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Evaluation of wetland flow and connectivity objectives and targets: inundation

Technical report supporting the NSW Basin Plan Matter 8 reporting 2019 to 2024

Department of Climate Change, Energy, the Environment and Water

Acknowledgement of Country

Department of Climate Change, Energy, the Environment and Water acknowledges the Traditional Custodians of the lands where we work and live.

We pay our respects to Elders past, present and emerging.

This resource may contain images or names of deceased persons in photographs or historical content.

Artist and designer Nikita Ridgeway from Aboriginal design agency Boss Lady Creative Designs created the People and Community symbol.

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Abbreviations

Term	Meaning
BOM	Bureau of Meteorology
BWS	Basin-wide Environmental Watering Strategy
DCCEEW	Department of Climate Change, Energy, the Environment and Water (NSW)
DPE	Department of Planning and Environment (NSW)
DPIE	Department of Planning, Industry and Environment (NSW)
EWR	environmental watering requirement
FDS	flood-dependent shrubland
FDW	flood-dependent woodland
FWI	Fisher water index
LTWP	long-term water plan
MDB	Murray–Darling Basin
MDBA	Murray–Darling Basin Authority
NDVI	normalised difference infrared index
NWW	non-woody wetland
OEH	Office of Environment and Heritage (NSW)
ORS	off-river storage
PCT	plant community type
RRGF	river red gum forest
RRGW	river red gum woodlands
TOA	top of atmosphere (Landsat)
UNSW	University of New South Wales
USGS	United States Geological Survey
WRPA	water resource planning area

Summary

The NSW Department of Climate Change, Energy, the Environment and Water (the department) monitors the ecological outcomes from watering regimes in the New South Wales (NSW) portion of the Murray–Darling Basin (MDB), including environmental water deliveries, in collaboration with partner agencies and research groups. Four main environmental themes are monitored: flows and connectivity, wetland vegetation, waterbirds and other species (frogs). The ecological objectives outlined in the long-term water plans (LTWP) describe the goals for each theme aligning with the expected ecological outcomes specified in the Murray–Darling Basin Authority's (MDBA) Basin-wide Environmental Watering Strategy (BWS).

This report evaluates progress towards meeting the LTWP 10-year targets for lateral connectivity (inundation extent and frequency of different vegetation types) in major floodplain wetland assets of 6 river valleys: Narran Lakes, Gwydir Wetlands, Macquarie Marshes, lower Lachlan floodplain, lower Murrumbidgee floodplain (Lowbidgee) and Millewa Forest (mid Murray). The focus is on documenting the ecological outcomes for the 10-year period between the 2013–14 and 2023–24 water years. Key outcomes are evaluated to determine progress made towards achieving the targets for this 2024 Matter 8 reporting.

Much of the MDB was severely dry between 2013 and early 2020, except for 2016–17. Lack of rain resulted in little to no natural river flows in the monitored wetlands. Environmental water was delivered to target core wetland habitat that otherwise would have remained dry, particularly in the northern MDB. However, some wetlands such as the Macquarie Marshes and Narran Lakes had become significantly dry by the end of 2019. Wetland conditions improved early to late 2020, with above average rainfall occurring across the MDB. Both NSW and Commonwealth environmental water was delivered to many floodplain wetland assets following rainfall events from March 2020, until the 2022–23 water year. During these periods of higher catchment rainfall, inundation facilitated hydrological connectivity in and across floodplain wetlands. This inundation extended across the landscape to both flood-dependent shrublands and flood-dependent woodlands.

Flood frequency regimes predominantly showed high percentages of core wetland vegetation meeting their environmental water requirements between 2013 and 2023. The contribution of environmental water enabled core wetland vegetation to meet its inundation frequency requirement despite periods of significantly dry conditions. Environmental water was used to support ecological outcomes from natural flood events, extending the duration and extent of inundation across each of the monitored wetlands. Improvements to environmental water delivery across the wetlands are still necessary to ensure that all other flood-dependent vegetation receives the required levels of environmental water.

