FFG	80–400	Medium
<i>Limnodynastes peronii</i>	Striped Marsh Frog		10–1180	Unknown
<i>Limnodynastes tasmaniensis</i>	Spotted Marsh Frog		10–1150	Unknown
<i>Neobatrachus pictus</i>	Mallee Spadefoot Toad		30–370	Unknown
<i>Neobatrachus sudelli</i>	Common Spadefoot Toad		10–440	Unknown
<i>Paracrinia haswelli</i>	Haswell's Froglet		10–910	Unknown
<i>Uperoleia laevigata</i>	Smooth Toadlet	DD	190–950	Unknown
<i>Uperoleia martini</i>	Martin's Toadlet ^b	DD	20–210	Unknown
<i>Uperoleia rugosa</i>	Rugose Toadlet	Vu, FFG	100–200	Unknown
<i>Uperoleia tyleri</i>	Tyler's Toadlet ^b	DD	20–210	Unknown

The genus *Litoria* belongs to the family Hylidae; all the other genera belong to the family Myobatrachidae. 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 *Flora and Fauna Guarantee Act 1988*. Mobility ratings are based on expert opinion. ^aElevation data may encompass multiple subspecies. ^bTyler's Toadlet and Martin's Toadlet may be the same species (taxonomy unresolved). Sources: Robinson (1998); M. Scroggie, N. Clemann and S. Saddler, ARI, pers. comm.

4.1 Model development

Patterns of landscape connectivity for amphibians were modelled using multi-neighbourhood and a single 5-km inverse weighted 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). The variables included in the amphibian connectivity model are described below. The spatial dataset used to inform model variables is detailed in Appendix A.

4.1.1 Habitat

All naturally occurring freshwater wetlands (salinity $<3000 \text{ mg L}^{-1}$) were treated as amphibian habitat. However, the habitat value of wetlands for amphibians is strongly influenced by the cover of aquatic vegetation (Hazell et al. 2001, Hazell et al. 2004, Clemann et al. 2013). Although the habitat value of human-made wetlands may often be lower than that of natural wetlands (Hazell et al. 2004), there may be cases where these wetlands provide important amphibian habitat, particularly when aquatic vegetation is present. Due to the level of uncertainty regarding the suitability of human-made wetlands as amphibian habitat, two models were developed with different assumptions about their habitat value (Table 3).

Table 3. Amphibian connectivity: model scenarios, model outputs and filenames.

Modelled scenario	Model outputs	File name
Only naturally occurring freshwater wetlands are treated as habitat	Connectivity surface	amphib_out_hnodam_pnodam.gdb
	Wetland connectivity score*	wetland2014_connectivity.shp field: amph_nodam
Both naturally occurring freshwater wetlands and human-made freshwater wetlands are treated as habitat	Connectivity surface	amphib_out_hdam_pnodam.gdb
	Wetland connectivity score*	wetland2014_connectivity.shp field: amph_dam

*located in the attribute table of output shape file: wetland2014_connectivity.shp

Freshwater natural wetlands ($< 3000 \text{ mg L}^{-1}$) were delineated from the WETLAND_CURRENT spatial layer. Saline wetlands are not considered habitat because the probability of amphibian occupancy is likely to be low (Morris et al. 2012).

Human-made wetlands were delineated by merging all categories of human-made wetlands in the WETLAND_CURRENT spatial layer (DELWP 2013) with those in the FARM_DAM_BOUNDARIES spatial layer (DELWP 2015). Human-made wetlands that were identified as being saline (e.g. salt-treatment works) were not treated as habitat.

In both models, amphibian habitat was constrained to a 25-m band (based on grid cell size) along the mapped boundary of natural wetlands. The remaining internal area was treated as a highly permeable surface. This was done to avoid over representing the availability of habitat for amphibians, particularly for large deep wetlands, of which most of the wetland area is not used. However, it is likely that habitat availability will be underestimated in large shallow, well-vegetated wetlands, where much of the wetland area may provide suitable habitat.

4.1.2 Permeability

The influence of different land-cover types on amphibian movement is not well established. At present we can only infer that urban development, sealed roads, rail networks and saline areas represent significant impediments to movement, whereas wet areas of the landscape (including stream networks) are highly conducive to movement.

Areas identified as frog habitat were assigned the highest permeability score (10), whereas sealed roads, rail networks and saline wetlands were assigned the lowest permeability score (1). All other areas were assigned a permeability score based on landscape wetness, which was estimated from a tolerance to inundation layer (ARI, DELWP 2014). This layer attributes a score to the landscape based on the probability of it supporting vegetation that is tolerant to inundation, and it provides a measure of landscape wetness.

