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APPLIED WETLAND SCIENCE

Wetlands Insight Tool: Characterising the Surface Water and Vegetation Cover Dynamics of Individual Wetlands Using Multidecadal Landsat Satellite Data

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Abstract

Wetlands around the world provide crucial ecosystem services and are under increasing pressure from multiple sources including climate change, changing flow and flooding regimes, and encroaching human populations. The Landsat satellite imagery archive provides a unique observational record of how wetlands have responded to these impacts during the last three decades. Information stored within this archive has historically been difficult to access due to its petabyte-scale and the challenges in converting Earth observation data into biophysical measurements that can be interpreted by wetland ecologists and catchment managers. This paper introduces the Wetlands Insight Tool (WIT), a workflow that generates WIT plots that present a multidecadal view of the biophysical cover types contained within individual Australian wetlands. The WIT workflow summarises Earth observation data over 35 years at 30 m resolution within a user-defined wetland boundary to produce a time-series plot (WIT plot) of the percentage of the wetland covered by open water, areas of water mixed with vegetation ('wet'), green vegetation, dry vegetation, and bare soil. We compare these WIT plots with documented changes that have occurred in floodplain shrublands, alpine peat wetlands, and lacustrine and palustrine wetlands, demonstrating the power of satellite observations to supplement ground-based data collection in a diverse range of wetland types. The use of WIT plots to observe and manage wetlands enables improved evidence-based decision making.

Keywords Wetland characterisation · Landsat · Earth observation · Australia · Hydroperiod · Hydrological regime

Introduction

Wetlands around the world deliver important ecosystem functions and services (Janse et al., 2019). High biodiversity values are globally recognised through international conventions such as the Ramsar Convention (UNESCO, 1994), Convention on Migratory Species (Navid, 1989), and the Convention on Biological Diversity (Blumenfeld et al., 2009; Davidson and Coates, 2011). Wetlands are also considered to be critical systems in reaching the United Nations Sustainable Development Goals (Jaramillo et al., 2019; The Ramsar Convention on Wetlands, 2018). However, wetlands worldwide are subject to a complex range of pressures (Bunn and Arthington, 2002; Dudgeon et al., 2006; Zhao et al., 2018; Finlayson et al., 2019) including shifts in temperature and rainfall (Finlayson et al., 2013; Armandine Les Landes et al., 2014; Nielsen et al., 2020), shifts in snow pack/permafrost dynamics (Avis et al., 2011), increasing water extraction (Verones et al., 2013; Armandine

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Les Landes et al., 2014), flow and flooding regime alteration by dams, weirs and floodplain levees (Kingsford, 2000; Kingsford and Thomas, 2004; Nielsen et al., 2020), human land-use changes (Fickas et al., 2016), invasive species and pollution (Dudgeon, 2019), and the deforestation of treed wetlands (Woodward et al., 2014). These pressures have resulted in an overall decline in global wetland area and condition over the last century (Davidson, 2014).

Wetland responses to these pressures occur on varying timescales. Some responses are near-instantaneous, such as vegetation loss after a fire (Brown et al., 2020) or clearing (Halabisky et al., 2016). Altered water regimes can produce lagged responses (Cunningham et al., 2008). Other responses occur on multi-decadal scales such as responses to shifting climatic patterns (Beeri and Phillips, 2007; Cockayne, 2021). Conceptual models of wetland change include gradual, step-change, and 'disturbance-recovery' models (Kennedy et al., 2014), and the detection of these changes needs to cover the duration of the change. Detecting these responses in Australian wetlands is complicated by the natural variability of their water regimes, with some wetlands predictably inundated permanently, seasonally, or intermittently, and other wetlands inundated unpredictably but persisting for long (episodic) or short (ephemeral) periods of time (Boulton et al., 2014). Traditional methods for observation of wetland systems involve targeted fieldwork campaigns and placement of sensors and loggers to measure change over time. While these methods produce high quality, validated results, they are limited in their spatial and temporal frequency by cost. Australia has a diverse array of wetland types, (Bino et al., 2016) with 67 wetland sites of international importance listed under the Ramsar convention (DCCEEW, 2021), many of which are challenging to survey.

Remote sensing can overcome constraints imposed by limited resources faced by wetland scientists and practitioners (Kotze et al., 2012; Klemas, 2013). Remote sensing methods have been used to detect wetlands (Baker et al., 2006; Adam et al., 2010; White and Lewis, 2011; Gabrielsen et al., 2016; Guo et al., 2017; Wulder et al., 2018; Kissel et al., 2020), classify wetlands (Baker et al., 2006; Guo et al., 2017), and map wetland inundation and extent (Thomas et al., 2011, 2015; White and Lewis, 2011; Ward et al., 2013, 2014; Fickas et al., 2016; DeVries et al., 2017; Wulder et al., 2018; Kissel et al., 2020). The 35-year archive of Landsat satellite data (Wulder et al., 2016) provides us with the unique ability to track how wetlands have been changing since 1987. These historical satellite imagery archives have been analysed to provide continental (Mueller et al., 2016; Krause et al., 2021b) and global (Pekel et al., 2016) insights into surface water dynamics. While such tools and analyses provide information on open water components of wetland systems, they do not capture the behaviour of most vegetated (palustrine) systems, nor do they capture the behaviour of ephemeral or seasonal waterbodies during periods when they are not inundated (Hu et al., 2017). One of the major barriers for the adoption of Earth observation (EO) data as a routine wetland management tool has been the need for training in its interpretation. Multitemporal data, where a satellite acquires multiple images of the same wetland at different times over periods of months or years, can be difficult to interpret unless presented with an intuitive data visualisation method (Lambin and Strahlers, 1994; Allen et al., 2012; Singh and Sinha, 2021).

In this paper we describe the Wetlands Insight Tool (WIT) workflow, an open-source tool for converting the 35-year archive of Landsat imagery into WIT plots. The WIT plots present time-series of hydrology and vegetation dynamics simultaneously, enabling wetland managers to interpret potential changes affecting the whole wetland as well as its ecosystem components. We achieve this by: 1) describing the pre-existing EO algorithms used to convert surface reflectance into biophysical parameters; 2) describing the WIT workflow that summarises these biophysical parameters into WIT plots for each individual wetland; 3) applying the WIT workflow to Australian Ramsar listed wetlands; and 4) discussing how the WIT plots capture the multi-temporal dynamics of selected Ramsar listed wetlands.

Study Area

Australia is a mid-latitude continent with a vast diversity of wetlands, ranging across sandstone plateau wetlands and billabongs in the tropical north, extensive lakes and floodplains inland, and saline lakes, freshwater marshes and alpine peatlands in the south. Australian wetlands encompass the full spectrum of hydrological regimes, including permanent, semi-permanent, seasonal, and ephemeral (Edgar et al., 2008). Australian wetland vegetation therefore varies widely, from salt lakes fringed with halophytic vegetation, to freshwater herbs, sedges, rushes, and grasses, to shrubland wetlands, and treed swamps (Brooks et al., 2014). Australia's Ramsar-listed wetlands provide great examples of some of this diversity.

In this study, we used the Ramsar Wetlands of Australia (Australian Government Department of Agriculture, Water and the Environment, 2019) as a sample dataset to demonstrate the use of the WIT workflow in characterising wetland behaviour. The six Australian Ramsar sites in external territories are excluded from this study as they are outside of continental Australia's satellite data footprint. WIT plots for included Ramsar sites and data can be viewed online[1] or downloaded.[2] Access information is provided in the Data

[1] https://maps.dea.ga.gov.au/#share=s-dJQFNnM33jQFrpO3G0vkaqOvJRc

[2] https://cmi.ga.gov.au/data-products/dea/669/dea-wetlands-insight-tool-ramsar-wetlands#details

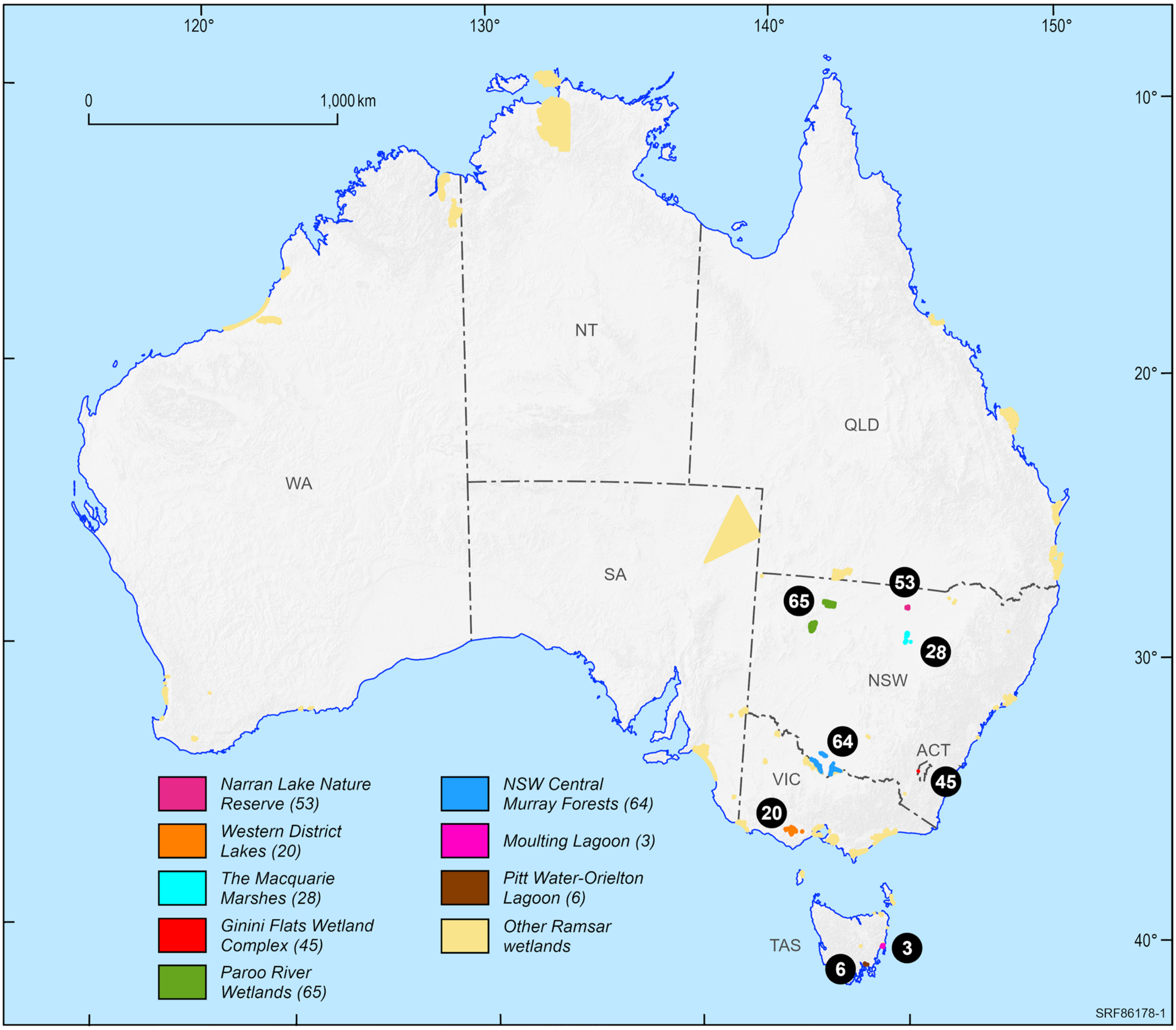


Fig. 1 Australia's Ramsar-listed wetlands, excluding those in external territories. Ramsar Sites highlighted in this study are labelled by name and Ramsar site number

Availability Declaration in this paper. Our case study Ramsar wetland sites provide examples of different wetland types across a range of climatic settings (Fig. 1).

