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Phil Papas[1] , Matt White[1], Belinda Cant[2], Peter Griffioen[3], Diane Crowther[1], Damien Cook[4]

[1]Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, 123 Brown Street, Heidelberg, Victoria 3084

[2]Department of Environment, Land, Water and Planning, Ballarat, 402–406 Mair Street, Ballarat, Victoria 3350

[3]Ecoinformatic Pty. Ltd., Montmorency, Victoria 3094

[4] Rakali Ecological Consulting, P.O. Box 188, Chewton Victoria 3451

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Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
Heidelberg, Victoria

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Department of Environment, Land, Water and Planning
PO Box 137
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Phone (03) 9450 8600
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Front cover photo: Seasonal herbaceous wetland in the Riverina (Diane Crowther).

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Summary

South-east Australia has a diverse array of wetlands, some of which have national and international conservation significance, including the 'seasonal herbaceous wetlands of the temperate lowland plains' ecological community which is listed as critically endangered under the Australian *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). This is the highest conservation significance category. The location and extent of many wetlands is well understood – especially in the lower south-east of South Australia and Victoria. However, our understanding of the location of the seasonal herbaceous wetlands community is limited. This is because the community has only been recently defined (in 2012) and typically occurs on fertile lowland plains – much of which is private land, predominantly agricultural, where there is limited access for surveys.

Key diagnostic characters and condition thresholds are used to identify the threatened ecological community. These wetlands are characterised as fresh and are usually inundated on a seasonal basis from winter and spring rainfall and then they dry out completely. In drought periods however, they may be dry for many years. Their vegetation structure is open (woody cover is absent to sparse) and the ground layer is dominated by herbs (grasses, sedges and forbs) adapted to seasonally wet or waterlogged conditions.

Seasonal herbaceous wetlands are particularly susceptible to impacts from agricultural and urban land uses because they occur on fertile plains and sometimes close to urban centres. Cropping, livestock grazing, forestry production, and urban, industrial and infrastructure development all threaten the existence and condition of this community.

Management and prioritisation of seasonal herbaceous wetlands for conservation or rehabilitation requires good knowledge of their location and their potential for restoration. In a few relatively small areas in south-east Australia, where surveys targeting the wetland community have been done, the number and location of wetlands that meet the key diagnostic characteristics and condition thresholds that define the national ecological community are known with a high degree of confidence. In addition to these known locations, the location of candidate seasonal herbaceous wetlands has been mapped across various spatial extents. However, these maps were principally derived from modelled native wetland vegetation, they vary in scale and accuracy and do not specifically map the defined EPBC ecological community.

In this study, we used a new approach to modelling the likelihood of occurrence of seasonal herbaceous wetlands across Victoria and adjoining areas of South Australia. Using field observations and data derived from the Landsat and ALOS satellite platforms, we modelled the spatial extent of this ecological community using Bagged Random Forests at a resolution of 25 m. The resultant model fits the field observations robustly and model validation suggests that the model extrapolates successfully even when presented with novel field observations. Model outputs include both an uncertainty surface and a likelihood surface. The likelihood surface depicts the mean likelihood of seasonal herbaceous wetland occurrence at each 25 m pixel and the uncertainty surface is the standard deviation derived from the set of 30 model predictions at each 25 m pixel. These two surfaces can be combined and/or thresholded for decision making contexts that may be more or less risk averse. The model found that seasonal herbaceous wetlands are extremely rare even within the bioregions in which they are known to occur. We estimate that they comprise less than 0.001% of the surface area of the relevant IBRA lowland bioregions in south-eastern Australia.

It is anticipated that additional training data from future field observations would further improve the existing model by reducing the variance within the feature space that is unexplained by the model. We therefore recommend that the model be periodically refreshed to include new data.

The model outputs are available from www.data.vic.gov.au/data/dataset/Seasonal-Herbaceous-Wetland-likelihood-model-V1 -output-(mean-and-standard-deviation) and will be useful tools for individuals and agencies that require an understanding of where seasonal herbaceous wetlands are likely to occur in the

landscape. Users include the Commonwealth Government, natural resource management agencies, non-government organisations, state and local government, land developers and landholders. Uses of the model outputs will include: raising awareness of this ecological community, assisting with planning, raising awareness of responsibilities under the EPBC Act, identifying areas to target for landholder incentive programs and assisting with provision of guidance to landholders on protection or restoration of seasonal herbaceous wetlands.

1 Introduction

Wetlands in south-east Australia

There are over 35,0000 naturally-occurring lacustrine (open water-dominated) and palustrine (vegetation-dominated) wetlands in south-eastern Australia in an area bounded by Adelaide in the west and Canberra in the east (Figure 1, DELWP 2013, Harding 2005, Taylor 2006). These wetlands have diverse geomorphic settings (e.g. craters of volcanoes, shallow depressions, lowland drainage lines, alpine plains), water sources (groundwater, local rainfall, rivers or streams), water regimes (permanent, seasonal, intermittent, episodic), water properties (fresh, saline, turbid, clear) and vegetation communities (in Victoria alone, there are 148 wetland Ecological Vegetation Classes described – DELWP 2016a).

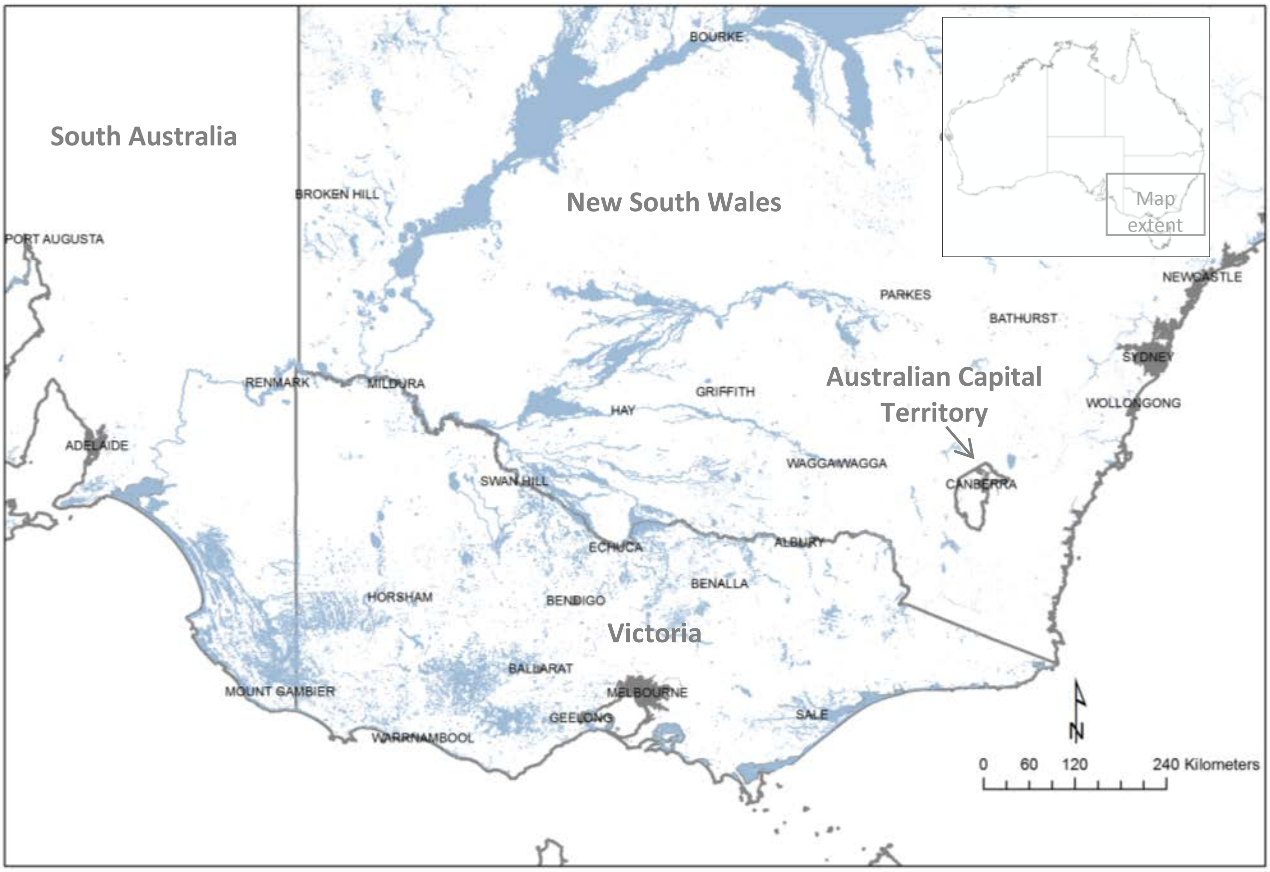


Figure 1. Map showing location of mapped wetlands (blue shading) in south-east Australia (Harding 2005, Taylor 2006, DELWP 2013). Polygon outlines have been enlarged to improve visibility.

In south-eastern Australia, there are wetlands of national and international conservation significance (Department of the Environment 2015, 2016a) and two nationally-listed wetland ecological communities of conservation significance: 'alpine sphagnum bogs and associated fens' and 'seasonal herbaceous wetlands of the temperate lowland plains' (hereafter referred to as seasonal herbaceous wetlands) (Department of the Environment 2016b).

The number and location of seasonal herbaceous wetlands are known with a high degree of confidence in a few relatively small areas in south-east Australia where surveys targeting the wetland community have been done (e.g. lower south-east of South Australia and restricted areas of Victoria (Taylor 2006, DELWP 2016b). However, on a broader scale our understanding of the location of individual seasonal herbaceous wetlands is limited. This is because the community has only been recently defined (2012) and also because the vast majority occur on private land. Improving knowledge on the distribution of these wetlands in the landscape across south-east Australia forms the basis of this report.

The seasonal herbaceous wetlands community

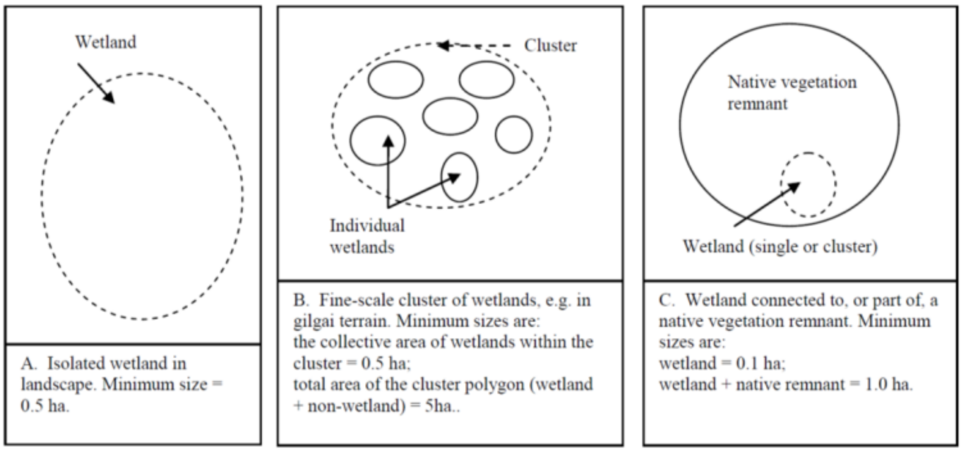
The community is listed as critically endangered under the Australian *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). This is the highest conservation significance category. This classification has been assigned to the community because it has a restricted geographic distribution, is subject to multiple demonstrable threats that could cause it to be lost in the immediate future, and has undergone a very severe change in its ecological integrity (Department of the Environment 2013). Only wetlands that meet size and condition thresholds (see Table 1) are included in the nationally listed ecological community as defined by the Threatened Species Scientific Committee(TSSC 2012b).