1. Introduction

The NSW Department of Climate Change, Energy, the Environment and Water (the department) manages the delivery of environmental water for 9 water resource planning areas (WRPA) in the MDB. These include the Gwydir, Macquarie–Castlereagh, Lachlan, Murrumbidgee, NSW Murray–Lower Darling, Barwon–Darling, Intersecting Streams, Namoi and Border Rivers (Figure 1). The department manages a portfolio of environmental water held by the NSW Government and manages water on behalf of the Commonwealth Environmental Water Holder. This is done in consultation with representatives from other government agencies, community groups, landholders, scientists and Aboriginal organisations through environmental water advisory groups.

Monitoring the ecological outcomes from the delivery of water due to natural and environmental flows in these wetlands is undertaken by the department in collaboration with partner agencies and research groups. Monitoring focuses on 4 themes: flows and connectivity, wetland vegetation, waterbirds and other species (frogs). These themes align with expected ecological outcomes specified in the MDBA's BWS (MDBA 2019) and the department's LTWP developed for each WRPA. To date, monitoring of inundation has focused on selected wetlands across the NSW MDB (Figure 1). The LTWP ecological objectives and targets for each theme are described in Appendix A.

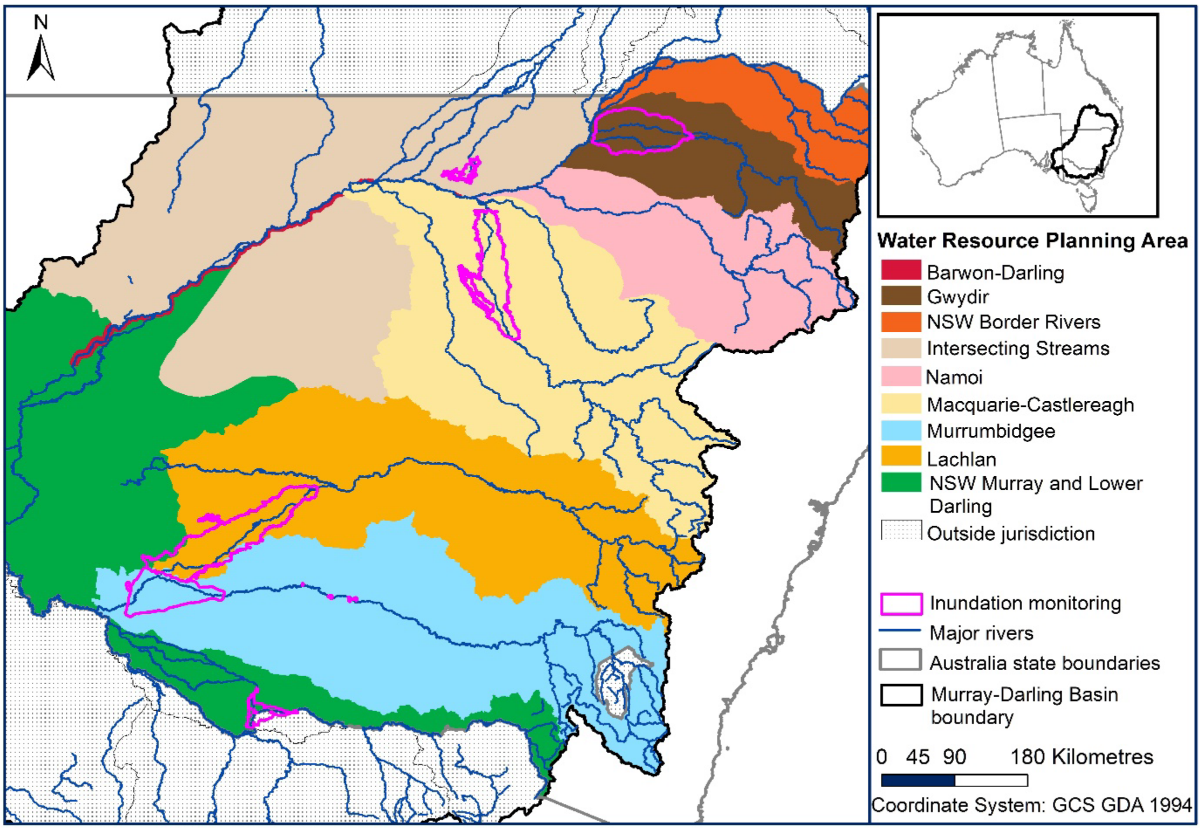

Figure 1 **Map displaying the 9 WRPAs in the NSW MDB where the department manages water delivery and the location of floodplain wetlands where lateral connectivity is monitored and evaluated for ecological outcomes**

1.1 Scope of this report

This report summarises the ecological outcomes related to inundation extent of the NSW MDB floodplain wetlands where the department and partners actively deliver and/or monitor environmental water. It Includes a preliminary assessment of progress towards objectives and targets in the LTWPs for the flows and connectivity theme for the 2013 to 2023 period. This document supports the 2024 NSW Matter 8 report.

1.2 Inundation objectives

For the 2024 Matter 8 evaluation, objectives for lateral connectivity (also referred to as inundation) were assessed in selected floodplain wetlands across 6 WRPAs. These wetlands included Narran Lakes, Gwydir Wetlands, Macquarie Marshes, lower Lachlan floodplain, Lowbidgee floodplain and Millewa Forest (mid Murray). The LTWPs (DPIE 2020a) for these WRPAs have 3 broad objectives related to inundation (Table 1). These objectives were assessed using 2 metrics, annual inundation extent and inundation frequency maps.