Ramsar Site #53: Narran Lake Nature Reserve – a semi-arid floodplain wetland system (Butcher et al., 2011).

Ramsar Site #20: Western District Lakes – a temperate wetland system with freshwater to saline lakes (Hale and Butcher, 2011).

Ramsar Site #28: Macquarie Marshes Nature Reserve – a semi-arid freshwater marsh wetland system (New South Wales Government Office of Environment and Heritage, 2012).

Ramsar Site #45: Ginini Flats Wetland Complex – a sub-alpine bog wetland complex (Wild et al., 2010).

Ramsar Site #65: Paroo River Wetlands – an arid inland riverine wetlands system with shrub-dominated wetlands, freshwater lakes and springs (Kingsford and Lee, 2010).

Ramsar Site #64: NSW Central Murray Forests – a semi-arid riverine forest wetland system (Harrington and Hale, 2011).

We use two additional sites to demonstrate the limitations of the tool:

Ramsar Site #3: Moulting Lagoon – a temperate lacustrine wetland (Department of Sustainability, Environment, Water, Population and Communities, 2008).

Ramsar Site #6: Pitt Water – Orielton Lagoon – a temperate estuarine and intertidal wetland (Dunn, 2012).

Method and Materials

Software Libraries

The WIT workflow demonstrated in this paper is built on the Python packages (Van Rossum and Drake Jr., 1995) dea-notebooks and dea-tools (Krause et al., 2021a), geopandas (Jordahl et al., 2020), numpy (Harris et al., 2020), pandas (McKinney, 2010; Reback et al., 2021), xarray (Hoyer and Hamman, 2017), scipy (Jones et al., 2001), matplotlib (Hunter, 2007), Shapely (Gillies et al., 2007), and opendatacube (Leith, 2018). We provide our WIT workflow as an open-source Python package with an Apache Version 2.0 Licence[3] on GitHub[4] (wit-tooling; Ai and Dunn, 2021).

The existing WIT workflow as supplied could be adjusted for application in other countries, with necessary changes to the names of variables and necessary alterations for different high performance computing environments. Applications in other countries require locally produced or available FC, WOfS and Analysis-Ready Surface Reflectance data products, or substitutes thereof, and testing of the performance of the resulting tool in these environments.

EO Analytics Platform

Digital Earth Australia (DEA) is the Australian Government program for managing and distributing Australia's freely available satellite imagery (Dhu et al., 2017; Lewis et al., 2017). Data are made available via the Australian national implementation of the open-source DEA Open Data Cube (ODC) data access, management, and analysis platform (Leith, 2018). The DEA ODC provides the platform on which the WIT workflow is run, enabling users to retrieve, process and store the results of a petabyte of Landsat data.

Input Datasets of the WIT Workflow

Ramsar Wetlands of Australia Dataset

The Ramsar Wetlands of Australia Dataset is a wetland boundary vector dataset available under a Creative Commons Attribution 3.0 Australia Licence (Australian Government Department of Agriculture, Water and the Environment, 2019). We created individual wetland sub-site polygons from the multipart Ramsar site polygons in the dataset using the QGIS Multipart to singleparts tool[5] (QGIS Development Team, 2021). Wetland polygon boundaries do not change over the period of time being analysed and the tool is used to demonstrate changes within the user-defined polygon.

DEA Landsat EO Data

DEA EO data are radiometrically and geometrically corrected into analysis-ready data, enabling users to retrieve corrected, cloud-masked raster data over time (Lewis et al., 2017; Dwyer et al., 2018). The DEA EO data archive includes data from the Landsat 5, 7–9 satellites over the Australian continent from 1987 onward. These satellites return to image the same place every 16 days (Engle and Weinstein, 1983). The Landsat data used in our study are processed to 30 m resolution (Lewis et al., 2017). The WIT workflow is calculated on pre-processed Landsat data corrected for sun angle and topographic effects (NBART: Li et al., 2010, 2012), with areas shaded by topography removed with reference to a Digital Surface Model (DSM; Geoscience Australia, 2014). Clouds and cloud shadows in the data are masked using the Automated Cloud-Cover Assessment (Irish et al., 2006) and Fmask cloud masking algorithms (Zhu and Woodcock, 2012).

Water Observations from Space

Water Observations from Space (WOfS)[6] is a decision tree classifier that uses Landsat imagery to identify unobstructed open water on a per-pixel basis. It has an accuracy of 98% over open water (Mueller et al., 2016). The WIT workflow uses the Water Observations Feature Layers published by DEA to check whether a pixel is classified as open water by the WOfS algorithm (Geoscience Australia, 2022).

DEA Fractional Cover

DEA Fractional Cover (FC; Geoscience Australia, 2015) uses the Vegetation Fractional Cover algorithm created by the Joint Remote Sensing Research Program (JRSRP; Scarth et al., 2010). The JRSRP algorithm estimates the fractions of photosynthetic vegetation, non-photosynthetic vegetation, and bare soil contained within an EO pixel. The FC photosynthetic fraction includes green leaves and grass; the non-photosynthetic fraction includes brown plant matter like branches, dry grass, and leaf litter; and the bare soil fraction includes bare soil, rock, and artificial surfaces (Geoscience Australia, 2015). The WIT workflow uses FC to provide

[3] https://github.com/GeoscienceAustralia/wit_tooling/blob/v2.1.0/LICENSE

[4] https://github.com/GeoscienceAustralia/wit_tooling/releases/tag/v2.1.0

[5] https://docs.qgis.org/3.22/en/docs/user_manual/processing_algs/qgis/vectorgeometry.html?highlight=multipart%20singleparts#multipart-to-singleparts

[6] Now known as DEA Water Observations

insights into the terrestrial dynamics of wetlands. Tracking the green (photosynthetic) vegetation, dry (non-photosynthetic) vegetation, and bare soil within a wetland can allow us to observe bushfires, weed incursions, and seasonal vegetation cycles. The WIT workflow uses FC to determine the per-pixel vegetation percentage. Note that we refer to 'dry vegetation' in this study as the non-photosynthetic vegetation component of FC, not as all non-'wet' vegetation.

Tasseled Cap Wetness

We use Tasseled Cap Wetness (TCW) to identify areas in wetlands that are wet, but not identified by the WOfS algorithm as open water. This includes areas of mixed vegetation and water like in palustrine wetlands. TCW is the third component of a Tasseled Cap Index analysis and can be thresholded to classify wet pixels (Fisher et al., 2016). Tasseled Cap Index analysis is a linear principal component analysis of Landsat imagery with a Procrustes' Rotation (Kauth and Thomas, 1976), producing three components roughly corresponding to brightness (TCB), greenness (TCG) and wetness (TCW; Roberts et al., 2018). We use the coefficients of Crist (1985) to calculate TCW from the DEA Landsat surface reflectance data in the WIT.

TCW has values between −12,915 and 7032 when applied to DEA Landsat data. As TCW increases, the pixel becomes wetter, with open water having TCW values near and above zero (Pasquarella et al., 2016). The continuous TCW could be rescaled to standardise the numbers, but we kept the large scale to preserve the resolution in our data type storage and reduce processing costs. We threshold TCW at −350, with values above this threshold used to characterise 'wet' pixels (see Fig. 12, Table 2 and accompanying text in Appendix A).

The validity and accuracy of WIT plots depends on the accuracy of the component EO algorithms. WOfS and FC have been extensively validated in previous studies (Mueller et al., 2016; Scarth et al., 2010), but our TCW threshold approach used here to identify mixed open water and non-water has not been previously used. The validation of the TCW threshold is described in detail in Appendix A.

Generating WIT Plots with the WIT Workflow

We used the WIT workflow to combine WOfS feature layers, the thresholded TCW, and FC into a stacked line summary plot we call a WIT plot. The stacked line plot has been used to display land cover changes as observed by Landsat in Hermosilla et al. (2018). It is an effective visualisation technique for identifying both the timing and magnitude of change. WIT plots visually summarise the historical behaviour of important wetland components: open water, 'wet' areas, green vegetation, dry vegetation, and bare soil, classified from Landsat observations since 1987.

Data Processing in the WIT Workflow

We collated available satellite imagery for the input polygon to produce the WIT plot. For each day that a satellite observation was collected over the polygon, the WIT workflow checked that at least 90% of the total polygon area had been clearly observed. This removed time steps with significant clouds or missing data, and ensured we were detecting comparable wetland dynamics. Once a clear time step had been identified, each pixel inside the polygon went through the workflow described in Fig. 2:

1. Check if the pixel is cloudy and/or there is no data. If so, then the pixel is classified as 'nodata'.
2. Check if the pixel is classified as open water by WOfS. If so, then the pixel is classified as 'open water'.
3. Check if the pixel is classified as wet by the thresholded TCW. If so, then the pixel is classified as 'wet'.
4. The percentage of the pixel classified as 'green vegetation', 'dry vegetation' and 'bare soil' from FC is returned.

'Nodata', 'open water', 'wet', and remaining pixels are mutually exclusive, with remaining pixels classified into percentages of 'green vegetation', 'dry vegetation', and 'bare soil'. The classified pixels within the polygon for each time step were combined to produce a percentage of the total polygon area at that time step that was open water, wet, green vegetation, dry vegetation and bare soil. The WIT plot is a graphical representation of the change in the wetland components over time.

Low Data Availability Periods in the WIT Plots

From 2003 onwards, failure of the onboard scan-line corrector (SLC) caused large stripes of missing data across the swaths from the Landsat 7 satellite (Markham et al., 2004). During the time period November 2011—April 2013 only the SLC-off Landsat 7 data was available. We indicate this period of low data availability by adding a white shaded overlay on the WIT plots between these dates. Shaded overlays are additionally added to other periods of insufficient data as described in section 3.4.3.