Seasonal herbaceous wetlands are fresh and are usually inundated by seasonal winter and spring rainfall and then dry out completely. In drought periods however, they may be dry for many years. Their vegetation structure is open (wood cover is absent to sparse) and the ground layer is dominated by herbs (grasses, sedges and forbs) that are adapted to seasonally wet or waterlogged conditions (TSSC 2012a). Further detail on their characteristics is provided in Table 1.

Seasonal herbaceous wetlands are purported to occur on the lowland plains of temperate south-eastern Australia in five IBRA bioregions and 18 subregions[1] (DSEWPaC 2012, Figure 2). The location of individual wetlands or the likelihood of any particular wetland being a seasonal herbaceous wetland however is known in a small part of these bioregions only.

Table 1. Diagnostic characteristics of the Seasonal Herbaceous Wetlands ecological community (adapted from TSSC 2012b).

Characteristic	Key features
Location	• Occur in the temperate climate zone of mainland south-eastern Australia (including south-east South Australia, parts of Victoria and southern New South Wales)
Size	• Typically small wetlands – many are less than 5 ha. The minimum size to be eligible for EPBC listing is either 0.5 ha for an isolated wetland, 0.5 ha for a collective area of gilgai[2] wetland or 0.1 ha for a wetland connected to a native vegetation remnant as shown in the diagram below (reproduced with permission from TSSC 2012b).



[1] Interim Biogeographic Regionalisation for Australia, Version 7 (DSEWPaC 2012).

[2] Gilgai refers to surface micro-relief formed by the shrinking and swelling of clays during alternate drying and wetting cycles. The surface eventually becomes covered by a pattern of small mounds and depressions that give the soil surface a 'pock-marked' appearance. Gilgai depressions are sometimes also called crabholes or melon-holes (TSSC 2012a).

Table 1 (continued). Diagnostic characteristics of Seasonal Herbaceous Wetlands (adapted from TSSC 2012b).

Characteristic	Key features
Landscape context	• Flat plains grading into slopes, below 500 m elevation • Associated soils are generally fertile, poorly draining clays derived from a range of geologies • Typically occur in rainfall zones with a winter seasonal rainfall pattern (wet winter/low summer rainfall), extending into a uniform seasonal rainfall pattern at the edge of its range • Mean annual rainfall is usually 400 to 800 mm per year but can be lower at the northern edge of its range • Occur on isolated drainage lines or depressions
Hydrology	• Water regime is seasonal: wetlands are typically inundated during winter-spring and subsequently dry out by late summer (in drought periods however, they may be dry for many years) • Rainfall is the main water source (these wetlands are not dependent on overbank flooding from riverine systems)
Water properties	• Salinity of the water is fresh to slightly brackish (mostly in the range 0 to1000 mg/L but can be up to 3000 mg/L), typically exhibiting a progressive increase in salinity as wetlands dry)
Biota	• Trees and shrubs are sparse to absent. When present, they mostly occur as fringing or scattered individuals and their cover accounts for no more than 10% across the wetland • Vegetative cover is dominated by a ground layer of native wetland graminoids (grasses and sedges) and/or native wetland forbs • Graminoids that are present often include one or more of the following taxa: *Amphibromus* spp., *Carex tereticaulis*, *Deyeuxia* spp., *Glyceria* spp., *Lachnagrostis* spp., *Poa labillardieri*, and *Rytidosperma duttonianum* (other graminoid taxa may also occur, though are not necessarily common) • At least one native wetland forb species must be present (preferably more) after the ecological community is inundated • The suite of forbs that may occur within the ecological community's range is variable and potentially large • Freshwater algae often are present when the wetland is wet or has been recently wet • Characteristic fauna that may be associated with the ecological community include invertebrate groups that are temporary water specialists • The types of fauna present can be highly variable and is dependent on the inundation history, current conditions and other factors
Condition	• To meet EPBC Act condition criteria 50% or more of the total cover of plants in the ground layer of the wetland during a 'typical' wet phase must be dominated by native species characteristic of the ecological community (see Appendix 1 for these characteristic species).

The project aimed to model the occurrence of the listed ecological community taking into account the condition threshold specified in Table 1.

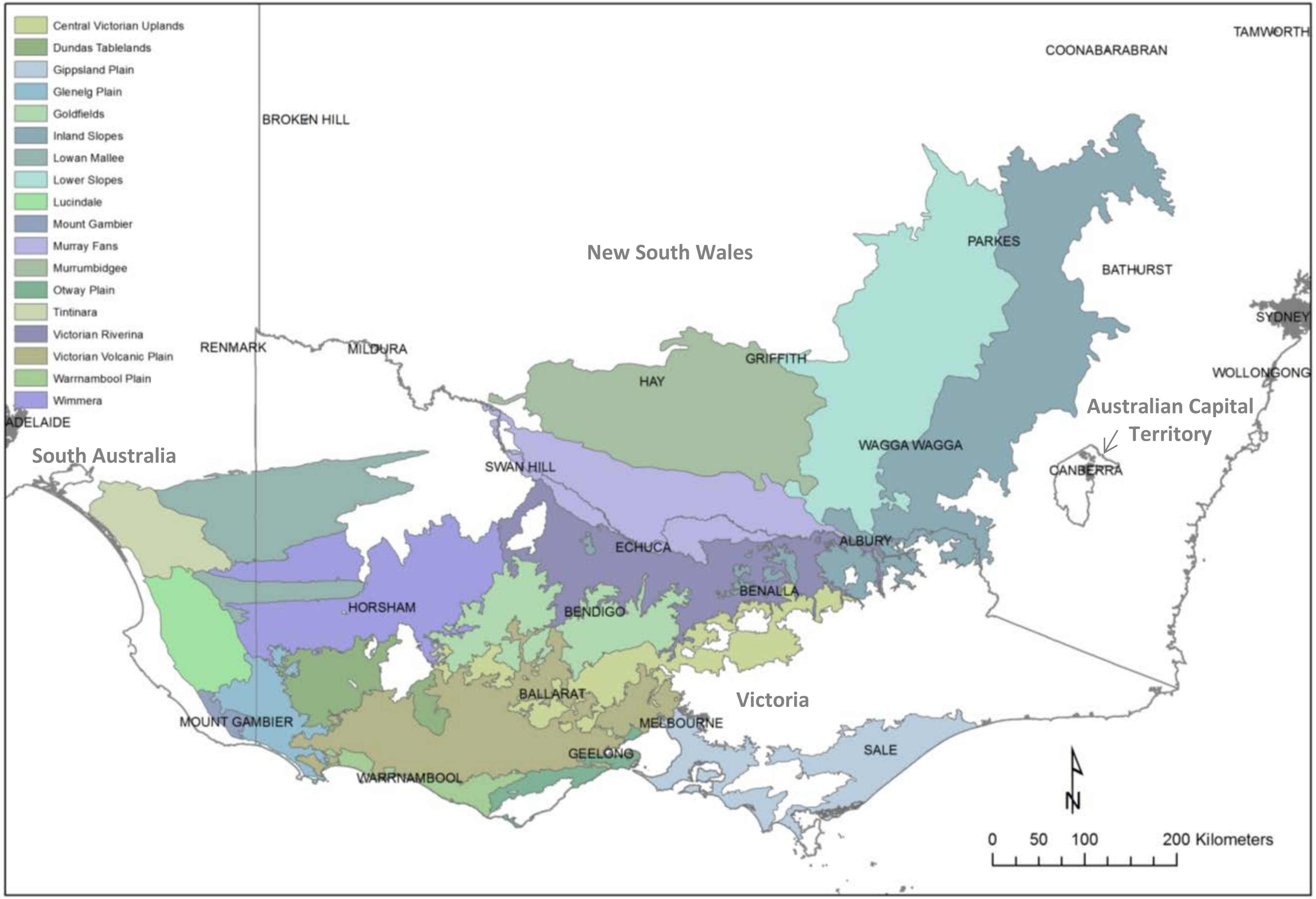


Figure 2. Map showing location of the IBRA subregions in south-eastern Australia where Seasonal Herbaceous Wetland ecological community is known to occur (Interim Biogeographic Regionalisation for Australia, Version 7 – DSEWPaC 2012, TSSC 2012b).

Threats to seasonal herbaceous wetlands

Wetlands on plains in south-east Australia where seasonal herbaceous wetlands occur, have been lost or degraded by impacts and anthropogenic disturbance associated with agricultural and urban land uses. In many places, large areas and numbers of wetlands have been lost (DEC 2006, State of the Environment 2011 Committee 2011). Such losses and degradation have also occurred in other parts of Australia (Balla 1994, Davis and Froend 1999, DPIW 2008, DEHP 2016) and globally (Davidson 2014).

Seasonal herbaceous wetlands are particularly susceptible to impacts from agricultural and urban land uses because they occur on fertile plains – which are often private land – and sometimes occur adjacent to substantial population centres. Cropping, livestock grazing, forestry production and urban, industrial and infrastructure development all threaten the existence and condition of this wetland community (TSSC 2012a, DEPI 2013, Dickson et al. 2014, Casanova and Casanova 2016). Land use in several bioregions is changing rapidly. For example, south-east of the Grampians Ranges on the Southern Volcanic Plain (see Figure 2) where a high density of seasonal herbaceous wetlands are known to occur, there has been an estimated 40% increase in the extent of cropping in the past 20 years (Casanova and Casanova 2016). There are many detrimental impacts from these and other land uses on seasonal herbaceous wetlands (Table 2).

Table 2. Some impacts of land use types on seasonal herbaceous wetlands.

Land use	Activity/processes	Impacts on seasonal herbaceous wetlands
Cropping in wetlands	Cultivation of the soil Application of pesticides (insecticide, herbicide, fungicide) Application of fertilizer Drains Raised beds	• Reduced germination of plants from the seed bank and reduced diversity of plants that establish • Invertebrate diversity and abundance can be impacted by cultivation and other physical changes • Changes in hydrology that occur when wetlands are modified to enhance their value as cropland • Chemical and physical disturbances associated with cropping wetlands can modify food availability and reduce the numbers of amphibians, reptiles and mammals that use wetlands as a refuge • Cropped wetlands support fewer waterbirds which rely on a mosaic of wetlands for feeding and breeding (Casanova and Casanova 2016)
Livestock grazing in wetlands	Removal of palatable biomass Treading in the wetland leading to pugging Transport of plant seeds into the wetland Deposition of urine and faeces in the wetland	• Usually detrimental changes in water quality, water regime, soil properties, physical form, invasive flora and vegetation health, structure and composition (Morris and Reich 2013, Peters et al. 2015) • Species that are very sensitive to grazing mostly absent or only exist in small numbers (DEPI 2013) • Invasion by pest plants
Plantation forestry near wetlands	Water extraction (uptake by pine and blue-gum forest)	• Altered water regime (less water) (Dickson et al. 2014)
Urbanisation	Levelling/filling Drainage Stormwater runoff Runoff from surrounding land	• Complete loss of wetlands • Altered water regime (reduced or excess water) • Nutrient enrichment that can lead to changes in vegetation (DEPI 2013) • Input of toxicants which can affect some aquatic invertebrates (Mackintosh et al. 2015)

State of knowledge on the location of seasonal herbaceous wetlands

Management and prioritisation of EPBC-listed seasonal herbaceous wetlands for conservation or rehabilitation requires good knowledge of their location and their potential for restoration. The number and location of these wetlands are known with a high degree of confidence in a few relatively small areas in south-east Australia where surveys targeting the wetland community have been done. These include 37 wetlands in the western growth corridor of Melbourne on the Southern Volcanic Plain (Melbourne Strategic Assessment project – DEPI 2013), 77 wetlands in the lower south-east of South Australia in the Southern Volcanic Plain, Naracoorte Coastal Plain and Murray Darling Depression bioregions (Dickson et al. 2014) and eight wetlands in the Riverina bioregion of Victoria (Cook and Bayes 2014).