4.1.3 Distance

The mobility of amphibians is highly variable. Some species are very sedentary and move <0.5 km, whereas other species disperse several to many kilometres. Dispersal ranges of Victorian amphibians have been classified by experts as: low (dispersal distance <0.5 km), medium (dispersal distance between 0.5 km and 1 km), high (able to disperse at least 1 km) or unknown (Morris 2012). The upper dispersal distance was considered to be 3 km. Greater dispersal distances may be achieved when dispersal occurs in a 'stepping-stone' fashion over generations (e.g. when each successive generation disperses).

To accommodate the variation in dispersal distances for amphibians as a group, connectivity was modelled using a range of distances: 200 m, 300 m, 500 m, 700 m, 1 km, 2 km and 3 km.

4.2 Spatial analysis

The permeability and habitat datasets for each of the two model scenarios—(i) natural wetlands and (ii) natural wetlands plus human-made wetlands—were converted to raster data, i.e. cells or pixels (25 m x 25 m), and analysed separately.

Patterns of landscape connectivity for amphibians were modelled using two analytical approaches—(i) Neighbourhood analysis and (ii) Inverse weighted distance analysis within a GIS framework, as described below. The outputs of these two approaches were combined to produce the connectivity surface. This is considered to be a more representative view of connectivity.

4.2.1 Neighbourhood analysis

For each cell, the mean value of all cells within a specified neighbourhood was calculated. This gave the relative amount of wetland habitat and the degree of permeability in the neighbourhood of each cell. Seven neighbourhood scenarios were run, based on the range of dispersal distances identified for the group (i.e. 200 m, 300 m, 500 m, 700 m, 1 km, 2 km and 3 km). The outputs of the neighbourhood analysis are available for each of the seven distances but were combined into a single surface to produce the amphibian connectivity surface.

4.2.2 Inverse weighted distance analysis

A single inverse weighted distance analysis was performed that assessed the distance of a particular cell in the landscape to wetland habitat, assigned it a score, and then adjusted the score based on the cost of moving through the intervening landscape (i.e. landscape resistance) (Ferwerda 2003). The landscape resistance was calculated as the inverse of the landscape permeability.

4.2.3 Connectivity surface

The geometric mean of the neighbourhood score and the inverse weighted distance score was calculated and recalibrated to produce connectivity values between 1 and 100, presented as a raster file at 100-m resolution (i.e. cell size 100 m x 100 m).

4.3 Model outputs

Two model outputs have been provided to inform an assessment of landscape-scale patterns of amphibian connectivity and are described below and summarised in Table 3.

4.3.1 Amphibian connectivity surface

A connectivity surface is provided for each of the two scenarios (Table 3). The connectivity surface gives the model predictions as a raster layer (25 m x 25 m grid). Each cell of the grid has been assigned a value reflecting the proximity and accessibility of wetlands for amphibians. Higher connectivity values indicate that amphibians have access to a greater amount of wetland habitat that is within reach and/or is connected by a highly permeable landscape. In contrast, wetlands with low connectivity values are more isolated from other wetlands because the amount of wetland habitat within the dispersal distance of amphibians is low and/or because the intervening landscape is difficult for amphibians to move through.

4.3.2 Amphibian connectivity scores

For the two connectivity surfaces described above, all naturally occurring wetlands within Victoria have been attributed an average amphibian connectivity score. This score represents the average connectivity value of all the cells within the wetland.

4.4 Model assumptions and caveats

The following assumptions and caveats are associated with the amphibian connectivity models and should be considered when using the modelling products.

4.4.1 Assumptions

- Wetlands in Victoria are accurately mapped.
- Only fresh wetlands are suitable amphibian habitat (maximum salinity when full <3000 mg L⁻¹).
- Attribution of fresh and saline wetlands in the wetland inventory (WETLAND_CURRENT) is accurate.
- Wetlands are fully inundated, and terrestrial areas of the landscape that are subject to inundation are wet and therefore permeable.
- Models of vegetation tolerance to inundation accurately represent landscape wetness.
- In models that include human-made wetlands, that all of these wetlands (excluding those identified as saline) are suitable amphibian habitat.

4.4.2 Limitations

- The connectivity models only apply to pond-breeding generalist species that are able to occupy most wetland types.
- Some amphibians may have higher or lower salinity tolerances than assumed in the model.
- All fresh, naturally occurring wetlands are considered to be suitable amphibian habitat. However, habitat value will vary depending on many factors, including: the cover of aquatic

vegetation, water quality, the presence of predatory fish and the presence of Chytrid fungus. This also applies to human-made wetland in models where they are treated as habitat.