Data Aggregation

Missing data poses explicit challenges to the WIT workflow. The WIT workflow removes observations with less than 90% clear pixels. This is to avoid biasing the results by implying that observed pixels are representative of the whole wetland even when many pixels are unobserved. The missing data check is problematic for wetlands that straddle Landsat swath boundaries, where the whole wetland is

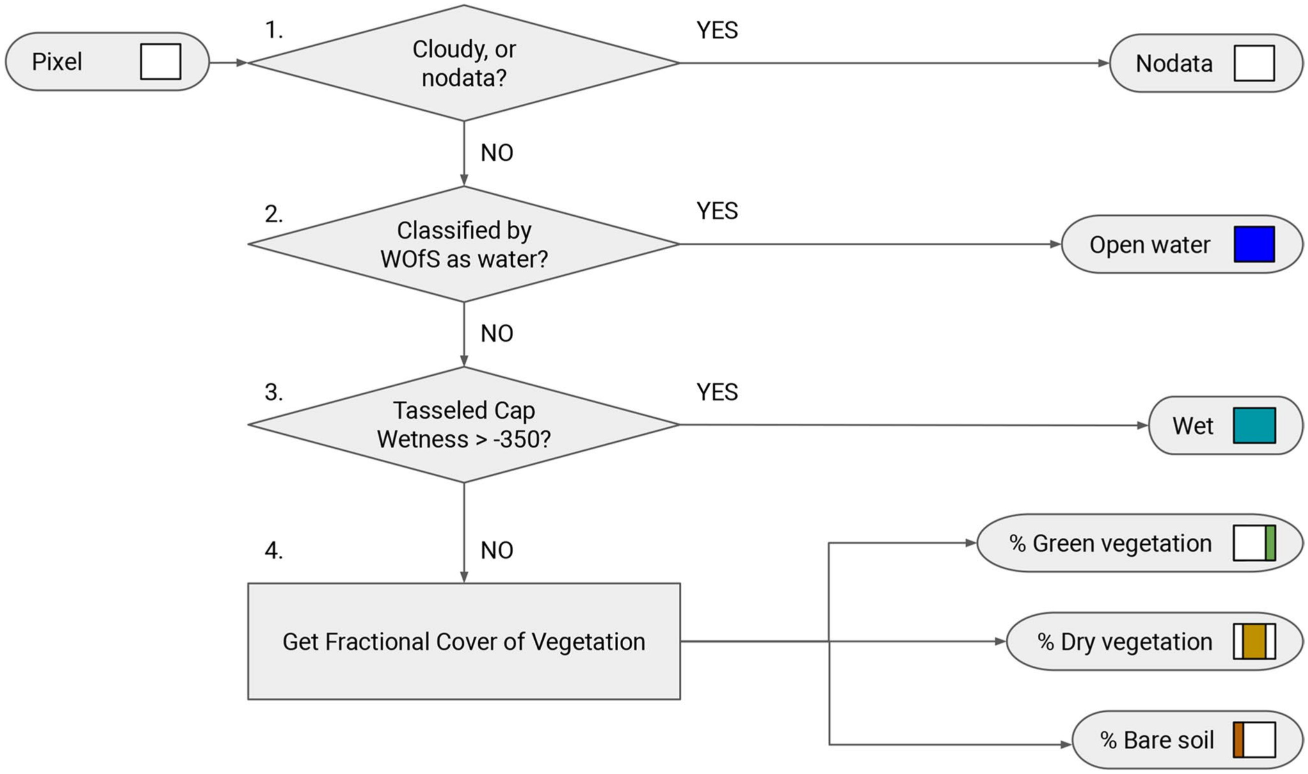


Fig. 2 Logical workflow for classifying a pixel to produce the WIT plots

not observed on a single day. To handle this, we aggregate observations over 16 days. The Landsat satellite revisit interval is 16 days, and this ensures that wetlands across swath boundaries were observed within the interval. Aggregating provides vital information on the behaviour of the whole wetland. This avoids the missing data problem but loses some temporal specificity for changes occurring over shorter observation periods (for aggregation details, please see Appendix C).

Every observed time step that met clear pixel criteria was plotted on the stacked line plot, producing a time-rich picture of observed wetland change. Once all the observations for the polygon have been processed, periods of insufficient data density, where the polygon repeatedly fails to record >90% clear pixels are flagged. Periods in which there are less than four observations in 12 months are shaded white in the WIT plots (section 3.4, Queensland Department of Environment and Science, 2019).

Output Data Access

The WIT plots for all of Australia's Ramsar listed wetlands are published as the interactive web service 'DEA Wetlands Insight Tool (Ramsar Wetlands) v4.0.0' on the DEA Maps platform (https://maps.dea.ga.gov.au/#share=s-dJQFNnM33jQFrpO3G0vkaqOvJRc). Metadata and links to download the entire CC BY 4.0-licensed dataset can be accessed at the official product site (https://cmi.ga.gov.au/data-products/dea/669/dea-wetlands-insight-tool-ramsar-wetlands#details).

A data package including the vector file, attributes, readme, and comma-separated values (CSV) and Portable Network Graphic (PNG) file results are publicly available via Amazon S3: https://data.dea.ga.gov.au/?prefix=derivative/ga_ls_wit_ramsar_class_myear_3/1-0-0/1986%2D%2DP35Y/ga_ls_wit_ramsar_class_myear_3_1986%2D%2DP35Y.zip. Appendix B Table 3 includes site and sub-site reference details for each figure to aid in data access.

Results – Ramsar Wetlands Case Studies

The WIT plots for our case study Ramsar sites are detailed in the sections below to demonstrate how the WIT workflow captures wetland hydrology dynamics including the onset of inundation events, proportion of wetland inundated, and duration of the inundation events. The examples also illustrate how WIT plots can be used to quantify the vegetation growth response to inundation events.

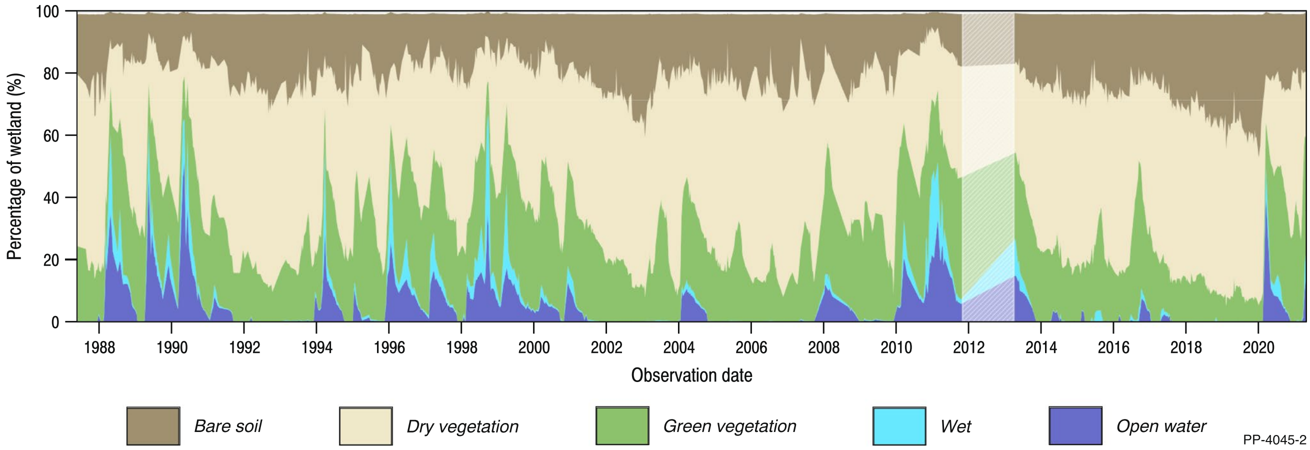


Fig. 3 WIT plot for Narran Lake Nature Reserve, New South Wales (Fig. 1, #53). Low data density is indicated by white shaded sections

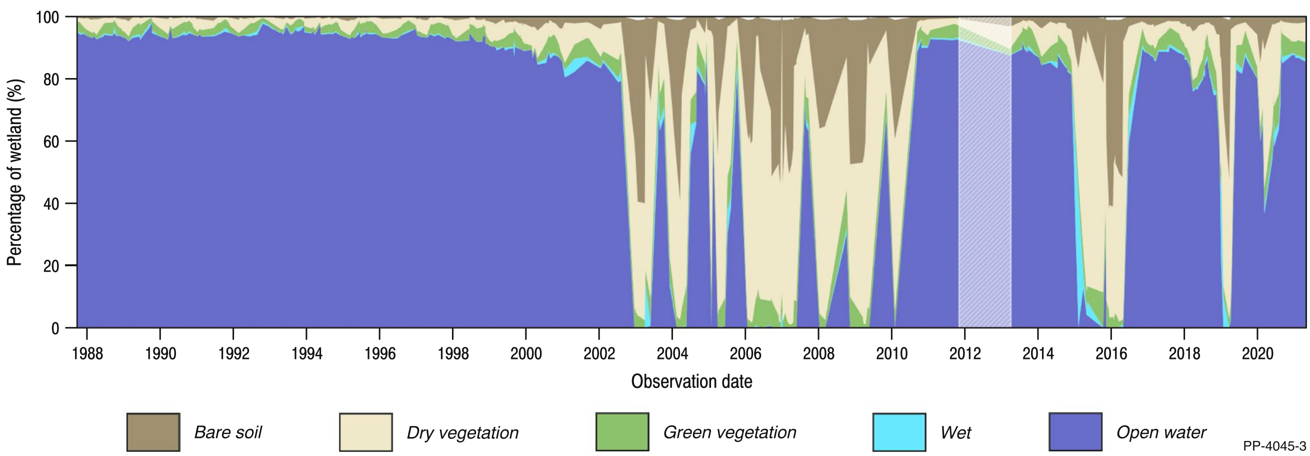


Fig. 4 WIT plot for Lake Gnarpurt, Victoria (Fig. 1, #20). Low data density is indicated by white shaded sections

Narran Lake Nature Reserve Ramsar Site #53 (8447 Ha)

Narran Lake Nature Reserve comprises large areas of lignum, forming dense shrubland thickets around a network of open water lakes which fill from river flows (Butcher et al., 2011; New South Wales National Parks and Wildlife Service, 2000). The high inter-annual variability of flows produces complex flooding patterns with frequent flooding occurring approximately every 2 years (New South Wales National Parks and Wildlife Service, 2000). This flooding regime is captured in the WIT plot (Fig. 3). The Narran Lake Nature Reserve Ramsar site polygon does not include lakes and flooded areas outside the site, such as Narran Lake.

Flows and flooding to Narran Lake Nature Reserve have been altered due to large-scale water resource development upstream (Thoms et al., 2008). Since 1992, periods of flooding have become punctuated by extended dry intervals. The WIT plot clearly shows distinct dry periods: 1992 to 1994, during the Millennium Drought from 2001 to 2009 (Van Dijk et al., 2013), and post-2017 (Fig. 3). These appear as an absence of 'open water' and 'wet' vegetation and with increasing proportions of 'dry vegetation' and 'bare soil' (Fig. 3).