In addition to these known locations, the location of candidate seasonal herbaceous wetlands has been mapped on previous occasions for various spatial extents:

- South-eastern Australia (DEWHA 2011)
- Glenelg Hopkins Catchment Management (CMA) region (GHCMA 2013)
- The western growth corridor of Melbourne (in addition to the wetlands identified with a high degree of confidence in the same study mentioned above; DEPI 2013)

These maps were principally derived from native vegetation mapping, modelling and/or aerial photo interpretation (API) (Table 3). The native vegetation datasets used to create the south-eastern Australian map (Figure 3) vary in scale and accuracy and do not specifically map the defined national ecological community (DEWHA 2011).

Table 3. Datasets used to develop existing seasonal herbaceous wetland maps.

Map	Jurisdiction	Dataset(s)
Commonwealth EPBC listing map (Figure 3, DEWHA 2011)	Victoria	• Modelled map of Plains Grassy Wetland and Plains Sedgy Wetland EVCs (DSE 2007)
	New South Wales (NSW)	• Mapped Swamp Grassland Wetland of the Riverine Plain (similar to Plains Grassy Wetland EVCs) (TSSCb 2012)
	South Australia	• Modelled Seasonal Herbaceous Wetland community based on information stored within the South Australian Wetland Inventory Database (SAWID), using physical and biological characters • The model predicted 86 seasonal herbaceous wetlands, 29 of which had high to very high ecological significance (TSSC 2012a, Dickson et al. 2014)
Glenelg Hopkins CMA (GHCMA 2013)	Victoria	• Modelled Plains Grassy Wetland, Aquatic Grassy Wetland, Plains Sedgy Wetland, Ephemeral Drainage-line Grassy Wetland, Sweet Grass Wetland, Herb-rich Gilgai Wetland EVCs (DSE 2007)
Melbourne Strategic Assessment map (DEPI 2013)	Victoria	• Aerial photo interpretation • Modelled map of Plains Grassy Wetland and Plains Sedgy Wetland EVCs (DSE 2007)

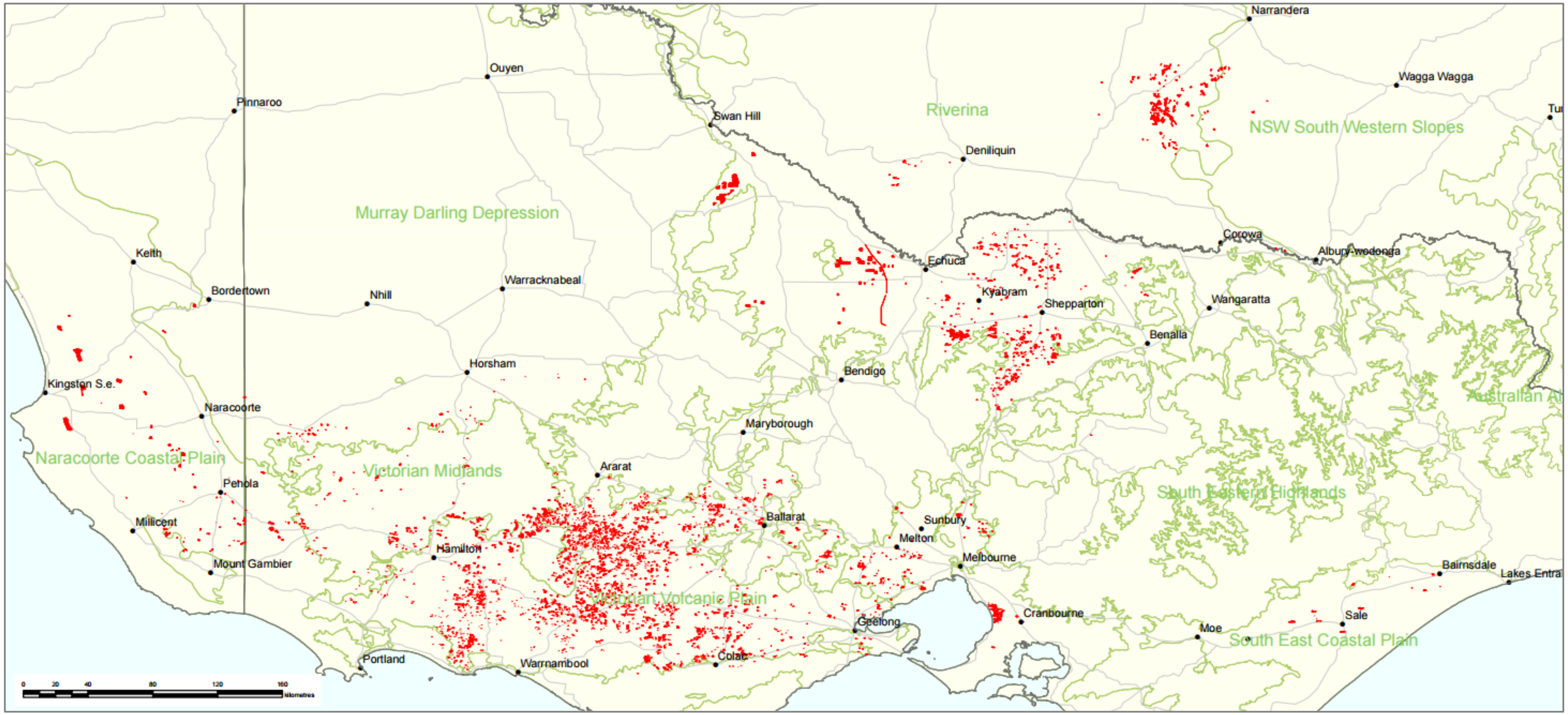


Figure 3. Map of where seasonal herbaceous wetlands are likely to occur (compiled from existing landscape scale datasets). Polygon outlines are enlarged to improve visibility (DEWHA 2011).

Maps of candidate seasonal herbaceous wetlands are useful for identifying potential EPBC-listed seasonal herbaceous wetlands. However, they do not include data on the likelihood and confidence of any particular wetland being a seasonal herbaceous wetland.

A new approach for predicting the location of seasonal herbaceous wetlands

Satellite data has long been used for predicting land-cover and vegetation-cover (Xie et al. 2008, Gómez et al. 2016). In this report we document an approach to modelling a highly dynamic ecological community across an extensive geographic region and across an extended period of time, using a time-series of both active and passive remote sensing data and machine learning algorithms.

The modelled geographic extent includes an area confined to the regions in Victoria and adjacent parts of South Australia to which we are confident the available training data applies (see Section 2). This includes the following IBRA subregions in Victoria: Gippsland Plain, Victorian Volcanic Plain, Victorian Riverina, Goldfields and Murray Fans and the following IBRA subregions in South Australia: Glenelg Plain, Mount Gambier, Lucindale, Wimmera and Lowan Mallee (Figure 4).

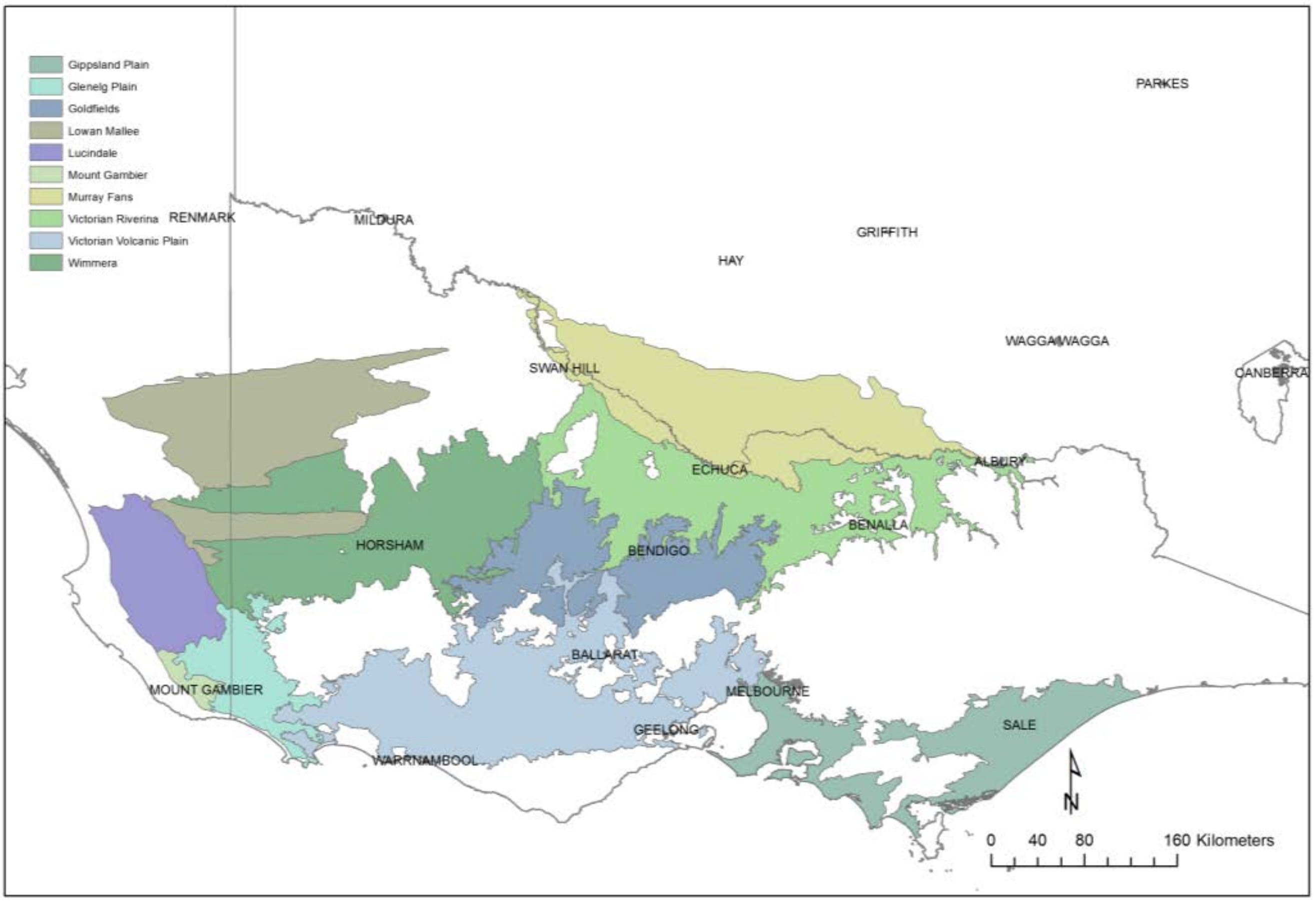


Figure 4. IBRA subregions that included training data for the modelling (approximate geographic extent of the model).