- Terrestrial areas that are subject to periodic inundation have been identified using models of vegetation tolerance to inundation and may not accurately represent landscape wetness in all parts of the landscape.
- Some amphibian species are able to breed in small, temporary pools of water. As such, areas of high permeability may also represent breeding areas for some species.
- The models do not consider the influence of artificial drainage channels on the permeability of the landscape.

4.5 Application

Two versions of the amphibian connectivity surface and two sets of wetland connectivity scores are available based on different assumptions regarding the utility of human-made wetlands for amphibians (Table 3).

In selecting which version is more appropriate for informing management, the value of human-made wetlands for amphibians in the region should be evaluated. It may also be helpful to compare the connectivity outputs between the two versions to understand the potential significance of human-made wetlands for connectivity when they do provide suitable habitat.

The amphibian connectivity surface identifies areas in the landscape where the amount, proximity and/or accessibility of suitable wetlands are greatest for pond-breeding generalist amphibians. Higher connectivity scores indicate that amphibians in these areas have access to a greater amount of suitable wetland habitat that is within reach and/or is connected by a highly permeable landscape. In contrast, wetlands with low connectivity are more isolated from other wetlands because the amount of suitable wetland habitat within the dispersal distance of amphibians is low and/or because the intervening landscape is difficult for amphibians to move through.

Highly connected wetlands that have become degraded may be considered a higher priority for restoration than wetlands that have low connectivity. This is because in highly connected wetlands, amphibians are able to access a greater range of resources and are able to leave and recolonise the wetland as local conditions change.

The amphibian connectivity surface can also be used to identify areas of the landscape that have high and low permeability for amphibian movement. Areas of high permeability may provide important links between wetlands and represent high priority areas for terrestrial habitat protection. Areas that have low permeability could be managed to improve permeability, once the reasons for low permeability have been identified. For example, where low permeability occurs due to water diversion by drainage, natural drainage patterns could be reinstated.

5 Wind-dispersed plant seeds

Plant seeds and vegetation fragments (collectively known as propagules) can disperse by water, wind or animal vectors. Wind is an important dispersal pathway for wetland plants because it 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 those species that occur in 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), indicating the potential significance of wind dispersal.

Plants can be grouped into three broad wind-dispersal categories based on seed terminal velocities, i.e. their falling speed (m s^{-1}) in still air once a constant speed has been reached (Soons 2006). The first group considered here are seeds that fall very slowly, with terminal velocities of below 0.3 m s^{-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). The second dispersal category contains plants with terminal velocities of $0.3\text{--}2 \text{ m s}^{-1}$. 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 10s 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 $>2 \text{ m s}^{-1}$. These plants are not adapted for wind dispersal, and seed is commonly deposited close to the parent plant.

Developing connectivity models of wind-dispersed plants requires an understanding of the relationship between wind speed and seed dispersal distance, as well as the frequency, speed and direction of wind across the landscape. Relationships between wind strength and dispersal distances have been described for several species with terminal velocities near 0.3 m s^{-1} (Table 4, M.B. Soons, *pers. comm.*). Predicting dispersal distances based on these relationships provides a conservative estimate of the dispersal distances of seeds with terminal velocities $<0.3 \text{ m s}^{-1}$, which are likely to disperse considerably further.

Table 4. Relationships between wind strength and dispersal distance for seeds with terminal velocities of $\sim 0.3 \text{ m s}^{-1}$. (M.B. Soons, *pers. comm.*)

m s^{-1}	km h^{-1}	Beaufort scale	Dispersal distance
0–10	0–36	calm to moderate winds	metres to 10s of metres
10–15	36–54	Fresh to strong breeze	100s metres up to 1 km
15–20	54–72	high wind to gale	between 1 km and 2 km
>20	>72–90	strong gale to violent storm	a few to several km

The data used in developing maps of potential seed dispersal by wind was generated by CSIRO using a global atmospheric model, the Conformal Cubic Atmosphere Model (CCAM). The CCAM model uses global atmospheric data collected by the European Centre for Medium Range Weather Forecasts at a 150-km resolution to interpolate wind data at a 30-km resolution every 30 min between 1980 and 2012. This results in approximately 142,560 wind observations per season (i.e. 48 times per day x 90 days per season x 33 years).

The model outputs are represented in a series of wind frequency surfaces that represent the percentage of total observations per season (approximately 142, 560) for each wind speed and wind direction category, which can be related to the maximum potential dispersal distance of wind-dispersed seeds.

GIS spatial layers and wind maps have been produced that display each of the 16 wind speed x direction surfaces for each season (Table 5).