Western District Lakes Ramsar Site #20 – Lake Gnarpurt Sub-Site (2513 Ha)

Lake Gnarpurt is a freshwater to slightly saline lake. It is classified as a semi-permanent body of water with an average depth of 2.57 m (Hose et al., 2008). Local rainfall is the predominant water source of Lake Gnarpurt and other lakes in the Western District Lakes Ramsar site (Butcher et al., 2011).

Periods of extended drought have led to the lake drying completely over the past century (Dahlhaus et al., 2008; Hale and Butcher, 2011). The WIT plot (Fig. 4) shows dry

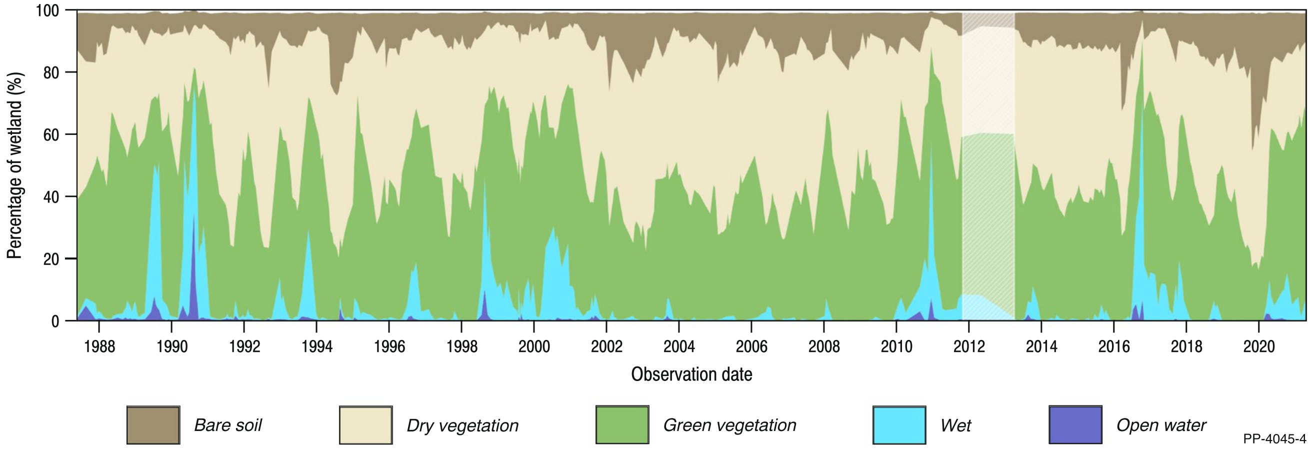


Fig. 5 WIT plot for Macquarie Marshes Nature Reserve Northern Section, New South Wales (Fig. 1, #28). Low data density is indicated by white shaded sections

periods during the Millennium Drought (2001–2009) and in 2015–2016 and 2019 after several years of rainfall deficit (Bureau of Meteorology, 2020a , 2015), with sustained inundation following periods of above average rainfall associated with La Nina events in 2010–11 and 2016 (Bureau of Meteorology, 2020b).

Water resource development, combined with the reduction in winter and spring rainfall associated with climate change, is likely to result in reductions in both water levels and waterbody permanence, leading to greater incidence of dry periods in the future (Hale and Butcher, 2011; Hose et al., 2008; Water Technology, 2010).

Macquarie Marshes Nature Reserve Ramsar Site #28 – Northern Section Sub-Site (11,953 Ha)

The Macquarie Marshes Nature Reserve is characterised by a complex mosaic of tall emergent grasslands, riverine forests, woodlands, sedgelands, open water lagoons, and large areas of terrestrial grasslands (New South Wales Government Office of Environment and Heritage, 2012). The complex is driven by variable flooding. The heterogeneous coverage and the high dynamism of vegetation is evident in the intra- and inter-annual fluctuations of the 'open water', 'wet', and 'green vegetation' proportions in the WIT plot (Fig. 5). The extended dry period of the Millennium Drought (2001–2009) can also be observed in the WIT plot (Fig. 5). During this period, flood extent ('open water') is minimal, and the proportion of 'green vegetation' rarely covers more than 40% of the Ramsar site compared to flooded years where 'green vegetation' can reach over 80% of the area. Large areas of 'dry vegetation' and 'bare soil' occur more frequently during dry periods. This is particularly noticeable in the WIT plot after the 2016–17 flooding (Fig. 5).

Ginini Flats Wetland Complex Ramsar Site #45 (350 Ha)

The Ginini Flats Wetland Complex Ramsar Site is characterised by snow gum woodlands surrounding three sub-alpine (1590 m) sphagnum shrub bogs. Regionally catastrophic bushfires in 2003 resulted in 50% of bog vegetation in the Ginini wetlands being burnt (Hope et al., 2009). Early post-fire recovery included the conversion of burnt sphagnum around the margins of each bog to tussock grassland, and rehabilitative channel damming targeted the restoration of open pools of water to flood the adjacent bog (Whinam et al., 2010; Wild et al., 2010).

Impacts of the 2003 bushfires are reflected in changes to the cyclicity and composition of water and vegetation dynamics at the site (Fig. 6). Pre-2003, the site was characterized by annual fluctuations in predominantly 'green vegetation' (60–80%) and 'wet' classes (40–60%). After 2003, and despite peatland channel damming, the magnitude of 'open water' and 'wet' classes were much reduced (<20%), and the system has instead cycled through a more depressed ratio of 'green vegetation' (<60%) to increased 'dry vegetation' (30–50%). Early post-fire peaks in 'bare soil' (>15%) were essentially recovered to pre-fire levels after 2012, with 'wet' showing increasing recovery since this time (Fig. 6).

Paroo River Wetlands Ramsar Site #65 - Peery Sub-site (47,295 ha)

Peery Lake is a large episodic lake (Timms, 2001) within the Peery Sub-site of the Paroo River Wetlands Ramsar site. It is one of the largest lakes of the Paroo overflow, a vast area dominated by mulga shrublands and other woody shrub species (Kingsford and Lee, 2010; Timms, 2001). Located in the arid zone, the episodic nature of flooding in Peery Lake

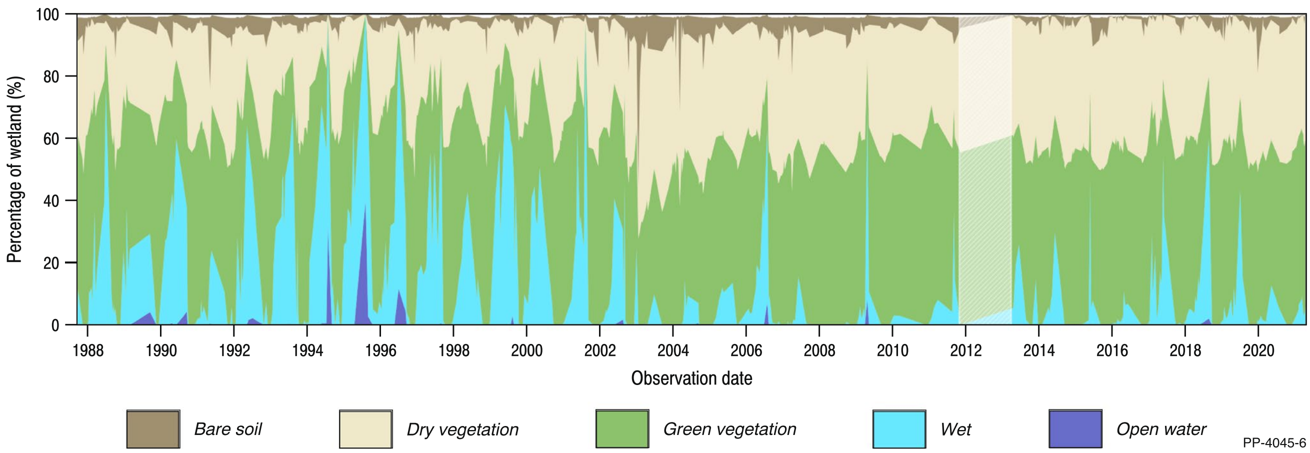


Fig. 6 WIT plot for Ginini Flats Wetland Complex, Australian Capital Territory (Fig. 1, #45). Low data density is indicated by white shaded sections

is due to highly variable inflows: the lake fills on average every 5 years, but flooding may last for up to years (Kingsford and Lee, 2010). This pattern is evident in the WIT plot (Fig. 7). The fluctuations in the proportion of 'green vegetation' in the WIT plot is indicative of vegetation response after flooding, with the large proportions of 'dry vegetation' and 'bare soil' indicative of the vast areas of sparse shrubland within the Ramsar site boundary (Fig. 7).

NSW Central Murray Forests Ramsar Site #64 - Millewa Forest Sub-site (13,647 ha)

Millewa Forest is a sub-site of the NSW Central Murray Forests Ramsar Site and represents a large riverine forest dominated almost exclusively by river red gums which surround the open water area of Moira Lake, as well as tall emergent grassland and sedgeland swamps (Harrington and Hale, 2011). At least 40% of the Millewa Forest persists as 'green vegetation', increasing up to 90% in response to flooding (Fig. 8). The seasonal nature of flooding within Millewa Forest is evident in the WIT plot, which shows annual spikes in 'open water' and 'wet', except for the years of the Millennium Drought (2001–2009) (Fig. 8). Following the Millennium Drought, flooded areas and the magnitude of the 'green vegetation' response were diminished compared to pre-2002 levels (Fig. 8).

Discussion

Advantages

The WIT workflow produces information on wetland dynamics over time in an intuitive and decision-ready format. The WIT plots make it easy to interpret the timing and magnitude of changes that are occurring within the wetland. The information is simplified into a series of water and vegetation metrics, making it interpretable without needing formal EO training or experience.

The WIT workflow provides wetland managers, environmental water managers, catchment managers, and ecologists with the ability to engage with continental satellite imagery archive data. The Ramsar wetland case studies presented above demonstrate how WIT plots provide insight into significant changes in wetland hydrology (e.g., Lake Gnarpurt), multi-decadal fluctuations in hydroperiod (e.g. Narran Lakes and Macquarie Marshes), the response of a wetland to the application of environmental flows (e.g. Millewa Forest), and the response of an alpine wetland to a fire event (e.g. Ginini Wetlands). Insight into these changes allows wetland practitioners to place the current state of these wetlands into the context of their multi-decadal behaviour. Wetland managers can then investigate changes of concern and demonstrate the hydroperiod benefits achieved by environmental flows. WIT plots can be combined with other data sources such as climate and weather data, groundwater bore, or stream gauge data to derive insight into how wetlands have responded to past climatic variations such as droughts, which may provide insight into how wetlands will respond to future climate perturbations. By including insights into vegetation dynamics alongside water and 'wet' categories, the WIT workflow provides an advantage over products such as the Global Surface Water Explorer (Pekel et al., 2016), which focusses solely on open water. The WIT workflow can characterise wetland behaviour when no open water is present.