2 Modelling methods

Statistical modelling or regression is the process by which mathematical relationships are established between dependent and independent variables. These relationships can then be used to make predictions of the dependent variable in regions beyond our existing knowledge, provided we have useful and more extensive independent data. In this study, the presence or otherwise of seasonal herbaceous wetlands is the dependent variable. It has only two possible states, 'presence' and 'absence' denoted by 1 or 0. The independent variables for this model are remotely sensed variables derived from either the Landsat or Advanced Land Observing Satellite (ALOS) platforms. While there may be many hydrological and hydro-geomorphological variables that would 'explain' the presence or absence of a seasonal herbaceous wetland, few if any, of these have been mapped in a repeatable and quantitative manner across our study area. For modelling the extent of seasonal herbaceous wetlands multi-temporal remotely sensed data are particularly useful as independent variables as they:

- are spatially explicit and extensive
- are rich in vegetation relevant information particularly in herbaceous vegetation types (such as seasonal herbaceous wetlands) where understoreys are not obscured by shrub or tree canopies
- contain inter-annual and intra-annual variation reflecting the response of the vegetation to season and/or wetting and drying regime
- resolve at scales useful for planning purposes
- are objective and free from human bias and error.

Dependent data

The positive dependent data (i.e. known seasonal herbaceous wetlands that meet EPBC listing criteria) was gleaned from expert elicitation and field observations made by various expert observers that were cognisant of the EPBC Act description of seasonal herbaceous wetlands. This includes over 200 seasonal herbaceous wetlands (Table 4, Figure 4) and 1800 individual sites within these wetlands. Expert elicitation involved asking wetland specialists with an intimate knowledge of wetlands in Victoria to identify wetlands that met the EPBC Act description of seasonal herbaceous wetlands (including condition threshold) from geo-referenced aerial photos. Field observations were collected by wetland specialists in a two-week field campaign in the following Victorian IBRA subregions: Wimmera, Riverina, Goldfields and Gippsland Plain.

Table 4. Positive dependent datasets (actual seasonal herbaceous wetlands) used in the model.

Jurisdiction	Type of training dataset	Approximate number of wetlands that meet EPBC criteria*
South Australia	Field survey (Dickson et al. 2014)	54
Victoria	Field campaign (commissioned by this study)	49
	Expert elicitation (commissioned by this study) – quadrat data assessment	35
	Expert elicitation (commissioned by this study) – expert knowledge	21
	Aerial photo interpretation and field validation of some sites (DEPI 2013)	37
	Field assessment (Cook and Bayes 2014)	8

* The exact number of wetlands cannot be determined for some datasets due to possible inaccuracies with the state jurisdictional wetland maps.

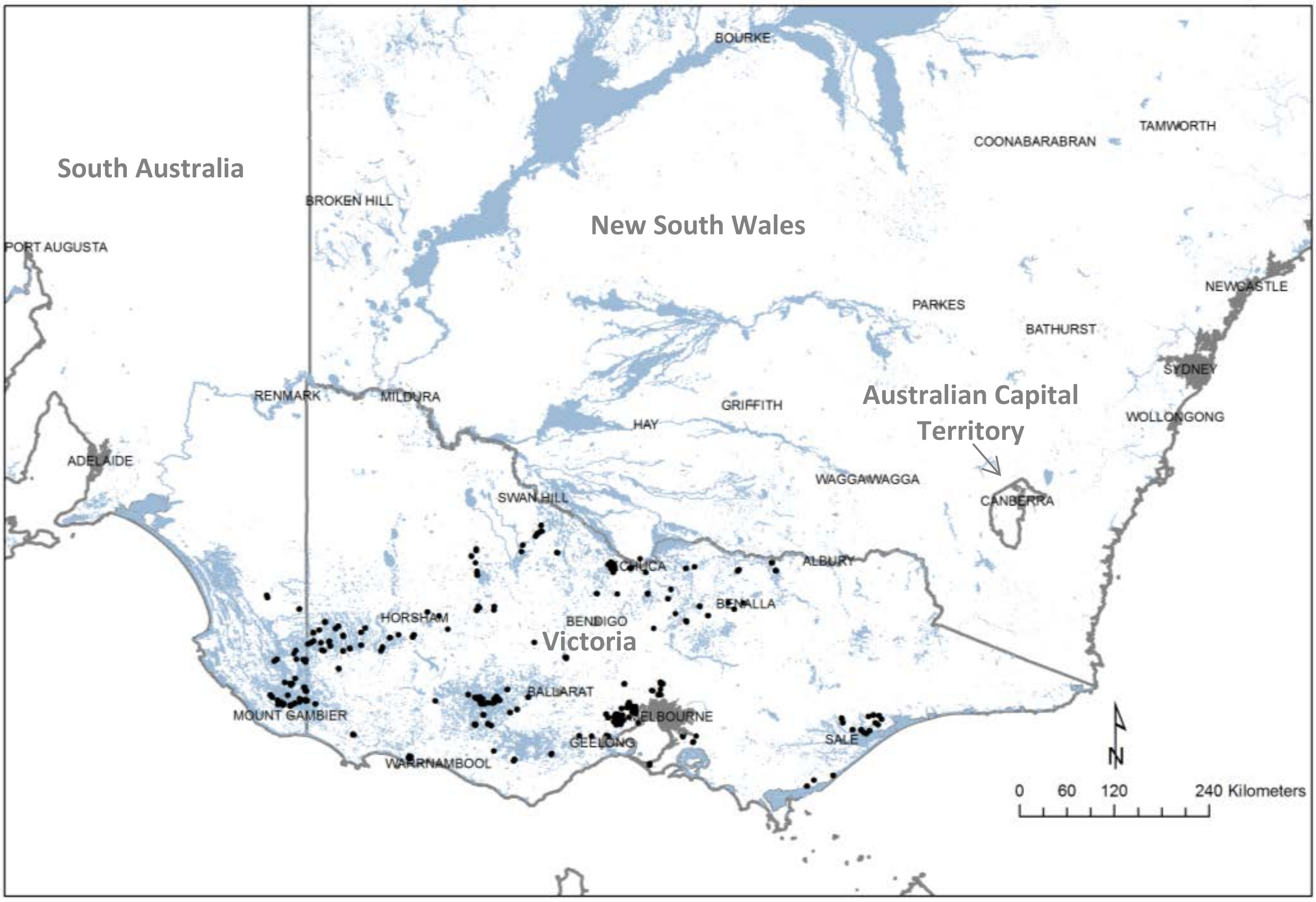


Figure 4. Positive dependent data (known seasonal herbaceous wetland sites – black dots) used in the model. Mapped wetlands are shown in blue shading (Harding 2005, Taylor 2006, DELWP 2013). Polygon outlines of mapped wetlands have been enlarged to improve visibility.

These training data (known seasonal herbaceous wetlands) were supplied as either point data or polygon data. All training data was supplied to the modelling process as georeferenced points and as such the polygon data were used to delimit the selection of additional positive point exemplars. The contrasting negative sites are a set of random (in this case 1,000,000 +) 'background absences'. Additional real 'absences', confirmed in the field or via interpretation of aerial photography, were also collated. This was done to prevent the model conflating the target (in this case seasonal herbaceous wetlands) with other geographically rare spectral signatures (such as those cast by factories, urban areas, quarries, coal mines, etc.) that may not be adequately sampled by the random allocation of absences in the geographic space. Finally the random absences were checked to make sure that no negative exemplars fell within the bounds of known seasonal herbaceous wetlands. The use of random absences in the geographic space is a robust strategy when the target of the model is likely to be relatively narrowly defined in terms of the independent variables (Phillips and Dudik 2008). To build a useful model we need presences and absences to discriminate between the variation within each of these classes as it is expressed in the independent data.

Independent satellite derived data

A range of satellite-derived variables that extend over the study area were used to create the spatial models. These included spectral reflectance data from the "thematic mapper" sensor mounted on the various Landsat missions[3] and synthetic aperture radar data from the ALOS-Phased Array type L-band Synthetic Aperture Radar (PALSAR) satellite[4]. A complete list of the independent data is provided in Table 5.

Using the Geosciences Australia data-cube and the National Computing Infrastructure, we created 36 independent datasets from the Landsat chrono-sequence. From a set of 'cloud-free' images we used Bands 1, 3, 4, 5 and 7 to create statistical summaries of various spectral indices over the period 2000–2010 inclusive (see Table 5). For both the Winter and Summer seasons[5] we derived the 25^{th}, 50^{th} and 75^{th} percentiles for each of the indices shown in Table 5 at every 25 x 25 m pixel in the study area. Over extended periods of time, various vegetation types and land-covers including exotic pastures, crops and wetlands can be characterised by their active growing season and dormant phases. These dynamics are captured in the seasonal spectral statistics over the decade.

ALOS-PALSAR data was included because it detects microwaves in the L-band[6], which provides structural information on the biomass vegetation (Shimada et al. 2009). This was thought to be useful in distinguishing among different vegetation types, particularly the discrimination between woody and non-woody vegetation. Individual orthorectified mosaics at 25m resolution are available for the years 2007–2010 inclusive. These four datasets were summarised as minimum, maximum and median bands.

Water Observations from Space data

The Water Observations from Space (WOfS) data suite includes a number of products that summarise surface water detection over the life (1987 to the present) of the Landsat Thematic Mapper sensor (Mueller et al. 2016). For each 25 m grid cell, WOfS reports on:

- the number of cloud-free satellite observations
- the number of occasions water was detected
- the percentage of clear observations on which water was detected
- the confidence that a water observation at each location is correct (Mueller et al. 2016).

We used the percentage of clear observations on which water was detected as an additional independent variable to predict seasonal herbaceous wetlands. WOfS was included as an independent variable as the frequency/duration of water detection was thought to be useful in distinguishing seasonal herbaceous wetlands from other open wetland types in some contexts. It also summarises 28 years of Landsat imagery rather than just the 10 year period 2000-2010.

Other variables considered

Other independent datasets were examined for use in the modelling. Terrain models derived from the Space Shuttle Radar Topography Mission (Geoscience Australia 2016) were considered but this product remains too coarse for reliably defining shallow surface depressions (Bhang and Swartz 2008). Rainfall and evaporation models were also considered, however we determined that phenological patterns associated with rainfall events and wetland filling events were well reflected in the spectral data. The Landsat derived Autumn and Spring seasons 2000-2010 were also trialled as additional variables in early iterations of the modelling process and were found to provide no significant model improvement.

[3] http://landsat.gsfc.nasa.gov/?p=3229

[4] http://www.eorc.jaxa.jp/ALOS/en/obs/overview.htm

[5] 'Winter' is defined as the months May-September inclusive and 'Summer' is defined as the months November to March inclusive.

[6] The L-band is the 1 to 2 Ghz range of the radio spectrum.

Table 5. Independent variables used in the modelling.

Variable	Satellite platform	Temporal extent	Pixel resolution	Seasons used	Statistics	Derivation
Enhanced Vegetation Index	Landsat	2000–2010	25 m	Winter (June 30–September 30) Summer (December 1–March 31)	25th, 50th, 75th percentiles	= (B4 – B3) / (B4 + 6*B3 – 7.5*B1 + 1) Where B1 = reflectance in the blue spectrum (0.45-0.52 µm) B2 = Reflectance in the green spectrum (0.52-0.60 µm) B3 = reflectance in the red spectrum (0.63-0.69 µm) B4 = Reflectance in the near infrared (0.76-0.90 µm) B5 = Reflectance in the mid-infrared (1.55-1.75 µm) B7 = Reflectance in the far infrared (2.08-2.35 µm)
Normalised Difference Moisture Index	Landsat	2000–2010	25 m	Winter (June 30–September 30) Summer (December 1–March 31)	25th, 50th, 75th percentiles	= (B4 – B5) / (B4 + B5) Where B1 = reflectance in the blue spectrum (0.45-0.52 µm) B2 = Reflectance in the green spectrum (0.52-0.60 µm) B3 = reflectance in the red spectrum (0.63-0.69 µm) B4 = Reflectance in the near infrared (0.76-0.90 µm) B5 = Reflectance in the mid-infrared (1.55-1.75 µm) B7 = Reflectance in the far infrared (2.08-2.35 µm)
Normalised Difference Soil Index	Landsat	2000–2010	25 m	Winter (June 30–September 30) Summer (December 1–March 31)	25th, 50th, 75th percentiles	= (B3 – B5) / (B3 + B5) Where B1 = reflectance in the blue spectrum (0.45-0.52 µm) B2 = Reflectance in the green spectrum (0.52-0.60 µm) B3 = reflectance in the red spectrum (0.63-0.69 µm) B4 = Reflectance in the near infrared (0.76-0.90 µm) B5 = Reflectance in the mid-infrared (1.55-1.75 µm) B7 = Reflectance in the far infrared (2.08-2.35 µm)

Table 5 (continued). Independent variables used in the modelling.