Table 5. GIS layers and wind maps

Season	GIS data file	Maps
Spring	Wind_Map_Template4X4_Spring_2015.mxd	Wind_Map_Spring_2015.png
Summer	Wind_Map_Template4X4_Summer_2015.mxd	Wind_Map_Summer_2015.png
Autumn	Wind_Map_Template4X4_Autumn_2015.mxd	Wind_Map_Autumn_2015.png
Winter	Wind_Map_Template4X4_Winter_2015.mxd	Wind_Map_Winter_2015.png

5.1 Assumption and caveats

- The wind data provided can only be used to inform the potential dispersal of seeds that have adaptations for wind dispersal. The data is most relevant to seeds with a falling velocity of between 0.3 and 2 m s⁻¹. The wind data may also inform the dispersal patterns of seeds with terminal velocities that are <0.3 m s⁻¹, but it should be recognised that seeds in this category will also be dispersed by convective uplift, which may deliver seeds over long distances and in different directions to those of turbulent winds.
- Dispersal distances predicted from each wind-speed category are considered to be the maximum distances. The number of seeds reaching the predicted dispersal distance is governed by the number of seeds available for dispersal. Where source populations are too small or seed production is low, seeds may not reach the maximal dispersal distances.
- The models do not consider whether barriers such as hills or forests constrain seed movement from one location in the landscape to another.

5.2 Application

An understanding of how wetlands are connected through the dispersal of plant seeds can help assess whether species that are locally extinct may recolonise through the dispersal of propagules from adjacent sites. It may also help to identify the potential spread of invasive plants from known source populations.

The following steps provide assistance in using the wind-dispersal maps to assess the distance, direction and relative likelihood of seed dispersal by wind to a site:

Step 1. Consider whether the species of interest has/have seeds that are wind dispersed.

Step 2. Identify the season(s) seeds are likely to be released, noting that the period of seed release may vary in different regions of the state.

Step 3. Select the seed wind-dispersal map that matches the season(s) of seed release.

Step 4. Examine the region of interest to identify:

- The maximum distance seed may disperse and the frequency of the events.
- If dispersal is more frequent in any particular direction.

An example of how the maps may be used to understand potential patterns of wind dispersal is provided below.

5.2.1 Example of application

The risk of an invasive species, dispersed by wind in spring and spreading from a source population in a region to the west of Geelong (as shown by the green circle in Figure. 1) can be evaluated by examining the spring wind maps.

The spring maps reveal the following information about potential patterns of dispersal of the invasive species in this area.

- Westerly winds of $0.5\text{--}10\text{ m s}^{-1}$ are most frequent, but winds at this wind speed are common from all directions. This indicates that wind-dispersed seeds are most likely to be dispersed very short distances (i.e. 10s of metres) in an easterly ($\pm 45^\circ$) direction, but dispersal in all directions over these short distances could occur.
- At wind speeds of $10\text{--}15\text{ m s}^{-1}$, wind arrives most frequently from the north and west. This indicates that wind-dispersed seeds will be carried from a source population several 100s of metres up to a maximum of 1 km in a southerly ($\pm 45^\circ$) and easterly ($\pm 45^\circ$) direction more often than in any other direction. The abundance of seeds available for dispersal will determine whether any seeds reach the maximum dispersal distance; most seed will disperse only 100s of metres.

Wind speeds $>15\text{ m s}^{-1}$ only arrive from the north and with very low frequency. This indicates that there is a very low likelihood that seeds will disperse more than 1 km in a south $\pm 45^\circ$ direction and that no dispersal over this distance is expected in any other direction.

In this example, understanding potential patterns of seed dispersal can help target weed surveillance and weed control activities.

Weed surveillance

- Wetlands that are 10s of metres from the source population have the greatest likelihood of invasion, particularly those to the east of the source population.
- Wetlands within 1 km south or east of the source population may be vulnerable to invasion. Surveillance should target suitable habitat within 1 km to the south and east of the source populations.

Weed management

- Weed management should first treat infestations that are up to 1 km upwind of the wetland to avoid reinfestation.