The WIT workflow is scalable and can be run over a single wetland or many thousands. The WIT workflow is easily parallelized as the results for each wetland polygon can be individually calculated. The scalability of the WIT workflow allows this tool to be applied over large-scale monitoring activities, like Australia's Ramsar wetlands or state-based wetland programs. For example, the WIT plots have already

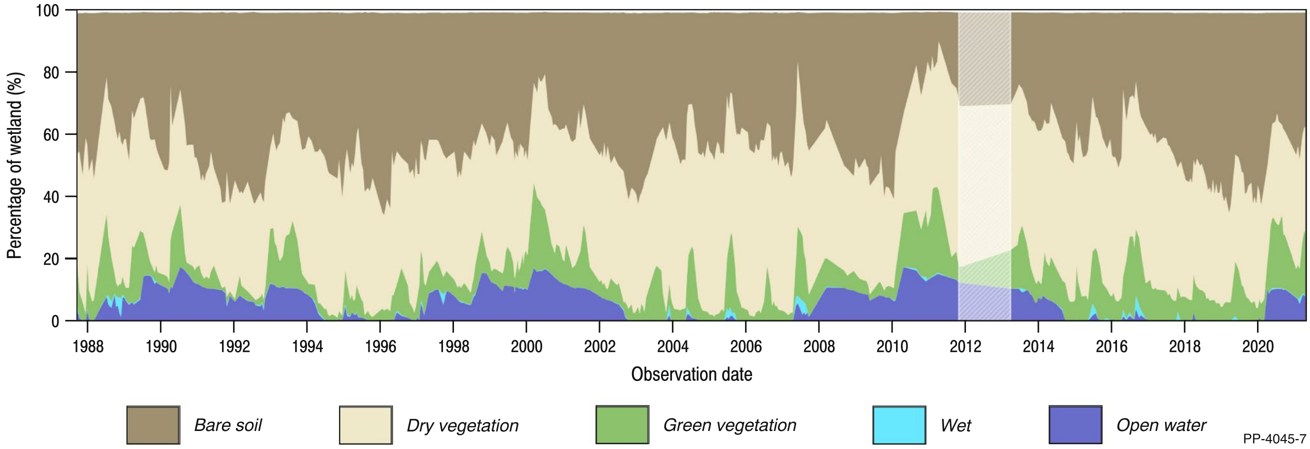


Fig. 7 WIT plot for Peery, New South Wales (Fig. 1, #65). Low data density is indicated by white shaded sections

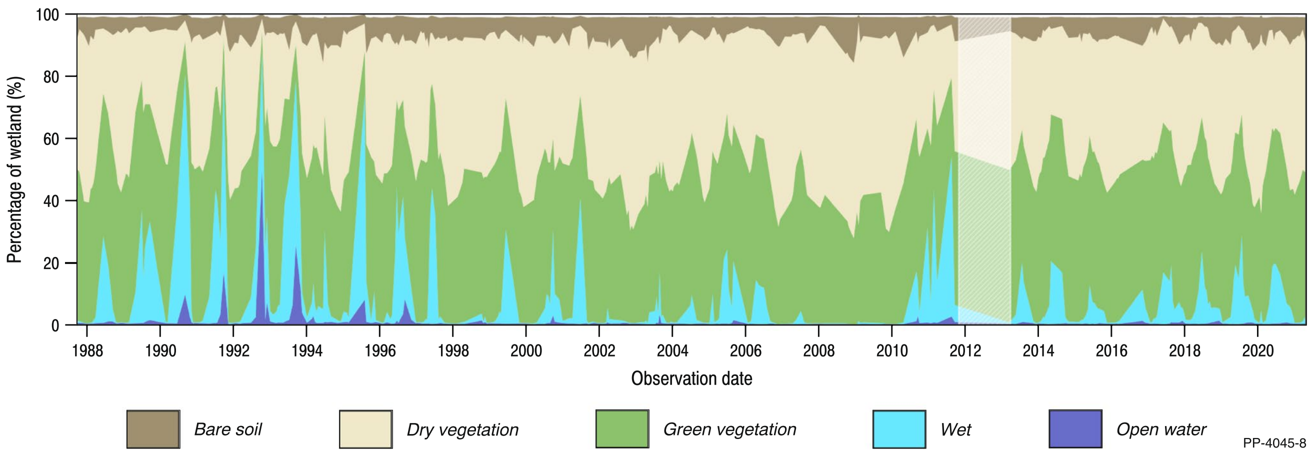


Fig. 8 WIT plot for Millewa Forest, New South Wales (Fig. 1, #64). Low data density is indicated by white shaded sections

found uses in Queensland's Wetland*Info* website.[7] The wetlands mapping displayed in Wetland*Info* is integrated with the WIT plots for 270,421 wetland polygons, providing additional temporal information for lacustrine and palustrine wetlands in Queensland (Queensland Department of Environment and Science, 2019). Applying the WIT workflow at this scale provides the opportunity to compare the hydroperiod changes and vegetation response of wetlands across the whole state of Queensland, providing spatio-temporal contextual information for each individual wetland.

The WIT workflow is transferable into new environments and applications where satellite data is available. The WIT workflow is run on user-defined polygons, making it tailorable to individual applications (e.g., looking at sub-sites within wetland areas as well as the wetland as a whole) and regions of interest. The capability of the WIT workflow to be run on multiple different wetland boundaries (not just the Ramsar site boundary) can be particularly useful when reporting on an entire wetland, such as the Macquarie Marshes. The WIT workflow can even be run on non-wetland polygons to provide insights into water and vegetation dynamics of any polygon region, such as a crop paddock, as long as the limitations of the method are understood. The ability to quickly and easily produce WIT plots means that it could become the basis for future operational management tools.

The WIT workflow enables a consistent and repeatable approach to quantifying and comparing the hydrodynamics of wetlands and their response to changes in hydrology. The WIT plots can contribute to ecological assessments, such as classifying the typology of wetlands under methods such as the International Union for Conservation of Nature (IUCN) Global Ecosystem Typology approach (Keith et al., 2022).

[7] https://wetlandinfo.des.qld.gov.au/wetlands/facts-maps/wetland-background/insight.html

Limitations

Limitations of Landsat Data

The use of Landsat satellite imagery to explore wetland dynamics comes with limitations in data frequency and density of available observations, caused by the revisit time of the satellite and the inability to 'see' the ground through cloud cover. Each Landsat satellite has a re-visit period of approximately 16 days, with events occurring between valid observations missed by the satellites. The 30 m resolution of Landsat data must also be remembered when considering the ability of WIT plots to resolve the behaviour of small or narrow/linear wetlands. The use of a stacked line plot as the visualisation mechanism for the WIT workflow makes the changes in percentage of water, wet vegetation, green vegetation, dry vegetation, and bare soil easier to visualise through time, but interpreting the WIT plots without an awareness of the limitations of the method and the satellites can lead to misreading the WIT plots and missing signals in the data. Users of the WIT plots need to understand the limitations of the underlying data, and limitations due to the linear interpolation of available observations in the WIT plots.

Landsat is an optical satellite and cannot see through cloud cover (Ju and Roy, 2008). Removing observations where clouds are present can cause underestimation of both the extent and duration of wet events as these often occur when there are clouds (Hermosilla et al., 2015). This affects the observation density in WIT plots and can bias some time series towards the dry season, (e.g. in the monsoon region of Northern Australia (Pfitzner et al., 2022)) or result in low data densities in regions affected by year-round cloud cover (e.g. Tasmania (Gill et al., 2017)). Additionally, the duration of events such as floods may not be accurately captured by satellite data due to sampling gaps (Rättich et al., 2020), and short-lived events may be mischaracterized or missed entirely by WIT plots.

Limitations of WIT Input Algorithms

WOfS is conservative: water is underestimated in mixed-signal pixels. The accuracy of WOfS drops to 74% in areas with mixed water and vegetation pixels (Mueller et al., 2016). The low accuracy in mixed water/vegetation pixels is a problem for the detection of water in wetland environments (Thomas et al., 2015). We address this in the WIT workflow by using WOfS only for the detection of open water pixels. We supplement WOfS with the TCW for mixed pixels (see Tasseled Cap Wetness) to better capture water within wetland areas.

FC is a vegetation unmixing algorithm and is not designed to resolve water. We therefore only make use of FC in pixels that are not already classified as 'open water' or 'wet' for that observation.

TCW may not accurately detect inundated vegetation in situations where vegetation is very thick, e.g. beneath tree canopy, under floating vegetation rafts, or in areas of tall dense macrophytes (see Thomas et al., 2015). This is a limitation of satellite observation-based classifications, as the lack of a water signal through the vegetation means that any water classifier will fail in this instance. Additionally, TCW is sensitive to plant and soil moisture (Crist and Cicone, 1984; Jin and Sader, 2005), requiring a careful interpretation of the 'wet' signal in thickly forested environments. Dark or shadowed dark soil can be misclassified as 'wet' due to the similar lack of signal reaching the satellite from dark, dark shadowed, or dark wet areas (Fisher et al., 2016; Kauth and Thomas, 1976). Using a predefined polygon helps to mitigate this, since the workflow will only be applied in regions already defined as wetlands.

Polygon Limitations

A WIT plot is strongly affected by the polygon enclosing the wetland and can be run on any user-provided polygon. The WIT workflow is not designed to detect changes in the spatial extent of a wetland, rather its hydrological regime. Users need to check that the polygons enclosing each wetland are still representative of the extent of the area of interest. If a wetland extent changes over time, the polygon used to represent that wetland area needs to be regenerated. This highlights the importance of the quality of the polygon used to create the WIT plot, and why these should be supplied by wetland managers. Wetland boundaries for Ramsar sites may not reflect current state of the wetland described, or the true extent of the wetland (Rogers et al., 2014) because Ramsar boundaries are mostly tenure based. The Ramsar wetlands have however been used as case studies in this paper due to their representation of Australian wetland types and availability of ground-based studies to compare the WIT plots to.

In cases where a wetland polygon includes significant non-wetland area, the WIT plots are composed of both the wetland and non-wetland area. This dilutes the results of interest with superfluous data. Figure 9 is an example of this where the plot is dominated by 'open water' throughout the time series, with a very strong water signal overwhelming the dynamics at the edge of the water. Similarly, if a poorly defined wetland polygon contained significant area of surrounding non-wetland vegetation (like a grassed paddock), the green vegetation proportion of the resulting WIT plot would over represent the area of photosynthetic vegetation within the wetland.