Variable	Satellite platform	Temporal extent	Pixel resolution	Seasons used	Statistics	Derivation
Normalised Difference Vegetation Index	Landsat	2000–2010	25 m	Winter (June 30–September 30) Summer (December 1–March 31)	25th, 50th, 75th percentiles	= (B4 – B3) / (B3 + B4) Where B1 = reflectance in the blue spectrum (0.45-0.52 µm) B2 = Reflectance in the green spectrum (0.52-0.60 µm) B3 = reflectance in the red spectrum (0.63-0.69 µm) B4 = Reflectance in the near infrared (0.76-0.90 µm) B5 = Reflectance in the mid-infrared (1.55-1.75 µm) B7 = Reflectance in the far infrared (2.08-2.35 µm)
Soil Adjusted Total Vegetation Index	Landsat	2000–2010	25 m	Winter (June 30–September 30) Summer (December 1–March 31)	25th, 50th, 75th percentiles	= [[(B5-B3) / (B5-B3+0.5)] * 1.5] - (B7/2) Where B1 = reflectance in the blue spectrum (0.45-0.52 µm) B2 = Reflectance in the green spectrum (0.52-0.60 µm) B3 = reflectance in the red spectrum (0.63-0.69 µm) B4 = Reflectance in the near infrared (0.76-0.90 µm) B5 = Reflectance in the mid-infrared (1.55-1.75 µm) B7 = Reflectance in the far infrared (2.08-2.35 µm)
Specific Leaf Area Vegetation Index	Landsat Thematic Mapper	2000–2010	25 m	Winter (June 30–September 30) Summer (December 1–March 31)	25th, 50th,75th percentiles	Thermal mapping, soil moisture studies and plant heat stress measurement
Horizontal Transmit - Vertical Receive Polarisation (HV)	ALOS PALSAR (L-band)	2007–2010	25 m	N/A	Minimum, Maximum, Median	Horizontal Transmit - Vertical Receive Polarisation (HV) “Backscatter” data reflecting the architecture of features on the surface of the earth
Water Observations from Space		1987–2014	25 m	N/A	% of images detecting water	Water detection count /(total image count - cloud detection count)

Modelling

The locations of both presences and absences were used to extract the spatially co-incident values for each of the independent data (see Table 5) to create a modelling dataset. We used the CLUS system (Struyf et al. 2011) to implement a regression tree model that employs, random forests, bagging and ensembling. The goal of regression trees is to predict the target (or dependent variable) based on the recursive partitioning of several input (independent) variables. Each leaf in the tree represents a value of the target variable given the values of the input variables represented by the path from the root to the leaf (Friedman 2001). Here we invoke predictive clustering trees (sensu. Kocev et al. 2007), a particular type of regression tree that generalizes learning trees as cluster hierarchies. Each decision node within the tree is supplied with a random sub-set of the independent variables from which a partitioning test is applied. Random Forests (Breiman 2001) are an ensembling method that utilises the average value from a group ('forest') of trees which overcomes the inherent inaccuracies in seeking a single parsimonious model. Bootstrap aggregating (or bagging), which is similar to model averaging (Breiman 1996), was used to further improve the accuracy of predictions. The resultant suite of 30 ensemble models were averaged to produce a consensus model through model voting.

Bagged random forests are well suited to modelling large sets of independent variables, many of which may be highly correlated. While over-fitting is often seen as a problem in statistical modelling, predictions of regression trees for independent data sets are not compromised by using a large number of variables and are generally superior to other methods (e.g. generalised linear models, generalised additive models, and multivariate adaptive regression splines; Elith et al*.* 2006).

Model validation

Two independent ensemble models were built; one that subsampled from all of the available presence and absence data and one that was restricted to sub-sampling from 90% of the presence and absence data. The latter model was tested in terms of its capacity to predict the 10% of the data held out of the modelling process. This testing indicated the underlying performance of the of the final model and the degree to which it is able to be generalised.

Model Application

The relationships between the dependent and independent data formulated by the consensus or ensemble model were applied to the independent data to create a spatially explicit expressions of the model comprising two layers or maps – specifically the mean likelihood of wetland presence and the standard deviation of likelihood determined from the thirty random forest models.

3 Model results and discussion

The R^2 or general 'fit' of the Seasonal Herbaceous Wetland model is extremely high at 0.963. However, when we created a model using the same set-up approach but using only 90% of the data and evaluated the model against this 10% 'hold-out' model the R^2 falls to 0.7409. While this remains high, the discrepancy suggests that only wetlands with a high degree of spectral fidelity to the field sites will be modelled with a very high degree of certainty (i.e. just 0.037% of the within model variance remains unexplained). However, if the test or hold-out dataset is indicative of the unknown environmental variance across and within seasonal herbaceous wetlands generally, then the model testing procedure suggests that approximately 25% of the variance within the feature space is unexplained by the model. How this unexplained variance translates to numbers of wetlands and/or the total area of seasonal herbaceous wetlands unaccounted for by the model remains unknown. This degree of over-fitting is to be expected given:

1. the highly variable nature of the community, in terms of the breadth of geomorphological, hydrological, land-use and climatic contexts in which the community can exist;
2. variation in species composition and structure within the community; and
3. the extremely high number of unique combinations of independent variables across the extensive study area.

The apparent importance of each independent variable is shown in Table 6 – expressed as the proportion of the total number of partition tests to which the specific variable was deployed. Care should be taken in interpreting these data as many of the input data are highly correlated, such that if one was removed from the analysis, another analogous variable would likely significantly change its ranking. It must be remembered that the variables are here used to build an accurate model as opposed to implying causation. Further to this, the frequent use of a co-variate to partition the data, does not imply a positive or negative correlation with the data, it merely implies its usefulness towards accurate prediction. However, it is interesting to note the predominance of soil and vegetation indices in the rank order of variables. This suggests that both seasonal extremes and intra-seasonal norms in terms of plant biomass production are important determinants in the model.

Table 6. Ranked variable importance.

Variable	Bag Count	Forest Count	Forest %Tests
Median Enhanced Vegetation Index Summer	30	1837	3.92
Median Normalised Difference Soil Index Summer	30	1830	3.91
Median Soil Adjusted Total Vegetation Index Summer	30	1806	3.86
Median Normalised Difference Moisture Index Summer	30	1755	3.75
Median Normalised Difference Vegetation Index Summer	30	1561	3.33
Median Enhanced Vegetation Index Winter	30	1532	3.27
Median Normalised Difference Moisture Index Winter	30	1413	3.02
25th percentile Soil Adjusted Total Vegetation Index Winter	30	1408	3.01
Median Normalised Difference Soil Index Winter	30	1387	2.96
Median Specific Leaf Area Vegetation Index Summer	30	1373	2.93
25th percentile Soil Adjusted Total Vegetation Index Summer	30	1290	2.75
Median Soil Adjusted Total Vegetation Index Winter	30	1270	2.71
25th percentile Normalised Difference Moisture Index Summer	30	1242	2.65
Median Normalised Difference Vegetation Index Winter	30	1217	2.6
75th percentile Normalised Difference Soil Index Winter	30	1195	2.55

Table 6 (continued). Ranked variable importance.

Variable	Bag count	Forest Count	Forest %Tests
25th percentile Enhanced Vegetation Index Summer	30	1183	2.53
25th percentile Normalised Difference Soil Index Summer	30	1152	2.46
Median Specific Leaf Area Vegetation Index Winter	30	1146	2.45
75th percentile Soil Adjusted Total Vegetation Index	30	1145	2.45
25th percentile Normalised Difference Vegetation Index Summer	30	1103	2.36
75th percentile Enhanced Vegetation Index Winter	30	1078	2.3
ALOS Radar Minimum value of HV ratio (see table 5)	30	1051	2.24
25th percentile Normalised Difference Vegetation Index Winter	30	1037	2.21
Water detection as % of cloud free images	30	1024	2.19
ALOS Radar Median value of HV ratio (see table 5)	30	1025	2.19
25th percentile Enhanced Vegetation Index Winter	30	1015	2.17
ALOS Radar Maximum value of HV ratio (see table 5)	30	1003	2.14
75th percentile Normalised Difference Moisture Index Winter	30	1001	2.14
25th percentile Specific Leaf Area Vegetation Index Summer	30	994	2.12
25th percentile Normalised Difference Moisture Index Winter	30	978	2.09
25th percentile Normalised Difference Soil Index Winter	30	977	2.09
75th percentile Normalised Difference Soil Index Summer	30	979	2.09
75th percentile Normalised Difference Moisture Index Summer	30	911	1.95
75th percentile Normalised Difference Vegetation Index Summer	30	899	1.92
75th percentile Enhanced Vegetation Index Summer	30	891	1.9
75th percentile Normalised Difference Vegetation Index Winter	30	878	1.88
25th percentile Specific Leaf Area Vegetation Index Winter	30	857	1.83
75th percentile Soil Adjusted Total Vegetation Index Winter	30	845	1.8
75th percentile Specific Leaf Area Vegetation Index Winter	30	814	1.74
75th percentile Specific Leaf Area Vegetation Index Summer	30	723	1.54

Figures 6–9 show the model applied to three locations in the study highlighted in Figure 5 (Natimuk in western Victoria, Streatham in south-western Victoria and Peechelba in north-eastern Victoria). The images alternate between: (a) the mean likelihood of the occurrence of seasonal herbaceous wetlands; and (b) the standard deviation of the likelihood of occurrence prediction (i.e. the uncertainty of the model). Note that regions of high likelihood are often associated with moderate to high uncertainty. This is likely a reflection of the highly variable spectral expression of these wetlands and their often singular regimes of wetting and drying.

The study suggests that putative seasonal herbaceous wetlands are very rare in terms of extent. Pixels exceeding a likelihood threshold of 0.5 (irrespective of uncertainty) constitute less than 0.001 % of the surface area of the nominated lowland bioregions (see Figure 4) within that region over which the model has been applied (see Figure 5).