Table 1 LTWP inundation objectives, indicators and assessment metrics

Objective	Indicator	Metric
EFI: The provision and protection of refugia habitats (e.g. core wetland area) during dry times.	Inundation connectivity	Annual inundation extent maps
EF2: The provision of required inundation regimes to create wetland and floodplain habitats across the landscape.	Inundation regimes	Inundation frequency maps
EF3: The provision of lateral connectivity across different wetland and floodplain habitats to enable movement and dispersal opportunities for water-dependent biota.	Inundation connectivity	Annual inundation extent maps

The annual inundation extent metric enables tracking of inundation across each floodplain wetland, and of the proportion of inundated vegetation across time (see section 2. Methods for more details). The flood frequency metric is used to monitor inundation regimes during a specific 10-year period and the maximum proportion of vegetation type inundated within the 10-year period (i.e. 2013–14 to 2022–23). Trends are evaluated by assessing the flooding regimes in selected vegetation groups against the corresponding environmental water requirements.

2. Methods

2.1 Wetlands monitored

Inundation extent and distribution were monitored as an indicator of lateral connectivity in Narran Lakes, Gwydir Wetlands, Macquarie Marshes, lower Lachlan floodplain, Lowbidgee floodplain and Millewa Forest (mid Murray) (Figure 1). Inundation maps were derived from Sentinel-2 and Landsat satellite images using methods modified from Thomas et al. (2015). The ecologically important aspects of the flooding regime included in this report are the inundation magnitude (annual extent and the proportion of vegetation type inundated) and the 10-year inundation frequency, which were tracked through time.

During the monitoring period, minimal rainfall and high temperatures were experienced. The average maximum temperatures were between 27 °C and 30 °C, which is 1.0 °C to 1.5 °C hotter than the long-term average, with extremes reaching up to 45 °C or more across parts of the 6 WRPAs (BOM, 2021b). Rain became widespread across the 6 WRPAs in early-to-mid-2020, with high rainfall events experienced (BOM, 2021a).