The size of polygons processed with WIT workflow will also influence the utility of the resultant WIT plots. While the WIT workflow does not explicitly limit the size of

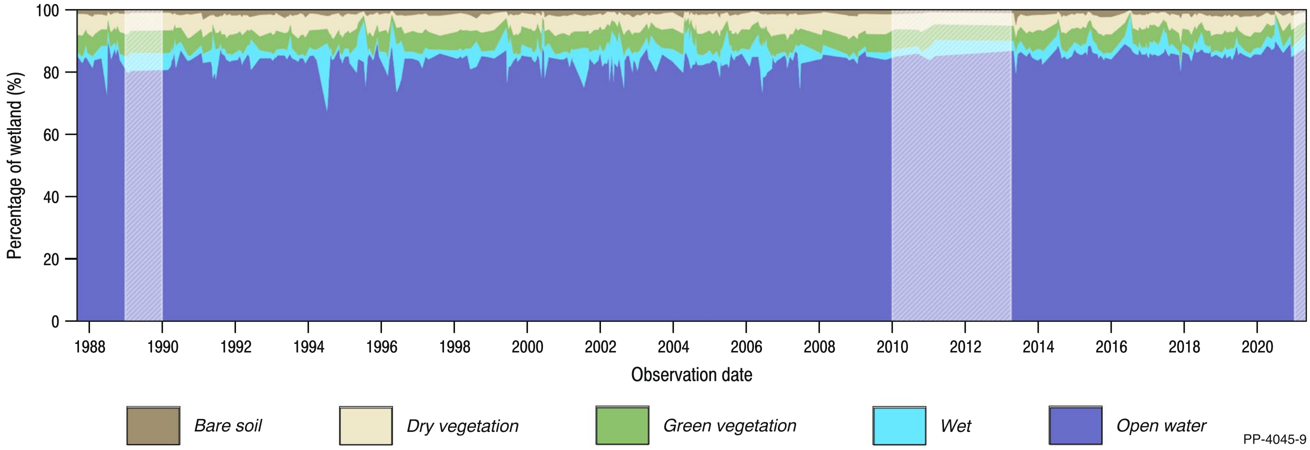


Fig. 9 WIT plot for Moulting Lagoon, Tasmania (Fig. 1, #3), an estuarine and intertidal system. Low data density is indicated by white shaded sections

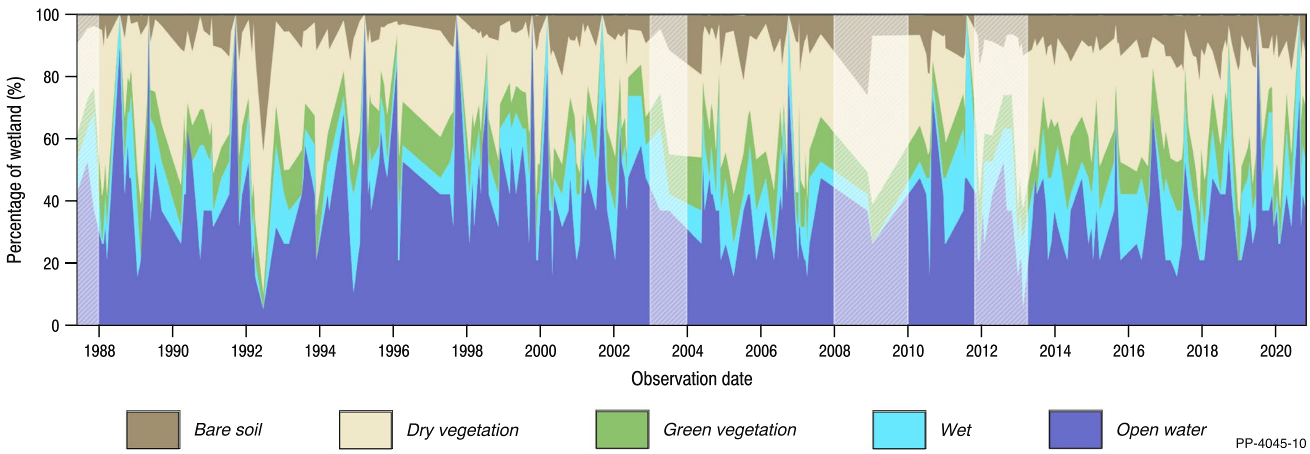


Fig. 10 WIT plot for Barren Island, a small island within Pitt Water – Orielton Lagoon, Tasmania (Fig. 1, #6) . This polygon touches a maximum of 4 Landsat pixels, meaning the resultant WIT plot is dominated by step-changes caused by changes in individual pixels. This makes the resultant plot noisy and difficult to interpret. Low data density is indicated by white shaded sections

polygons that can be run through it, polygons that are small will not give meaningful results as the WIT plot will be heavily dominated by noise in the individual pixels, rather than a realistic change (e.g. Figure 10). Additionally, the 30 m pixel resolution of Landsat in DEA means that small features such as springs or gullies may be missed.

Biophysical Limitations

Satellite-based indicators of water and vegetation need to be interpreted with caution, since they are unable to provide information about the specific characteristics of water or vegetation detected. For example, the green vegetation fraction represented in the WIT plots is not necessarily non-invasive vegetation. Invasive aquatic weeds could cause an increase in 'green vegetation' which represents a decrease in wetland condition. The green vegetation fraction does not provide any information about important ecological characteristics like vegetation maturity, and therefore cannot provide information about the number of mature, hollow-bearing trees or the amount of juvenile recruitment or survival.

The FC algorithm is sometimes inaccurate when it comes to distinguishing bare soil from dry vegetation for certain soil background colours (Bai et al., 2021). For example, the Lake Gnarpurt plot (Fig. 4) may overestimate the amount of dry vegetation present due to the soil colour of the lake bed being misclassified as dry vegetation.

Similarly, the water classes do not provide information on whether the water is clear, highly turbid, or contains significant chlorophyll concentration, noting that thick algal mats on the surface of an inundated area will not necessarily be identified as a 'wet' pixel due to the limitations of the water classifier. This means that shifts in water quality that impact on the limnology of the wetlands will not be captured in these WIT plots. Increased hydroperiod can be detrimental to vegetation communities that are dependent on seasonal fluctuations in water levels and cycles of wetting and drying, and therefore this characteristic needs to be carefully interpreted rather than used as a straightforward metric. In the Australian context, many wetlands dry completely either seasonally, intermittently, or episodically, and the vegetation is adapted to these conditions through long-lived seedbanks and employing several modes of dispersal (wind, waterbirds and water; Roberts et al., 2017). Additionally, areas classed as 'wet' are not necessarily limited to the inundated wetland footprint and may be the result of recent rainfall. This again highlights the importance of using well defined wetland polygon boundaries in this tool.

The WIT plots are designed for use in freshwater rather than tidal wetlands. The rapid changes in surface water extent caused by tidal fluctuations make for noisy plots, and the green vegetation fraction of important intertidal vegetation communities such as saltmarshes, mangroves and seagrasses need to be interpreted with reference to tidal influence (specifically the presence or absence of water mixed in with the vegetation) to avoid misleading results.

Importantly, the WIT plots represent surface area rather than depth. Consequently, the WIT plots do not provide insight into the amount of habitat available to species that have specific water depth requirements to complete their life cycle.

Workflow Limitations

Providing the WIT plots as a summary of the spatial pixels means that the spatial coverage of the data for a single date is obscured. Where limited cloud cover (<10%) occurs in an observation included in a WIT plot, the spatial distribution of the cloud cover and its contribution to the uncertainty are not captured in the result. If specific data points within the WIT plot appear anomalous, we recommend that users visually assess imagery from the corresponding date to identify whether the cloud is obscuring a key component of the wetland.

Conclusion and Future Work

The WIT workflow summarises the information contained in multidecadal satellite imagery and presents that information in a way that is accessible to a wide range of wetland stakeholders. The information presented by the WIT plot for a particular wetland provides insight into how that wetland changes over time and places its current behaviour into historical context. The results presented in this paper illustrate how WIT plots provide insight into a range of different Australian wetlands.

We demonstrated the WIT plots' applicability to wetlands with flows changed by water resource development (Narran Lake Nature Reserve), drought (Lake Gnarpurt Sub-site), and wildfire (Ginini Flats Wetland Complex). We also demonstrated the ability of the WIT plots to capture wetland dynamics on multiple temporal scales; multi-year episodic (Peery Lake), semi-permanent (Lake Gnarpurt Sub-site), seasonal (Millewa Forest), approximately 2-yearly (Narran Lake), and variable (Macquarie Marshes Northern Section).

The WIT workflow is open source and can be applied to any region. Future work can extend and enhance the tool. The WIT workflow could be used as an input to temporal Object-Based Image Analysis (OBIA) classifications, to separate wetlands into behaviour classes, e.g., for the application of Sustainable Development Goal monitoring. The use of multi-dataset based OBIA for wetland delineation is suggested by Halabisky et al. (2018).

Future work will include identifying areas of permanent water in a wetland (e.g., for coastal wetlands). This will allow us to remove permanent water and identify only water that changes behaviour, increasing the utility of the WIT plots for managing wetlands in tidal areas. Sorting imagery by tide level would allow 'like-for-like' comparison of intertidal wetland behaviour, similar to Bishop-Taylor et al. (2019). Both these additions could make the WIT workflow more useful for intertidal wetlands.

The WIT plots provide information on a per-wetland basis. When comparing multiple wetlands simultaneously it becomes necessary to compare metrics such as inundation or vegetation growth dynamics. Providing these metrics on a per-event, annual, or decadal basis would enable comparisons of multiple wetlands within or between catchments. The WIT plots are a spatio-temporal rather than event-based, spatial representation of wetland cover. Wetland management often requires identifying the spatial distribution of inundation or vegetation responses. Interactive WIT plots that allow users to visualise the spatial distribution of cover types for a particular point in time are currently being explored.

The WIT plots make historical wetland dynamics accessible. Using the WIT workflow will allow wetland managers to make better decisions and improve the management of our crucial wetland systems.