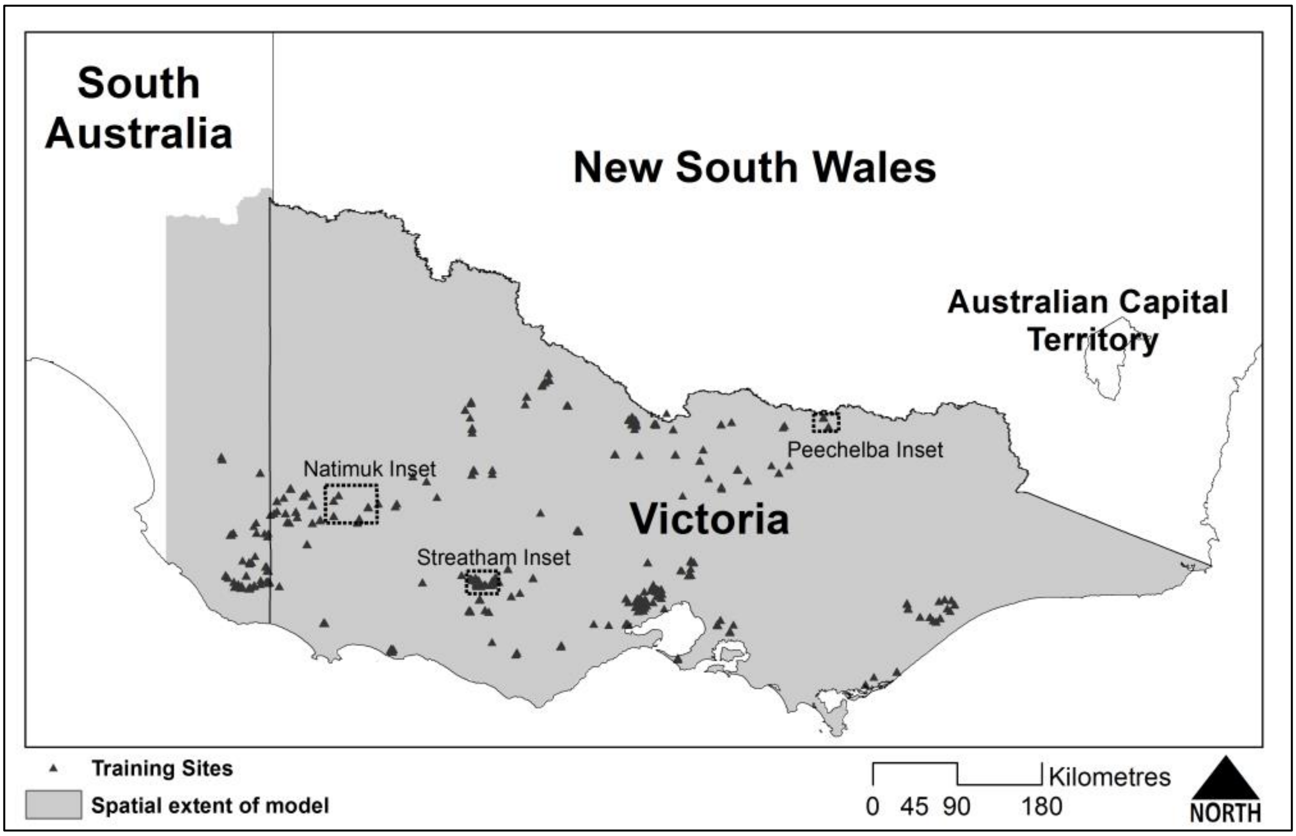


Figure 5. The shaded area delimits the spatial extent of the model as a final product. Insets are presented in the subsequent figures.

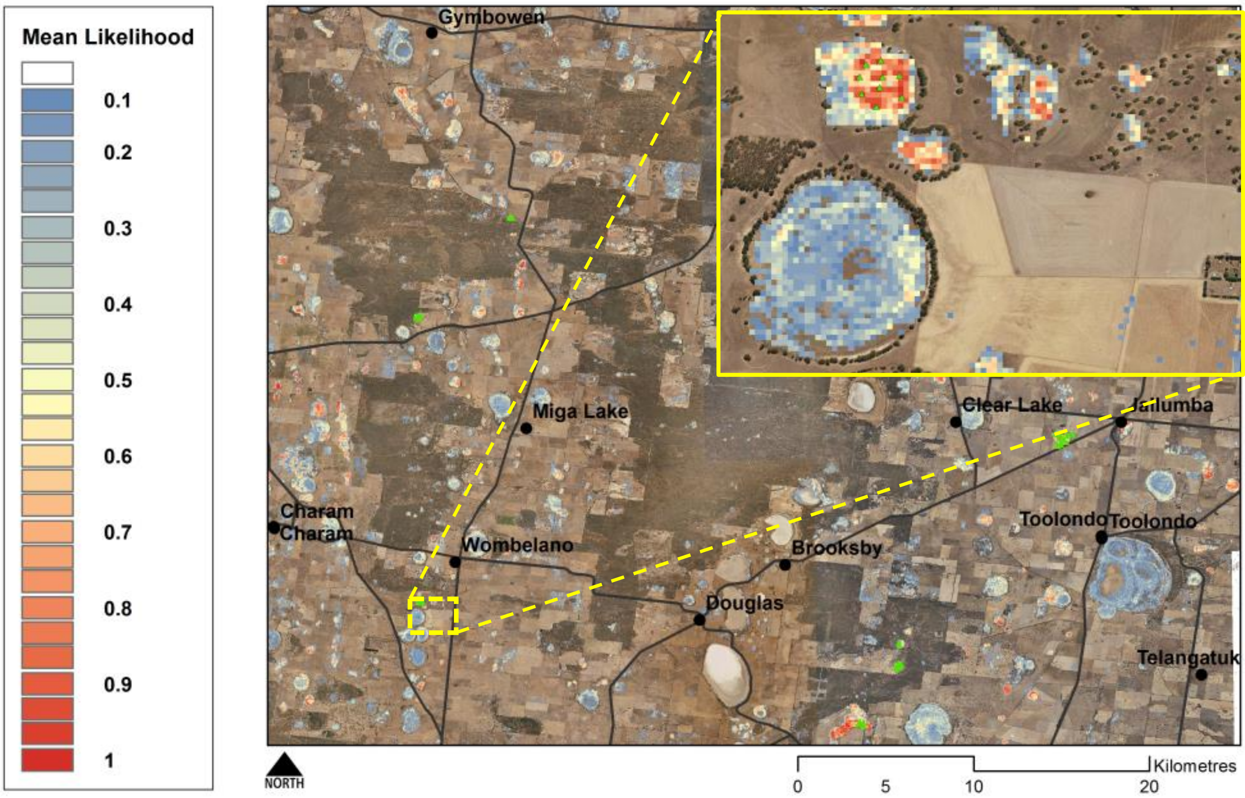


Figure 6a. Natimuk inset. Spatial expression of the mean likelihood model to the south and west of Natimuk in western Victoria. Green triangular markers highlight the location of model training sites. The yellow box insert in the top right hand corner shows the figure at a finer resolution such that individual 25 x 25 m pixels are apparent.

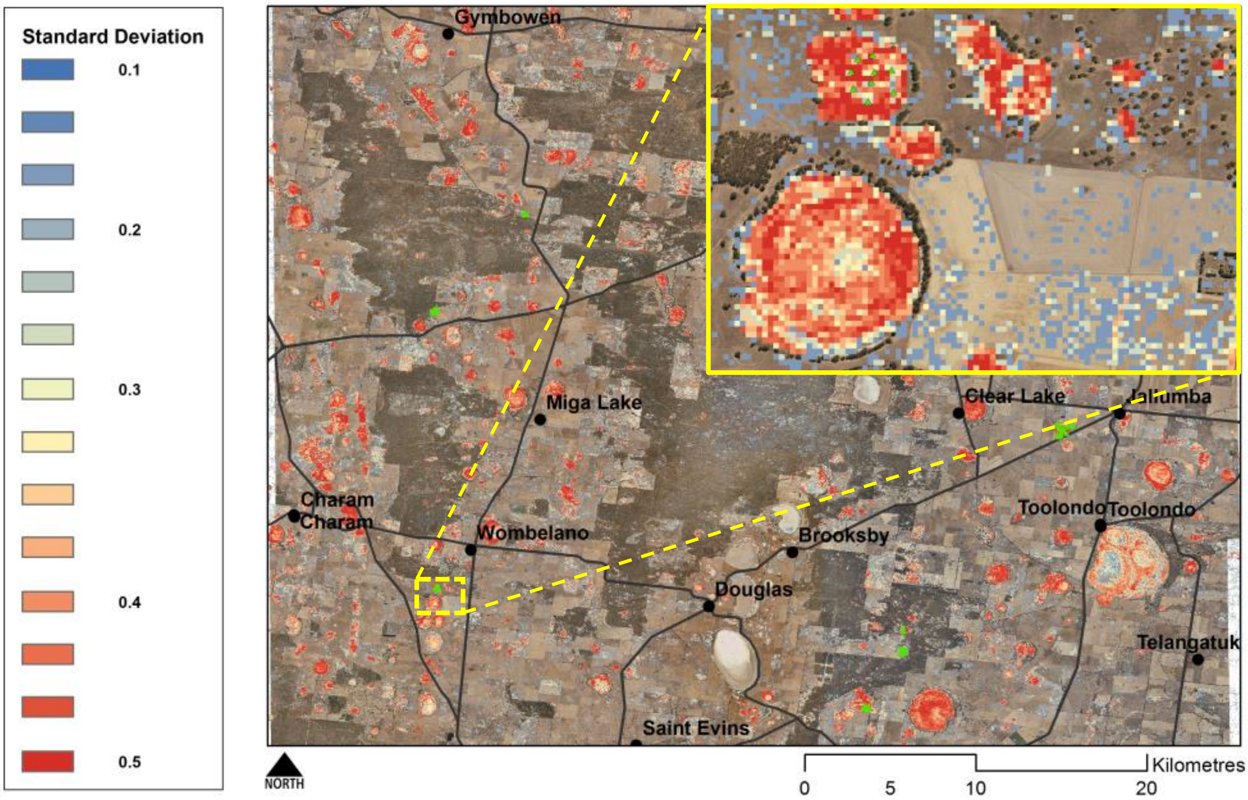


Figure 6b. Natimuk inset. Spatial expression of pixel resolution uncertainty of the likelihood model to the south and west of Natimuk in western Victoria. Green triangular markers highlight the location of model training sites. The yellow box insert in the top right hand corner shows the figure at a finer resolution such that individual 25 x 25 m pixels are apparent.