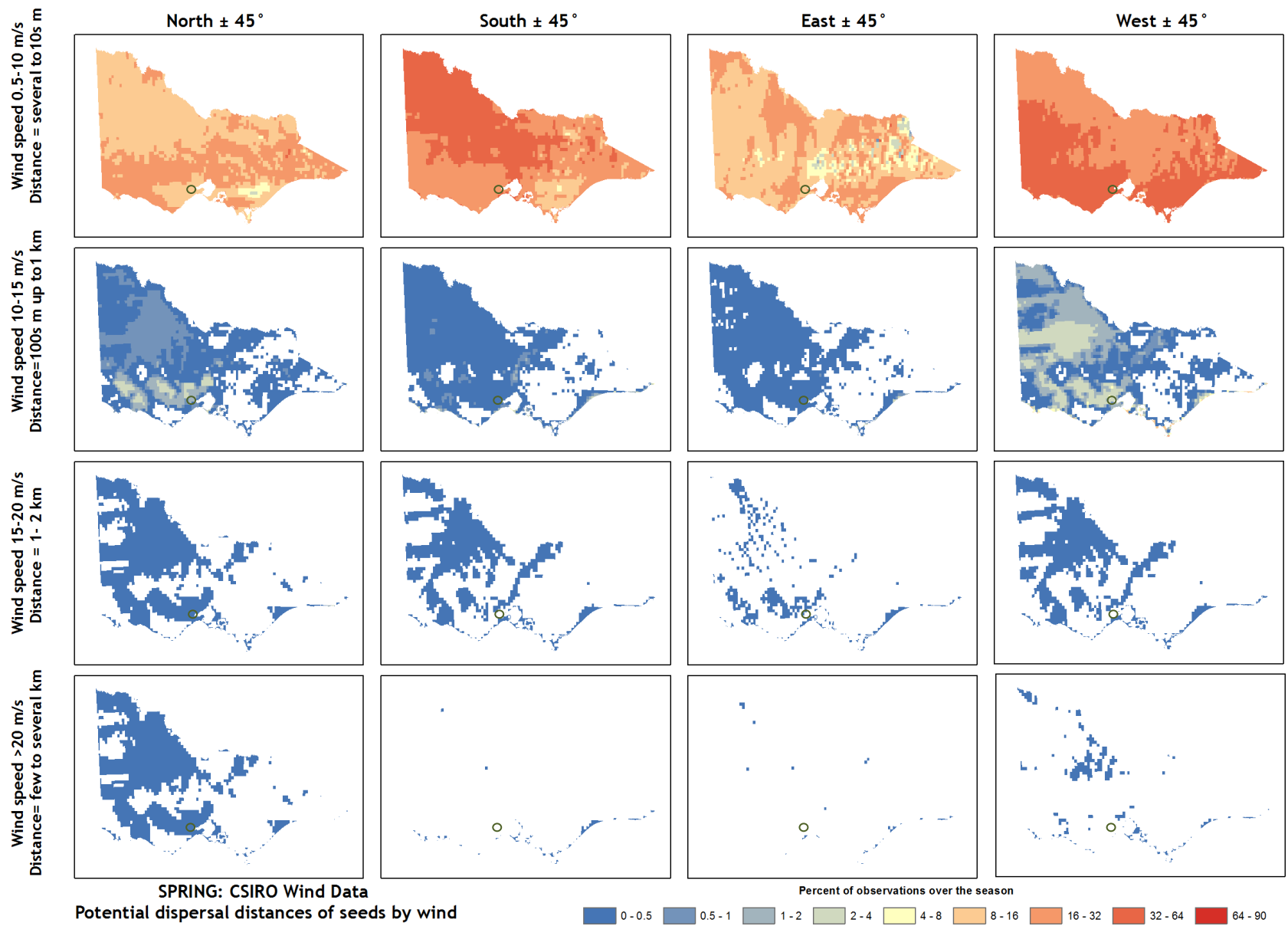


Figure 1. Spring: wind frequencies for four wind speeds (m s^{-1}) from each of four wind directions (N, S, W, E $\pm 45^\circ$). Wind data modelled by CSIRO. Green circles indicate the area discussed in the 'Example of application' provided in the text.

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Appendix A

Table 1A. Summary of data sources used in connectivity models.

Data source	Attribute	Use in models
WETLAND_CURRENT (DELWP 2015)	Naturally occurring wetlands	Habitat: Waterbirds
	Fresh naturally occurring wetland	Habitat: Amphibian
	Saline naturally occurring wetlands	Permeability: Amphibians
WETLAND_CURRENT (DEWLP 2015) and FARM_DAM_BOUNDARIES (DELWP 2015) (merged)	Human-made wetlands	Habitat: Waterbirds
	Fresh human-made wetlands	Habitat: Amphibians
	Saline human-made wetlands	Permeability: Amphibians
Tolerance to inundation layer (ARI–DELWP)	Landscape wetness	Permeability: Amphibians
VICMAP: Built-up areas	Built-up areas	Permeability: Amphibians
VICMAP: Transport spatial layers	Sealed road and rail network	Permeability: Amphibians
Conformal Cubic Atmosphere Model (CSIRO)	Frequency and direction of selected wind-speed categories	Wind patterns relevant to plant-seed dispersal

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