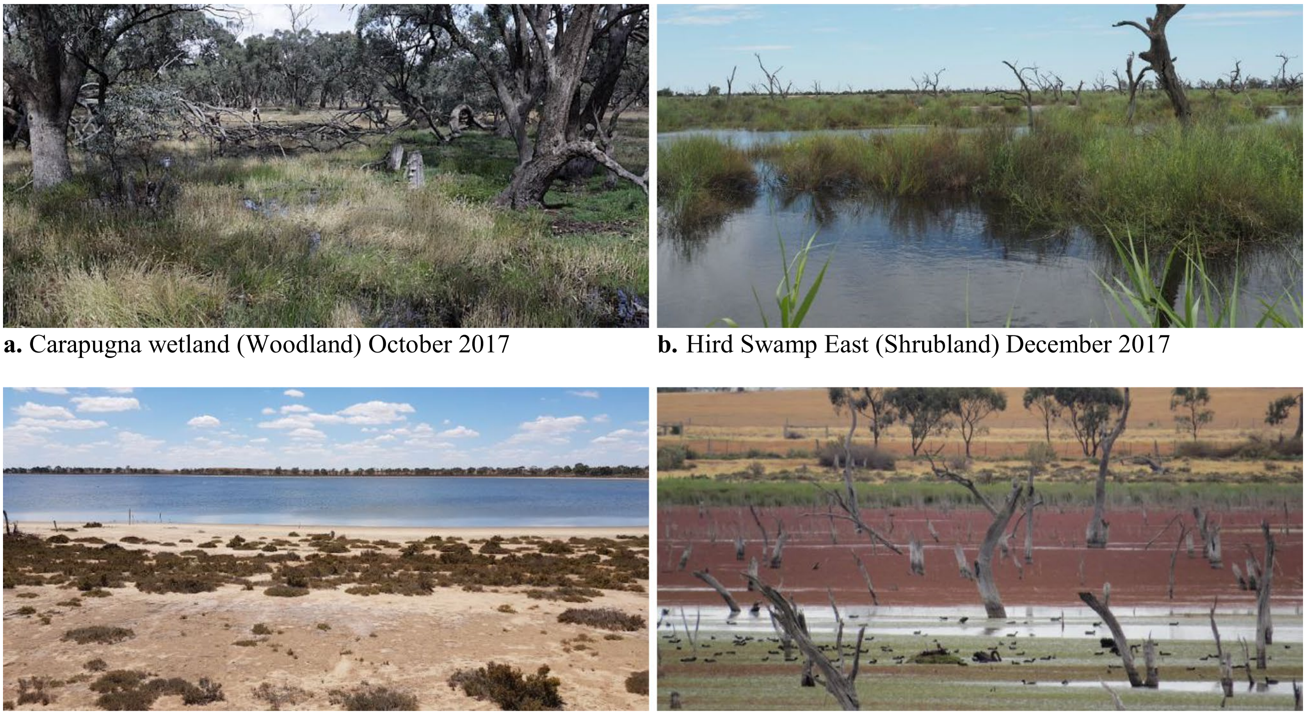
Appendix A Tasseled Cap Threshold

Methods

Datasets

The reference inundation extent map for the Macquarie Marshes was generated from a 28 June 2016 Landsat image using the method of Thomas et al. (2015) (DPE, 2020).

We used wetlands field observations from the Wetland Monitoring and Assessment Program (WetMAP) for environmental water (Papas et al., 2021) project for the WIT workflow validation. As part of waterbird monitoring, WetMAP recorded the estimated area



a. Carapugna wetland (Woodland) October 2017

b. Hird Swamp East (Shrubland) December 2017

c. Lake Elizabeth (Open water) February 2019

d. Lake Murphy South (Open water and macrophytes) October 2019

Fig. 11 Photographs of the different wetland types contained within the WetMAP surveys. **a.** Carapugna wetland (Woodland) October 2017. **b.** Hird Swamp East (Shrubland) December 2017. **c.** Lake Elizabeth (Open water) February 2019. d. Lake Murphy South (Open water and macrophytes) October 2019

of standing water for 19 wetlands from 2017 to 2020 (Table 1). The proportion of water in each wetland was estimated independently by two observers using a categorical scale (0 = absent, 1 = 1–<5%, 2 = 5–<25%, 3 = 25–<50%, 4 = 50–<75%, 5 = >75%). If estimates from the two observers diverged, then percentage cover was discussed and a mutually agreed value determined. Wetlands were photographed in each survey, and adjustments to the estimated water cover were made if discrepancies were detected between the photographs and observer estimates.

The ephemeral wetlands in the field observation dataset all received environmental water during the study period. Of the 151 wet surface area observations included in the WetMAP waterbird dataset, we discarded the observations associated with four wetland sites due to low numbers of good quality observations, resulting in 141 observations that contributed to our comparison. Photographs of the WetMAP wetlands (Fig. 11) show the diversity of wetland types captured in our validation dataset. They include wetlands with a high tree canopy cover (e.g., Fig. 11a), shrubland (e.g., Fig. 11b), open water dominated (e.g., Fig. 11c), and wetlands that combine both open water and submerged/semi-emergent macrophytes (e.g Fig. 11d).

Tasseled cap wetness threshold determination

This appendix describes the process for setting the TCW threshold used in the Wetlands Insight Tool. We developed a TCW threshold to identify 'wet' pixels by comparing TCW to known inundation extents in the Macquarie Marshes, a large floodplain wetland in the Murray-Darling Basin of south-eastern Australia (Thomas et al., 2015). We chose the Macquarie Marshes for threshold calibration as the area is a heterogeneous landscape of mixed cover types including open water, wet, and dry vegetation types, and is where flooding is unreliably detected by open water index classifications (Thomas et al., 2015).

We identified a TCW threshold value of −350 by comparing TCW threshold maps from thresholds of 0 to −600 at −50 intervals derived from a 28 June 2016 Landsat image observation over the Macquarie Marshes, with a reference inundation extent map generated from the method of Thomas et al. (2015) (DPE, 2020). We chose the threshold for the WIT workflow to minimise the absolute difference in extent between the observed inundated area and the area of thresholded TCW (Fig. 12). The area of the map identified as 'wet' by the TCW threshold decreases as the TCW threshold is increased from −600

Table 1 Table of WETmap project wetland names, identification codes, dominant vegetation types and water regimes

Name	Code	Dominant vegetation type	Water regime
Vinifera Floodplain	VINI	Woodland	Periodically Inundated - Episodic
Carapugna	CARA	Woodland	Periodically Inundated - Seasonal
Heywood's Lake	LAHE	Open water	Periodically Inundated - Episodic
Little Lake Meran	LLME	Open water/aquatic macrophytes	Periodically Inundated - Episodic
Round Lake	ROLA	Open water	Permanent
Lake Meran	LAME	Open water	Permanent
Lake Murphy South	LAMU_S	Open water/aquatic macrophytes	Periodically Inundated - Episodic
Lake Murphy North	LAMU_N	Open water/aquatic macrophytes	Periodically Inundated - Episodic
Lake Elizabeth	LAEL	Open water	Permanent
Lake Cullen	LACU	Open water	Permanent
Wirra-Lo Brolga Swamp	WILO_BS	Open water/aquatic macrophytes	Periodically Inundated - Seasonal
Wirra-Lo Lignum Swamp	WILO_LS	Shrubland	Periodically Inundated - Seasonal
McDonalds Swamp	MASW	Emergent graminoids	Periodically Inundated - Episodic
Hird Swamp East	HISW_E	Shrubland	Periodically Inundated - Episodic
Hird Swamp West	HISW_W	Open water	Periodically Inundated - Episodic
Richardson's Lagoon East	RILA_E	Open water	Periodically Inundated - Seasonal Episodic
Richardson's Lagoon West	RILA_W	Open water	Periodically Inundated - Episodic
Lake Yando	LAYO	Woodland	Periodically Inundated - Episodic
Black Swamp	BLSW	Open water/woodland fringe	Periodically Inundated - Seasonal/Episodic
Reedy Swamp	RESW	Open water/woodland fringe	Periodically Inundated - Episodic
Gaynor Swamp	GASW	Shrubland/emergent graminoids	Periodically Inundated - Episodic
Neds Cortner Central	NECC	Shrubland/open water	Periodically Inundated - Episodic
Moodie Swamp	MOSW	Emergent graminoids/aquatic macrophytes	Periodically Inundated - Episodic

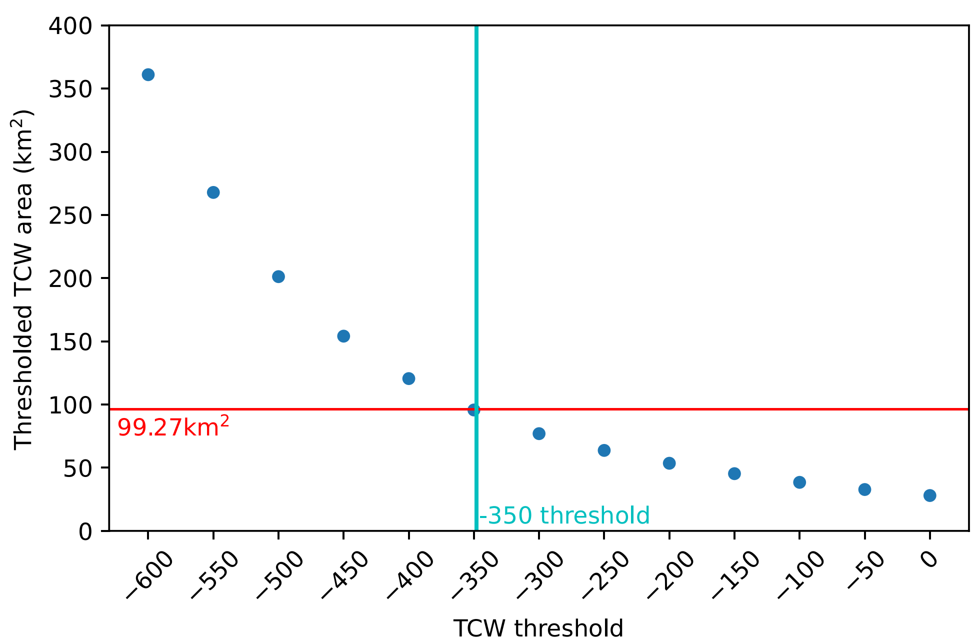


Fig. 12 Comparison between the area identified as 'wet' by the TCW threshold and the set threshold. The red horizontal line is the area identified by inundation mapping (99.27 km^2) and the cyan vertical line is the chosen threshold (−350). Blue dots represent thresholded TCW maps for the reference date 28 June 20160

to 0. The maps for the thresholded TCW above the −350 line (thresholds −300, −250, −200, −150, −100, −50, 0) underestimate the area identified as wet by the reference map. Thresholds below the −350 line (−400, −450, −500, −550, −600) overestimate the area identified as 'wet' by the reference map.

Table 2 Comparison between the 'wet' and 'non-wet' areas identified in the reference inundation extent map of 28 June 2016 (DPE, 2020) with the 'wet' and 'non-wet' areas identified by the thresholded TCW analysis

TCW threshold	TCW 'wet' area (km^2)	Reference map 'wet' area (km^2)	TCW 'non-wet' area (km^2)	Reference map 'non-wet' area (km^2)	total map area (km^2)
0	27.98	99.27	2722.82	2651.53	2750.8
−50	32.73	99.27	2718.07	2651.53	2750.8
−100	38.41	99.27	2712.39	2651.53	2750.8
−150	45.29	99.27	2705.51	2651.53	2750.8
−200	53.51	99.27	2697.29	2651.53	2750.8
−250	63.68	99.27	2687.12	2651.53	2750.8
−300	76.94	99.27	2673.86	2651.53	2750.8
−350	95.68	99.27	2655.12	2651.53	2750.8
−400	120.51	99.27	2630.29	2651.53	2750.8
−450	154.09	99.27	2596.71	2651.53	2750.8
−500	201.18	99.27	2549.62	2651.53	2750.8
−550	267.81	99.27	2482.99	2651.53	2750.8
−600	360.96	99.27	2389.84	2651.53	2750.8

The threshold overlay analysis was performed in QGIS with statistics generated using Python. Maps were visually compared to assess the performance of the TCW thresholds, and the total 'wet' and 'non-wet' areas from the TCW threshold maps were compared to 'wet' and 'non-wet' areas calculated from the reference inundation map (Table 2). The TCW threshold map that mapped the area most closely to the reference map was the −350 threshold. For the 28 June 2016 reference inundation map, the area identified as inundated was 99.27 km^2. The −350 threshold underestimated the reference map 'wet' area, with an area of 95.68 km^2, and overestimated the 'not-wet' area with 2655 km^2 where the reference map 'non-wet' area is 2651.33 km^2. The threshold chosen is conservative.