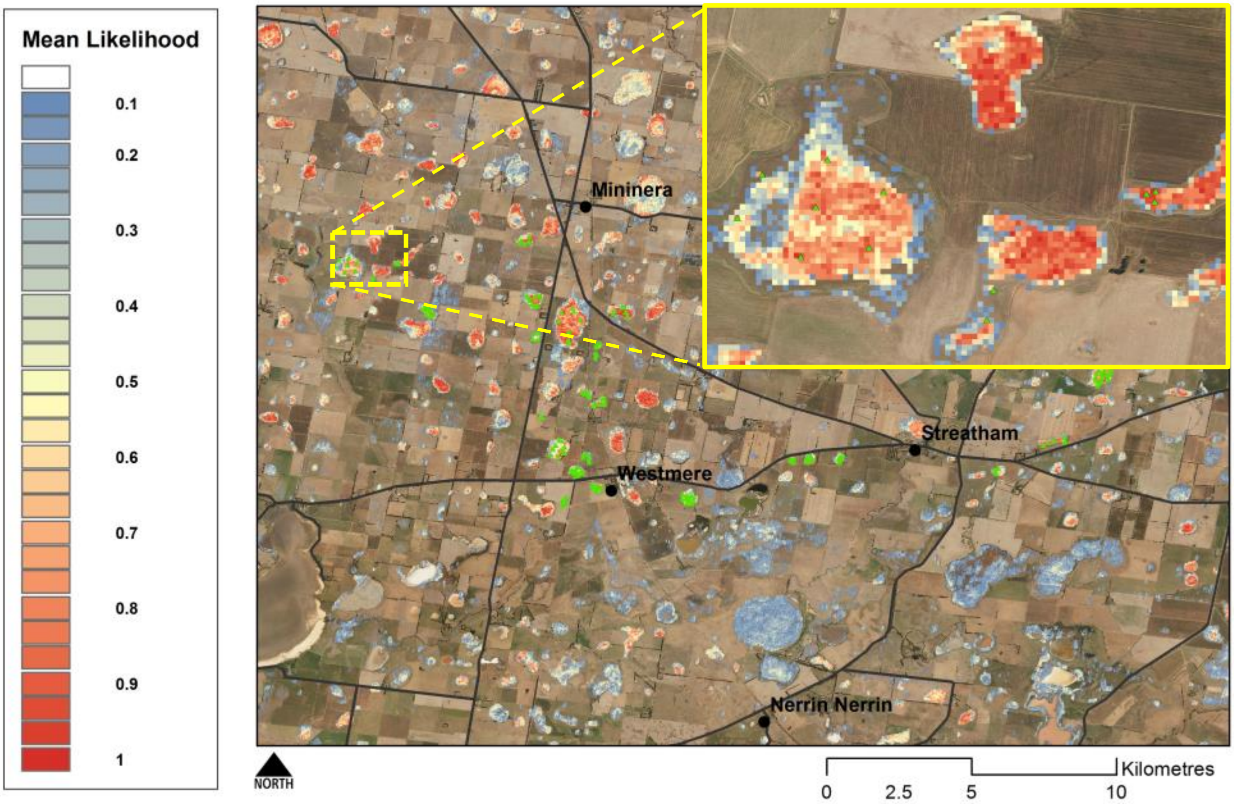


Figure 7a. Streatham inset. Spatial expression of the mean likelihood model around Streatham on the Victorian volcanic plains in south-west Victoria. Green triangular markers highlight the location of model training sites. The yellow box insert in the top right hand corner shows the figure at a finer resolution such that individual 25 x 25 m pixels are apparent.

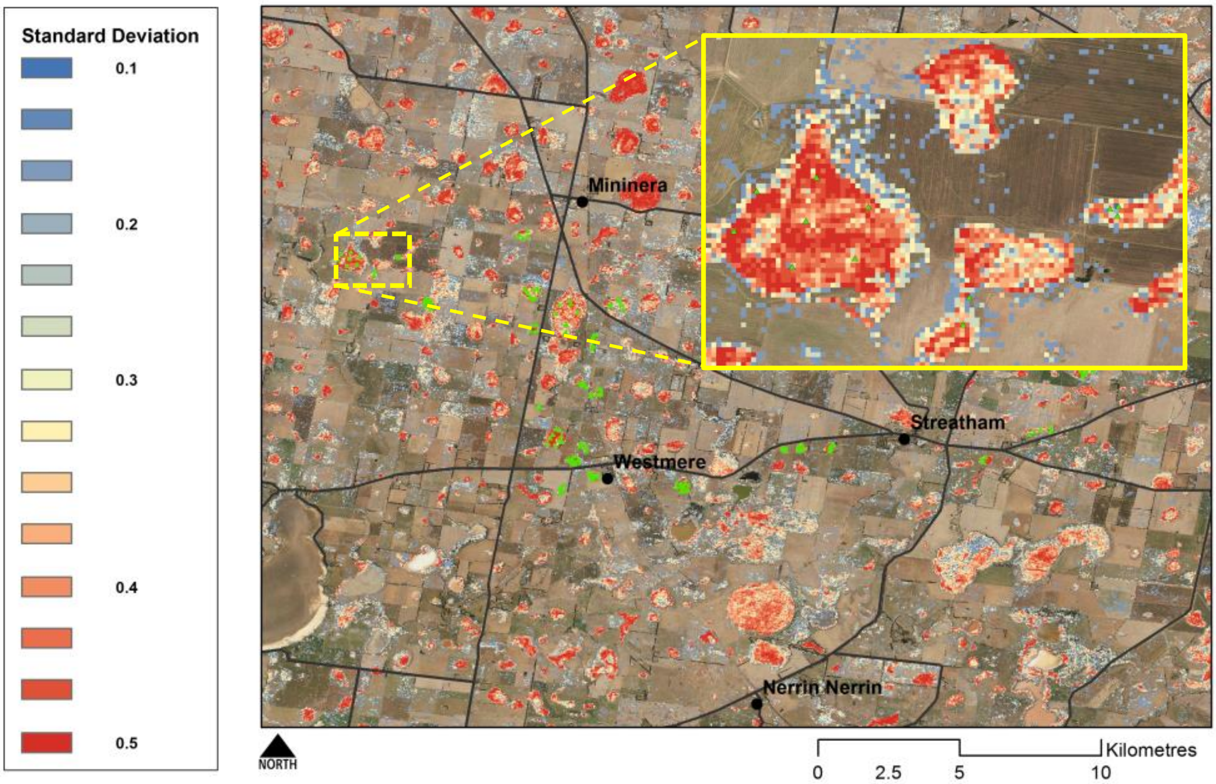


Figure 7b. Streatham inset. Spatial expression of pixel resolution uncertainty of the likelihood model around Streatham on the Victorian volcanic plains in south-west Victoria. Green triangular markers highlight the location of model training sites. The yellow box insert in the top right hand corner shows the figure at a finer resolution such that individual 25 x 25 m pixels are apparent.

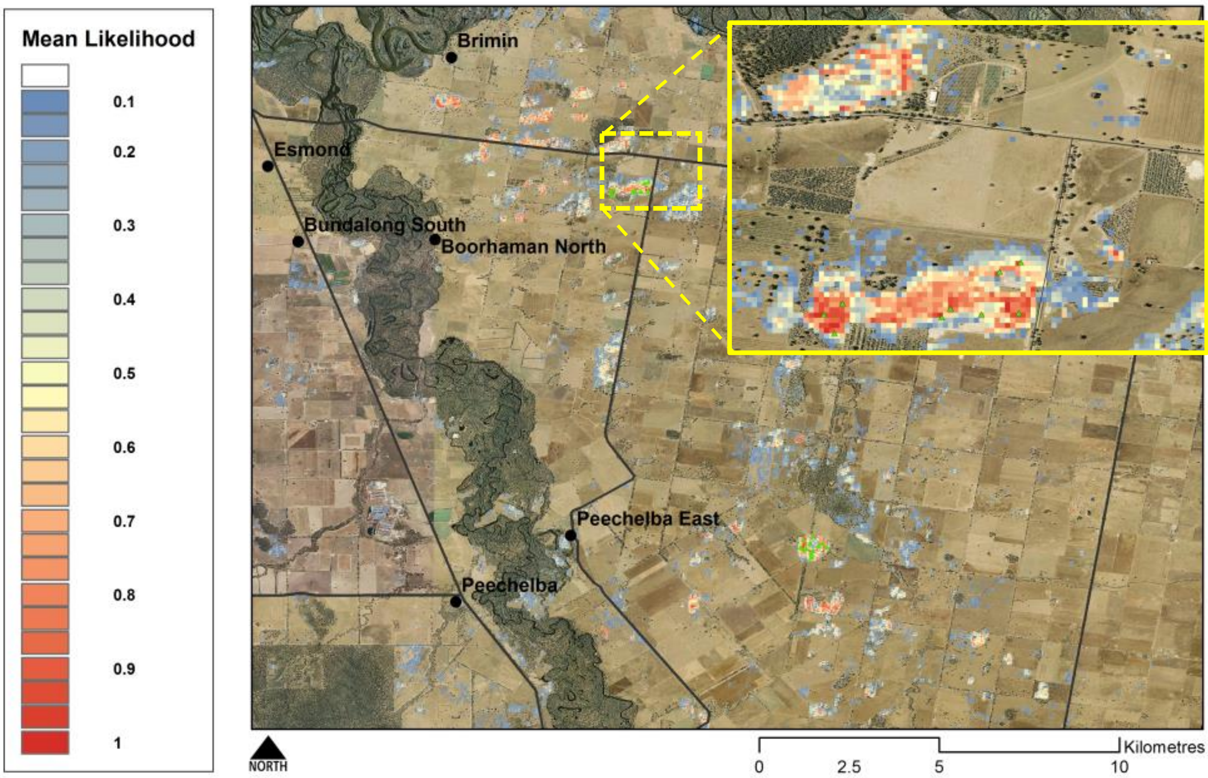


Figure 8a. Peechelba inset. Spatial expression of the mean likelihood model adjacent to the lower reaches of the Ovens River in north-east Victoria. Green triangular markers highlight the location of model training sites. The yellow box insert in the top right hand corner shows the figure at a finer resolution such that individual 25 x 25 m pixels are apparent.

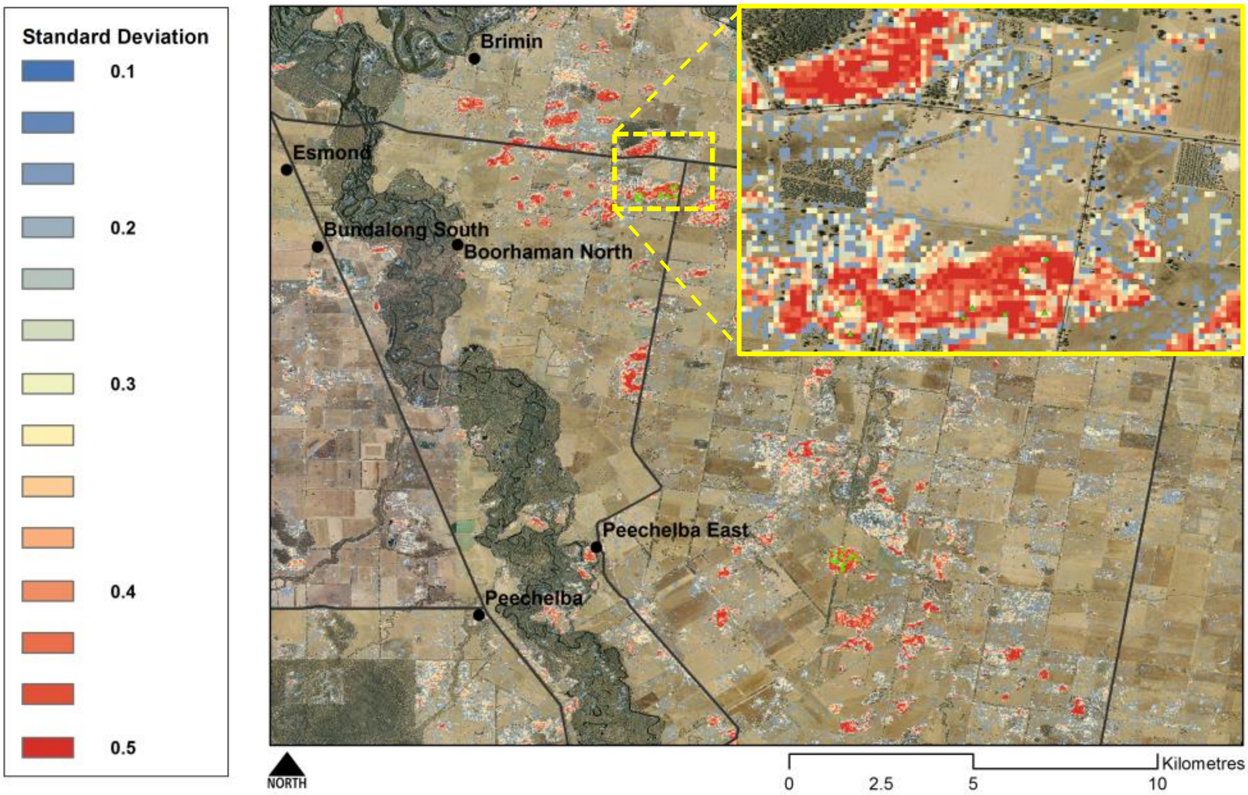


Figure 8b. Peechelba inset. Spatial expression of pixel resolution uncertainty of the likelihood model adjacent to the lower reaches of the Ovens River in north-east Victoria. Green triangular markers highlight the location of model training sites. The yellow box insert in the top right hand corner shows the figure at a finer resolution such that individual 25 x 25 m pixels are apparent.