2.2 River flows

To describe the fluctuations of flow over the monitoring period, river flow data was obtained from gauges relevant to each wetland from WaterNSW (WaterNSW, 2021) . Data were obtained for the period 1 January 2012 to 30 June 2023. Some dates in this range contain no data, with missing data interpolated linearly. The daily flow data was transformed to 6-month cumulative flows by summing values for the preceding 180 days so that for each date the value represents the total water flow for the last 6 months. Basic statistics were calculated from this data to describe median flow conditions, as well as when minimum and maximum flows were experienced during the monitoring period.

2.3 Imagery processing

Since 2018, imagery from the Sentinel-2 satellite has been used to produce inundation maps with a 10 m spatial resolution and a 5-day temporal resolution. Before 2018, imagery from the Landsat 5–8 satellites, which had 30 m spatial resolution was used, depending on availability.

Landsat top of atmosphere (TOA) reflectance data was obtained from the United States Geological Survey (USGS), while Sentinel-2 TOA data is obtained from the European Space Agency. TOA reflectance data are then corrected for atmospheric effects and bidirectional reflectance effects to create a standardised surface reflectance product. For Sentinel-2 images, the 20 m shortwave-infrared bands (B11 and B12) are resampled to match the resolution of the 10 m bands (B2-B4, B8). Surface reflectance data is then used to produce the normalised difference infrared index (NDVI) and the Fisher water index (FWI) (Fisher, Flood & Danaher, 2016). These indexes are subsequently used to create inundation maps over the floodplain wetlands (see Equation 1 and 2 below).

Equation 1

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Equation 2

$$\text{FWI} = 1.7204 + 171\text{Green} + 3\text{Red} + 70\text{NIR} + 45\text{SWIR1} + 71\text{SWIR2}$$

To produce contiguous maps covering the full extent of the monitored wetlands, reflectance data and indices of individual tiles obtained on a single day are mosaiced together and clipped to the required extent.

2.4 Creating inundation maps

Inundation maps for single dates are produced from satellite images that are either free of cloud or contain low cloud cover as long as core wetland areas are not obscured. A modified version of Thomas et al. 2015 inundation mapping method is applied to the satellite imagery. This approach classifies inundated areas into water, mixed (pixels partially containing open water) and vegetation (vegetation that is obscuring water) classes.

Reflectance data is analysed visually. An appropriate threshold is applied to the FWI to determine the location of water-containing pixels. The application of a second, lower threshold is conducted to identify mixed pixels. A threshold for NDVI is applied to determine where inundated vegetation may be present. Threshold values for FWI and NDVI need to be sufficiently high to separate inundated and non-inundated areas. These thresholds may need to vary within an image, and between images collected on different dates or covering different wetlands. This can be due to factors such as soil type, moisture content, variation in wetland vegetation growth stages and seasonal variation in solar angle. To improve accuracy, ancillary data is applied to different sets of thresholds locally within the mapped extent. If clouds are present, their extent is manually digitised and any class within the polygon is classified as cloud.

The final inundation map is recoded to 3 classes representing total inundated area, off-river storage (ORS), and cloud-masked (Table 2). The first class denotes the total inundated area, which includes water, mixed and vegetation pixels (Table 3). The second class represents inundation in ORS, consisting of pixels classified as water or mixed and within ORS areas (Table 3). The third class is for cloud-masked pixels if any are present (Table 3).

Table 2 List of classes in the final recoded inundation map

Class	Description
1. Inundated	Pixel is inundated, containing classes 1, 2 or 3 (Table 3 below)
2. ORS	Pixel contains inundated ORS classes 7 or 8 (Table 3 below)
3. Cloud	Pixel contains cloud

Table 3 Full list of inundation classes detected.