Results - TCW Threshold Validation

We validated the 'wet' component of WIT plots by comparing the TCW results against field observations collected by the Wetland Monitoring and Assessment Program (WetMAP)

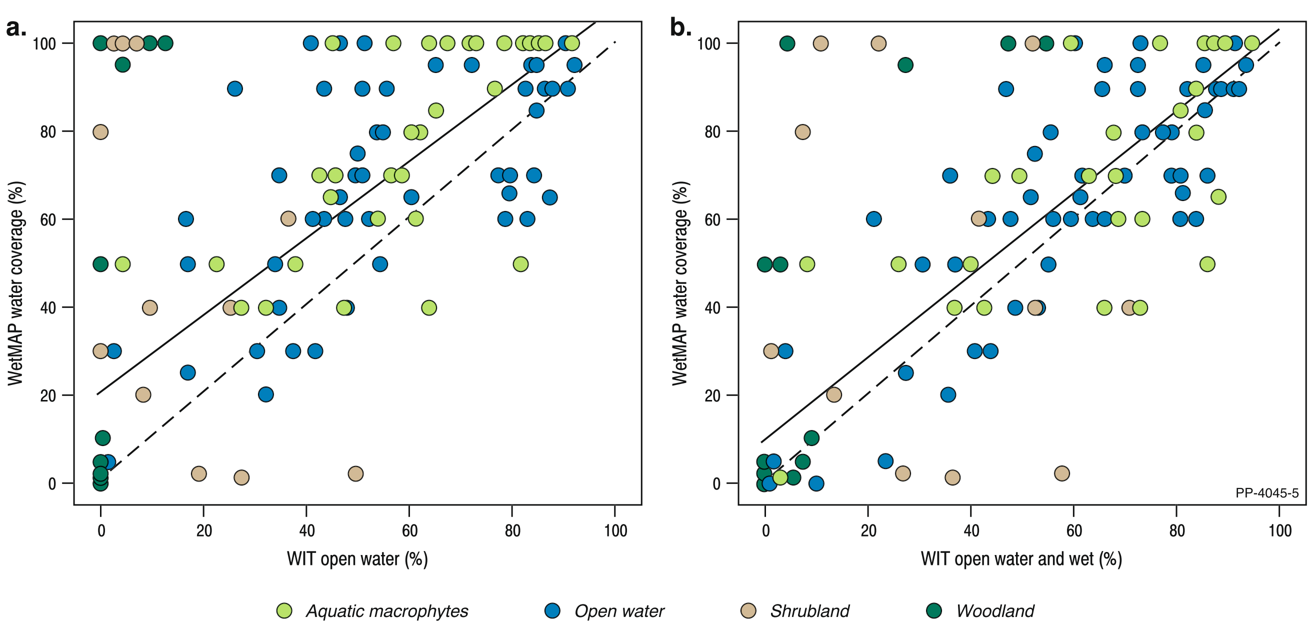


Fig. 13 **a** Field observations of water coverage percentage plotted against WIT plot open water percentage and against (**b**) the combined WIT plot open water and wet percentage. Linear fit between the observed and WIT plot water coverage shown as a solid line with the 1:1 line shown dashed. Wetland observations are coloured by the dominant vegetation type (see Table 1 in Appendix A.1.1)

for environmental water (Papas et al., 2021). (see Table 1 and Fig. 11 in Appendix A.1.1).

We generated WIT plots for each WetMAP wetland boundary. For each WetMAP observation, we then compared the WetMAP standing water areas to the WIT 'open water', as well as the sum of WIT 'open water' and 'wet' components. Where WIT plot observation dates did not align with WetMAP observation dates, we linearly interpolated WIT plot values to estimate the values at the time of field observation.

The field observations include 141 individual observations recorded at different times from 19 wetland sites. For each wetland site, WetMAP provides the dominant vegetation type. To quantify how the inclusion of the 'wet' class improved our estimates of inundation extent we evaluated the correlation using Pearson's correlation coefficient (r).

Figure 13 shows the WIT plot and WetMAP observations plotted against each other with each observation coloured by its dominant vegetation type. Figure 5a shows the correlation between inundation extent observed in the field and inundation extent from only the WOfS open water classifier. As previously stated, WOfS underestimates inundation extent. This is particularly notable in the cluster of woodland and shrubland points in the top left of Fig. 13a. The inclusion of thresholded TCW results in a better correlation between WIT plot and WetMAP observations as shown in Fig. 13b. This effect is most noticeable for the vegetated wetlands, especially those dominated by aquatic macrophytes.

The WetMAP water coverage observations are correlated with the WIT 'open water' component with $r = 0.71$, and are better correlated with the WIT 'open water' plus 'wet' with $r = 0.79$. Also shown in Fig. 5 is a line of best fit. To account for the uncertainty in both the WetMAP and WIT plot observations, we found this line using orthogonal least squares with an estimated WetMAP uncertainty of ±5% and an estimated WIT plot uncertainty of the square root of the water area percentage. The underestimation of water coverage, as represented by the y-intercept of the linear best-fit line, is improved by the inclusion of the 'wet' class. It drops from 20% with just 'open water' to 9% for 'open water' plus 'wet'.

Appendix B Ramsar Site and Sub-site reference details

(Table 3)

Table 3 Paper figure, Ramsar Site number and name, State, Sub-site FeatureID, and name for each Wetland Insight Tool plot in this paper. Sub-site FeatureID refers to the vector file available via the Data Availability statement download and can be viewed on the DEA Maps platform alongside the WIT plot for the site

Paper Figure	Ramsar Site number	Ramsar Site name	State	Sub-site FeatureID	Sub-site name
Figure 3	53	Narran Lake Nature Reserve	NSW	70	Narran Lake Nature Reserve
Figure 4	20	Western District Lakes	VIC	190	Lake Gnarpurt
Figure 5	28	The Macquarie Marshes	NSW	22	Northern Section
Figure 6	45	Ginini Flats Wetland Complex	ACT	178	Ginini Flats Wetland Complex
Figure 7	65	Paroo River Wetlands	NSW	76	Peery
Figure 8	64	NSW Central Murray Forests	NSW	29	Millewa Forest
Figure 9	3	Moulting Lagoon	TAS	128	Moulting Lagoon
Figure 10	6	Pitt Water-Orielton Lagoon	TAS	216	Barren Island

Appendix C Aggregation details

This appendix describes the process of aggregating data within wetland polygons that fall across satellite path-row boundaries.

Polygons of wetlands contained by the path row are treated differently to polygons of wetlands which fall across multiple path-rows. If 90% or more of the polygon is within the path/row or the area of intersection between adjacent path/rows, the polygon is treated as contained by the path/row.

Large wetland polygons that cover multiple path-rows or small wetland polygons that fall on boundaries often intersect more than one path/row. For these wetland polygons where less than 90% of the area of the wetland polygon falls within a single path row, observations are aggregated by time, as path/row observations are taken at different times. Polygons where this happens are aggregated using a 16-day aggregation, to combine observations taken in consecutive passes. Day 0 is the date and time of the first overpass at the location, with subsequent overpasses for the location occurring on day 1 (overlap is to the east) or day 15 (overlap is to the west).

The aggregation starts from day 0 and aggregates all observations until day 15 by filling empty pixels with pixels from subsequent observations. This is then repeated for day 16 to day 31.

Acknowledgements We acknowledge and show respect to Australia's traditional custodians and their long and continuing connections to the land and waterways.

Work in this paper was performed on the traditional lands of the Ngunnawal, Ngunawal, and Ngambri people, and on the lands of and with assistance from the Quandamooka Peoples of Minjerribah (North Stradbroke Island). WetMAP data were collected for this paper on the traditional lands of the Barapa Barapa, Dja Dja Wurrung, Jardwadjali, Ngurai Illam Wurrung, Wadi Wadi, Latji Latji, and Wadawurrung peoples.

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Code Availability We created the software program wit_tooling to implement the generation of WIT plots for multiple wetlands (Ai and Dunn, 2021). wit_tooling is open-source code under an Apache-2.0 licence and available on GitHub (https://github.com/GeoscienceAustralia/wit_tooling). wit_tooling was run on the Australian National Computational Infrastructure (NCI) High Performance Computing (HPC) research facility at the Australian National University to generate the dataset used in this paper. DEA storage, management, and analysis of large EO datasets is supported by the NCI HPC environment (Evans et al., 2015; Lewis et al., 2017).

Author Contributions This study was conceived by Bex Dunn, Emma Ai, Leo Lymburner, Claire E. Krause and Kate C. Fickas. All authors contributed to the study design and analysis. Code to create the WIT plots was written by Bex Dunn, Emma Ai, and Matthew J. Alger. Code to create the validation plots was written by Bex Dunn, Matthew J. Alger, and Ben Fanson. Validation data and methods were contributed by Ben Fanson and Phil Papas with validation methodology additionally contributed by Matthew J. Alger. The first draft of the manuscript was written by Bex Dunn, Matthew J. Alger, Claire E. Krause, Leo Lymburner, Rachel Nanson, Phil Papas, Mike Ronan, and Rachael F. Thomas and all authors commented on multiple versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The DEA Wetlands Insight Tool (Ramsar Wetlands) v4.0.0 dataset is available as an interactive web service on the DEA Maps platform (https://maps.dea.ga.gov.au/#share=s-dJQFNnM33jQFrpO3G0vkaqOvJRc). Metadata and links to download the entire CC BY 4.0-licensed dataset can be accessed at the official product site (https://cmi.ga.gov.au/data-products/dea/669/dea-wetlands-insight-tool-ramsar-wetlands#details).

A data package including the vector file, attributes, readme, and comma-separated values (CSV) and Portable Network Graphic (PNG) file results are publicly available via Amazon S3: https://data.dea.ga.gov.au/?prefix=derivative/ga_ls_wit_ramsar_class_myear_3/1-0-0/1986%2D%2DP35Y/ga_ls_wit_ramsar_class_myear_3_1986%2D%2DP35Y.zip

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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