Model caveats

The model should be used and interpreted within the context of a set of caveats. Firstly, the predictions, beyond the set of known sites, should be considered to be a set of plausible candidate sites only until confirmed in the field following an appropriate sequence of rainfall event(s). The seasonal herbaceous wetland community has only recently been described and a significant proportion of its extent is likely to be on private land. Further field investigations and modelling may be required in the future if the model is to be extended into physiographic, hydrological and climatic contexts that have not yet been surveyed in the field.

Secondly, the likelihood of seasonal herbaceous wetland occurrence is not demonstrably a surrogate for wetland condition or quality. Sites used as training were determined to be suitable for this purpose, on the basis that they met all the criteria that define the community for legislative purposes (see Section 1). Therefore our training sites potentially encompass the full range of condition states within the community's broad circumscription. Further to this, it is likely that some wetland sites that fall outside the set of condition states defined by the EPBC Act, will have a similar remotely sensed signature to that of the field training sites. This is because some of the subtle criteria in the listing such as species composition cannot be readily determined using satellite data. The satellite data can only reliably discern seasonal and inter-annual patterns of vegetation growth and surface water distribution. As such, the model may promote wetlands that largely replicate the phenological patterns of seasonal herbaceous wetlands but may be dominated by exotic plants. It is also possible that wetlands that are periodically augmented by water sources other than rainfall – which would exclude them from the EPBC Act definition of seasonal herbaceous wetlands – may also be mis-identified in the application of model as the target community.

Finally, spatial considerations, specifically extent and grain size (pixel resolution), must be taken into account when interpreting the spatial model. The spatial extent over which the model can be considered to be useful and reliable is currently unknown. In theory the model could be applied to Landsat data collected from the same epoch and transformed and statistically summarised in the same way. We have currently confined the model to those regions in Victoria and adjacent parts of South Australia to which we are confident the available training data applies (see Table 4). Also the model cannot reliably model seasonal herbaceous wetlands that manifest below the grain size of the independent satellite derived data. This is due to the fixed pixel grid into which the predictions are made (25 x 25 m). As such, wetlands that would meet the defining criteria for seasonal herbaceous wetlands will likely be missed entirely or alternatively will have low likelihood as a consequence of the spatial scale at which they occur in the field. Because of this, the occurrence of seasonal herbaceous wetlands associated with paleo-drainage features, gilgai formations and other fine scale arrangements of wetlands, such as are found within recent basalt flows, may be poorly reflected in the model.

Use of the model

The outputs of the model – its likelihood and uncertainty surface – will be a useful tool for any agency or person requiring an understanding of where seasonal herbaceous wetlands are likely to occur in the landscape. Importantly, uncertainty is explicit in the model which is an improvement over other maps such as the EPBC map. Table 6 summarises some of the potential end-users and uses of the model outputs.

Table 6. Potential users and their use of the model outputs.

User	Uses
Commonwealth Government	• Providing guidance to stakeholders on likely location of seasonal herbaceous wetlands • Assisting with enforcement of the EPBC Act
NRM agencies (e.g. CMAs) and landholders[7]	• Raising awareness of seasonal herbaceous wetlands • Identifying areas to target for landholder incentive programs (such as Wetland Tender (DELWP 2015a)) • Assisting with provision of guidance to landholders on protection or restoration of seasonal herbaceous wetlands (see below the table for further information) • Raising awareness of responsibilities under the EPBC Act • Identifying areas for carbon storage offsets
State government agencies	• Raising awareness of seasonal herbaceous wetlands • Conservation reserve planning • Identifying areas for carbon storage offsets
Non-government agencies[8]	• Raising awareness of seasonal herbaceous wetlands • Identifying areas to target for restoration
Local government[7]	• Raising awareness of seasonal herbaceous wetlands • Assisting with urban planning
Land developers[7]	• Raising awareness of seasonal herbaceous wetlands and responsibilities under the EPBC Act • Assisting with urban planning

[7] Communication and promotion of the model outputs and report to landholders will likely occur via NRM agencies.

[8] Communication and promotion of the model outputs and report to these users will likely occur via state government agencies.

Wetland restoration and recovery

Mechanisms that deliver wetland protection and restoration programs vary among jurisdictions and regions. Mechanisms include incentive programs for landholders to protect high quality wetlands, market-based auctions targeted at landholders to maintain and restore wetlands (such as the Wetland Tender program in Victoria – DELWP 2015a) or government grants that support collaborations among NRM agencies, non-government organisations and landholders to implement management interventions.

Model outputs will assist in identifying areas where there are likely to be seasonal herbaceous wetlands that could either be targeted for protection or investment. Restoration potential (or feasibility of restoring them) should take into account landscape context (e.g. climate, land use, geomorphology), attributes of the current vegetation at the site (e.g. species attributes and propagule attributes), factors that affect vegetation recovery at the site (Roberts et al. 2016) and the connectivity among wetlands (Morris 2012, DELWP 2015b). A framework for assessing the feasibility of wetland recovery proposals is currently being developed (Roberts et al. in prep).

Improving the models

As these restricted and threatened wetlands have only been recently described and most of those remaining are on private land and are therefore not readily accessible, new field discoveries will be made into the future. We recommend that the model be periodically refreshed to include these new observations – this will reduce the variance within the feature space that is unexplained by the model.

Also it is likely that in the future new imagery will become available that will sample rainfall patterns and wetland inundation regimes that were not encountered between 2000 and 2010. Of particular utility to any future modelling efforts would be the acquisition of an accurate digital surface model (such as that derived from LiDAR data) such that hydrological modelling could be used to further refine the modelling and improve the models.

Model output description and obtaining the data

Model outputs include both an uncertainty surface and a likelihood surface. The likelihood surface depicts the mean likelihood (of 30 independent models) of seasonal herbaceous wetland occurrence at each 25 x 25 m pixel and the uncertainty surface is the standard deviation derived from the set of 30 likelihood of occurrence predictions at each pixel. These two surfaces can be combined and/or thresholded for decision making contexts that may be more or less risk averse. The spatial extent of the model is currently confined to the regions in Victoria and adjacent parts of South Australia to which we are confident the available training data applies (see Table 4).

The likelihood and uncertainty surfaces and their metadata is available on the Victorian Government open data website (www.data.vic.gov.au/data/dataset/Seasonal-Herbaceous-Wetland-likelihood-model-V1 - output-(mean-and-standard-deviation)

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Appendix 1

Native plant species typically present in the Seasonal Herbaceous Wetland ecological community. This is an indicative rather than comprehensive list of native plant species likely to be found in the ecological community. Individual wetlands may not include all species on the list, or may include other species not listed here. There can be considerable variation in the composition and abundance of wetland species among wetlands and between years and seasons. Many species will only be evident when the wetland is, or has recently been, inundated with water (TSSC 2012b).

Scientific name	Common name
GRAMINOIDS (GRASSES AND GRASS-LIKE PLANTS)	
Amphibromus fluitans	river swamp wallaby-grass
Amphibromus macrorhinus	long-nosed swamp wallaby-
Amphibromus nervosus	common swamp wallaby-
Amphibromus sinuatus	wavy swamp wallaby-grass
Amphibromus spp.	swamp wallaby-grasses
Baumea arthrophylla	fine twig-sedge
Carex tereticaulis	poong'ort
Chorizandra enodis	black bristle-sedge
Deyeuxia quadriseta	reed bent-grass
Eleocharis acuta	common spike-sedge
Eleocharis macbarronii	grey spike-sedge
Eleocharis pallens	pale spike-sedge
Eleocharis pusilla	small spike-sedge
Eragrostis infecunda	southern cane-grass
Glyceria australis	Australian sweet-grass
Isolepis spp.	club sedge
Juncus spp.	rushes
Lachnagrostis aemula s.l.	leafy blown-grass
Lachnagrostis filiformis	wetland blown-grass
Pentapogon quadrifidus var. *quadrifidus*	five-awned spear-grass
Poa labillardieri	common tussock-grass
Pseudoraphis paradoxa	slender mud-grass
Rytidosperma duttonianum (formerly	brown-back wallaby-grass
Schoenus apogon	common bog-sedge
Schoenus tesquorum	soft bog-sedge
Walwhalleya proluta	rigid panic

Continued overleaf

Appendix 1 (continued)

Scientific name	Common name
FORBS (OTHER MONOTYLEDONS)	
Damasonium minus	star fruit
Diuris spp. *	donkey orchids
Hypoxis spp. *	golden stars
Lepilaena australis	austral water-mat
Microtis spp. *	onion orchids
Ottelia spp. *	swamp lilies
Potamogeton cheesemanii *	pondweed
Potamogeton tricarinatus s.l.	floating pondweed
Prasophyllum spp. *	leek orchids
Thelymitra spp. *	sun orchids
Triglochin alcockiae *	southern water ribbons
Triglochin procera s.l.	water ribbons
Triglochin striata *	streaked arrowgrass
FORBS (BROAD-LEAF WILDFLOWERS)	
Allittia cardiocarpa (formerly *Brachyscome*) *	swamp daisy
Alternanthera spp.	joyweed
Asperula conferta *	common woodruff
Asperula subsimplex *	woodruff
Brachyscome basaltica *	woodland swamp-daisy
Calocephalus lacteus *	milky beauty-heads
Calotis spp. *	burr daisies
Centipeda spp.	sneezeweed
Craspedia paludicola *	swamp billy-buttons
Craspedia variabilis	billy-buttons
Crassula helmsii	swamp crassula
Eclipta platyglossa	yellow twinheads
Elatine gratioloides	waterwort
Epilobium spp.	willow-herb
Eryngium vesiculosum *	prickfoot
Haloragis spp.	raspwort
Helichrysum sp. aff. *rutidolepis* (Lowland Swamps)	pale everlasting
Limosella australis	austral mudwort
Lobelia concolor *	milky lobelia
Lobelia irrigua	salt pratia
Lobelia pratioides *	poison lobelia
Lythrum hyssopifolia	small loosestrife
Mentha satureoides	creeping mint
Microseris spp. *	yam-daisy
Montia australasica (formerly *Neopaxia*) *	white purslane
Myriophyllum spp.	water-milfoil

Continued overleaf

Appendix 1(continued)

Scientific name	Common name
Ornduffia reniformis (formerly *Villarsia*) *	running marsh-flower
Persicaria decipiens	slender knotweed
Pycnosorus globosus	drumsticks
Ranunculus diminutus	brackish plains buttercup
Ranunculus inundatus s.l. *	river buttercup
Ranunculus sessiliflorus	annual buttercup
Rumex bidens	mud dock
Samolus repens	creeping brookweed
Selliera radicans	shiny swamp-mat
Senecio psilocarpus *	swamp fireweed
Stellaria angustifolia	swamp starwort
Swainsona spp. *	swainson pea
Teucrium racemosum *	grey germander
Utricularia spp. *	bladderwort
Xerochrysum palustre *	swamp everlasting
FERNS & FERN-ALLIES	
Isoetes spp. *	quillwort
Marsilea drummondii	common nardoo
Marsilea spp. *	nardoo
Pilularia novae-hollandiae *	austral pillwort

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