Class	Description
1. Water	Water-containing pixels
2. Mixed	Pixels containing water and another land cover class
3. Vegetation	Pixels containing water covered by vegetation
4. Cloud	Cloud/cloud shadow
5. Water/crop	Water detected in cropping areas
6. Mixed/crop	Mixed pixels detected in cropping areas
7. Water/ORS	Water within ORS areas
8. Mixed/ORS	Mixed pixels within ORS areas
9. Not inundated	Pixels with no water identified

2.5 Cumulative annual extent maps

All single date maps produced for each water year (July–June) were combined to produce a map of the cumulative extent of inundation detected. These 'annual inundation extent maps' show where inundation has been detected at least once during the water year. The maps were created using the recoded, 3-class inundation map. Using all maps produced for that water year, the number of times each pixel is classified as either inundated or ORS was counted. Inundated pixels with a count greater than zero are reclassified as '1'. ORS pixels with a count greater than zero are classified as '2'.

2.6 Trends in inundation extent

Annual inundation extent maps were used to monitor inundation across floodplain wetlands according to the sub-regional boundaries. These maps were compared against vegetation mapping for each monitored wetland to identify inundation trends within vegetation community types. Where possible, vegetation maps developed close to the year the Basin Plan was implemented were used to provide a baseline assessment of the inundation extent trends within vegetation community types over time (Table 4). In instances where vegetation mapping was unavailable for the period of Basin Plan implementation, the latest available vegetation mapping was relied upon. All vegetation mapping was classified to the plant community type (PCT) level and aggregated to vegetation functional groups (Table 5).

Table 4 **List of vegetation maps used in analysis**

Wetland	Map date	Source
Narran Lakes	2016	Ecological Australia
Gwydir Wetlands	2023	Department of Climate Change, Energy, the Environment and Water
Macquarie Marshes	2013	Office of Environment and Heritage
Lower Lachlan floodplain	2012	Office of Environment and Heritage
Lowbidgee floodplain	2008–2014	Office of Environment and Heritage
Millewa Forest	2010	Office of Environment and Heritage

Table 5 **Full list of vegetation functional groups and example PCTs**

Vegetation functional group	Example PCT
Non-woody wetland	Shallow freshwater wetland sedgeland in depressions on floodplains on inland alluvial plains and floodplains
Flood-dependent shrublands	Lignum shrubland wetland of the semi-arid (warm) plains (mainly Riverina Bioregion and Murray–Darling Depression Bioregion)
River red gum forests	River red gum tall to very tall open forest/woodland wetland on rivers on floodplains mainly in the Darling Riverine Plains Bioregion
River red gum woodlands	River red gum grassy chenopod open tall woodland (wetland) on floodplain clay soil of the Darling Riverine Plains Bioregion and western Brigalow Belt South Bioregion
Flood-dependent woodlands	Black box woodland wetland on NSW central and northern floodplains including the Darling Riverine Plains Bioregion and Brigalow Belt South Bioregion.

Wetland inundation extents were calculated using zonal statistics, by counting the number of inundated pixels in each of the sub-regional boundaries and vegetation functional groups. Two datasets were generated: one quantifying the total area for each wetland, and one quantifying the inundation within vegetation functional groups for available water years between 2013 and 2023 for each wetland.

2.7 10-year rolling flood frequency maps

Annual inundation extent maps developed in a 10-year period were combined to produce a flood frequency map. Maps were combined by reclassifying ORS pixels as ‘one’ and summing values. The flood frequency map has values from zero (never inundated) to 10 (inundated annually). As maps prior to 2018 have a lower spatial resolution, these maps were resampled to 30 m to match the Landsat data. These maps were produced for each overlapping 10-year period (i.e. 2000–20, 2001–21 etc.) to create a set of rolling flood frequency maps for each monitored wetland region. The most recent 10-year flood frequency map (2013 to 2023) was integrated into this evaluation to assess the inundation regimes across each of the floodplain wetland landscapes. Zonal statistics were used to calculate the proportion of area covered by each flood frequency class during this 10-year period for all floodplain wetlands.

2.8 Trends in inundation frequency

To characterise the inundation regimes experienced by vegetation functional groups, the frequency of inundation for each group was assessed using the 10-year flood frequency maps. Two analyses were performed. The first analysis shows the proportion of each vegetation group that was covered by each flood frequency class for the latest 10-year period (2013 to 2023). Zonal statistics were used to count the number of pixels for each flood frequency class in vegetation functional groups for each wetland. The second analysis shows the change of inundation regimes over time for each vegetation functional group using 10-year flood frequency maps since 2004 (i.e. 2004 to 2014, 2005 to 2015, 2013 to 2023).

To improve statistical reliability, a random sub-sample of points was generated across all wetlands to sample flood frequency values for all vegetation functional groups in each wetland. To ensure representativeness, sampling was stratified by area of PCT polygons. Each polygon was sampled at one point per hectare (ha) with a minimum distance of 100 m between points. For smaller polygons of one to 10 ha in size, the minimum distance constraint was reduced to 50 m. The centroid of polygons was used for areas less than one hectare in size (Table 6).

Table 6 List of spatial conditions for assigning random points across PCT patches

PCT polygon size	Spatial condition between points
< 1 ha	Single point placed at the centroid
1–10 ha	50 m buffer between points
> 10 ha	100 m buffer between points

3. Results

3.1 Flow conditions

During the monitoring period, flows were low during the dry period from 2013 to mid-2020 due to prevalent hot dry conditions. A particularly dry period occurred across the basin between 2019 and 2020, with minimum 6-month cumulative flows identified in most gauges except for in the Murrumbidgee (Table 7). This period was particularly severe for wetlands in the northern MDB. Gauges for these wetlands (Narran River, Mehi River, Gingham channel and Macquarie River) showed minimum cumulative flows less than 4% of the median. Minimum flow values from gauges in the southern MDB were between 13% and 56% of the median.

Where available, small environmental flows were delivered to both riverine and wetland assets during the dry period (2013 to 2020). These deliveries, along with runoff from increased rainfall in 2016, provided flows in all 6 surveyed wetlands. Unregulated flow pulses entered the riverine systems, inundating the Macquarie Marshes from early 2020, and continued to inundate the wetlands within the 6 WRPAs from early 2021 (Figure 2 and Figure 3). In late 2022 to early 2023, the highest 6-month cumulative flows at all river gauges were observed (Table 7) with peak flows seen in December 2022 (Figure 2 and Figure 3).

Table 7 **Summary statistics of 6-month cumulative river gauge flows (GL) calculated from daily river flow data between 2012 and 2023**

Gauge name	Max	Min	Median	First quartile	Third quartile	Date of Maximum	Date of Minimum
Narran River at Wilby Wilby (422016)	647.8	0.0	4.4	0.0	34.5	19/06/2022	19/01/2014
Mehi River at Moree (418002)	562.7	2.5	72.0	27.5	165.7	5/01/2023	27/10/2020
Gingham channel at Teralba (418074)	382.0	0.5	17.8	9.0	59.4	2/02/2023	13/01/2020
Gwydir River at Allambie Bridge (418078)	343.0	0.1	15.3	8.7	51.6	3/02/2023	31/12/2019
Macquarie River D/S Marebone weir (421090)	553.2	0.2	100.5	38.4	284.7	3/12/2022	26/01/2020
Lachlan River at Booligal (412005)	799.2	7.9	39.9	17.7	215.8	6/02/2023	28/08/2020
Lachlan River at Hillston weir (412039)	1331.3	12.1	95.0	44.2	323.0	18/01/2023	15/08/2020
Murrumbidgee at D/S Maude weir (412004)	3738.4	85.5	268.9	179.5	462.4	5/12/2022	22/08/2014
Murrumbidgee at Redbank (410041)	1861.4	79.0	291.7	190.2	901.0	28/12/2022	12/07/2018
Murray River downstream Yarrawonga weir (409025)	9960.4	1046.0	1862.4	1524.0	2535.2	15/12/2022	10/08/2017

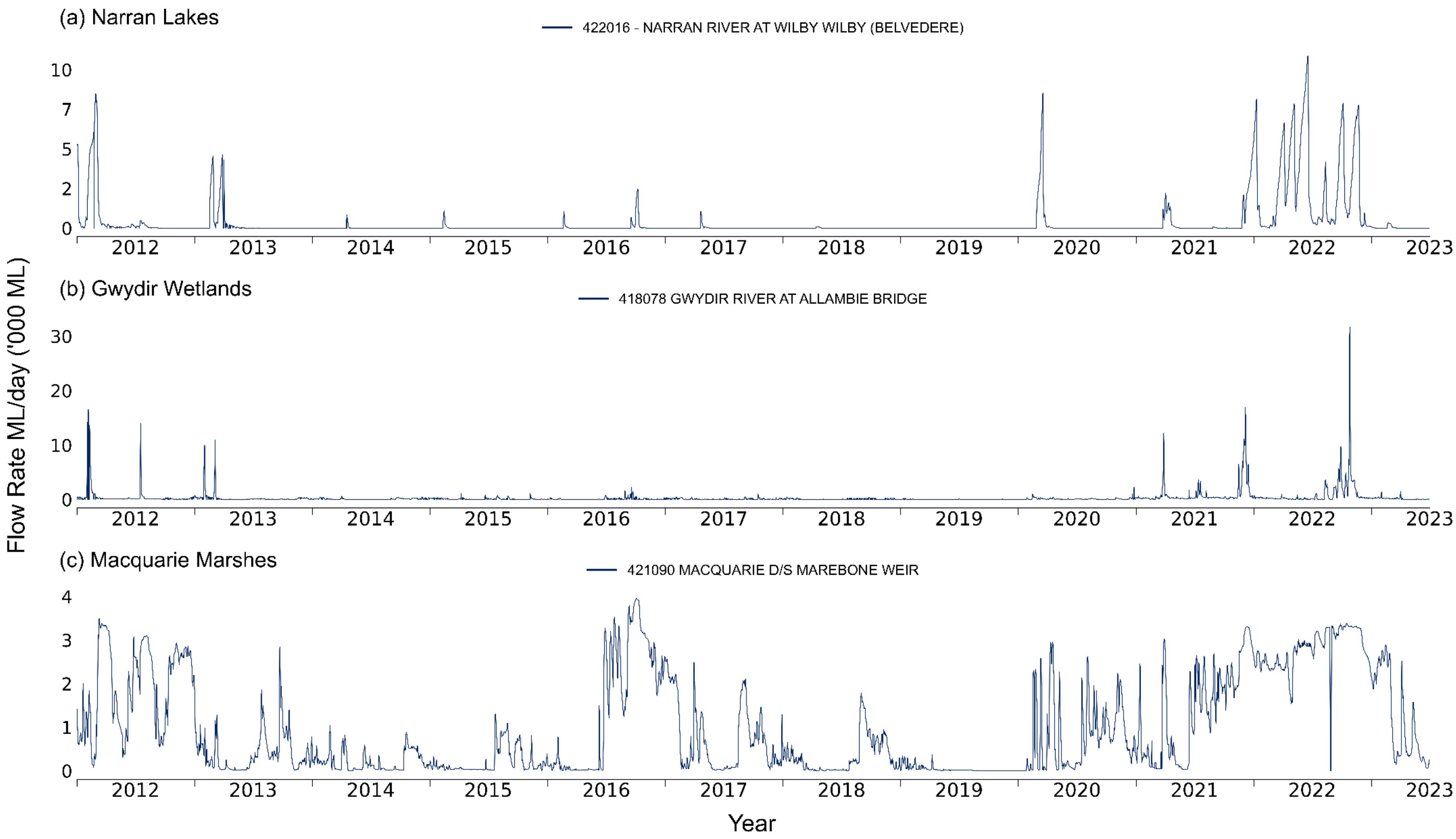

Figure 2 **River flows from 1 January 2012 to 30 June 2023 for the (a) Narran Lakes; (b) Gwydir Wetlands; and (c) Macquarie Marshes**

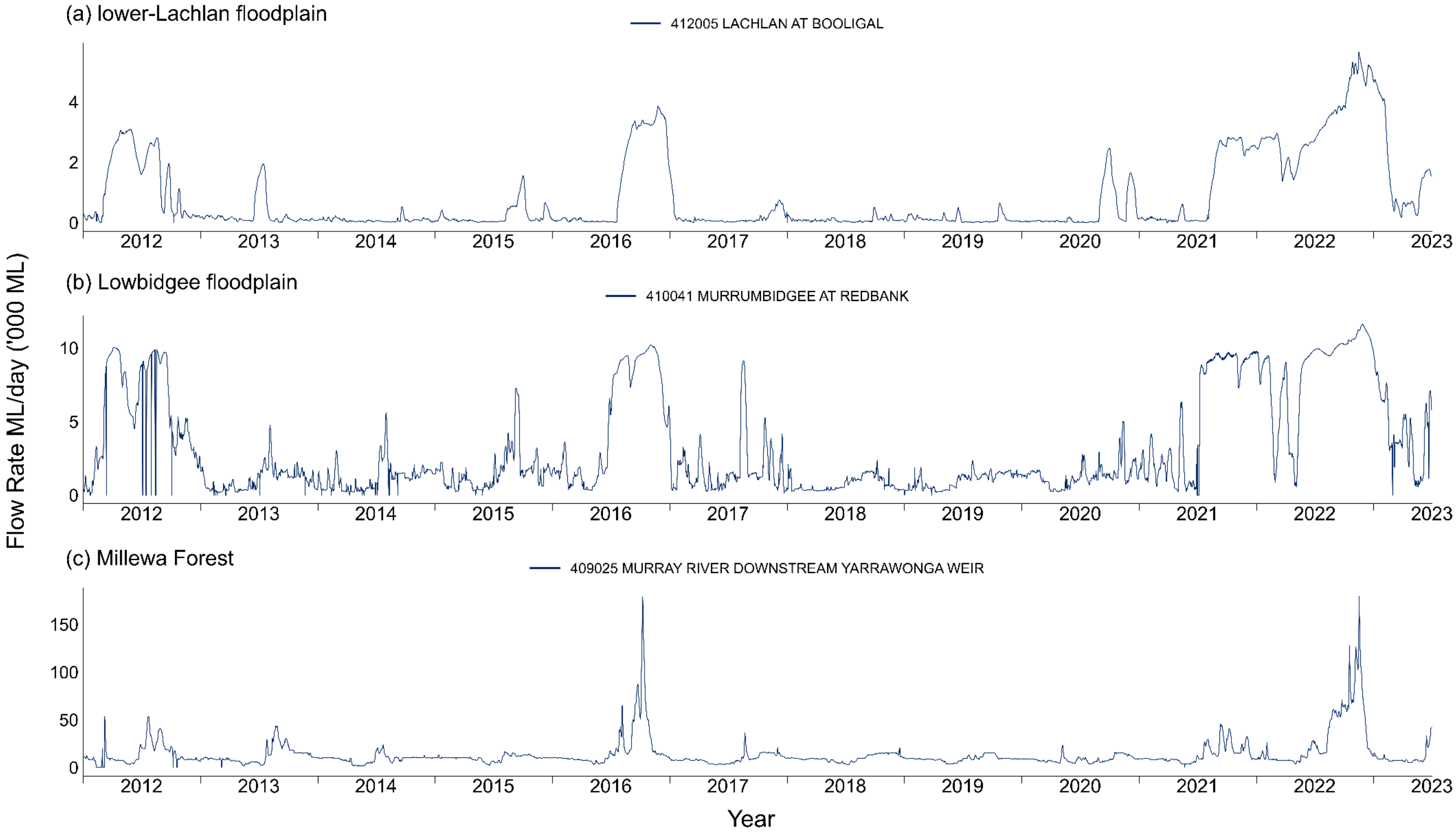

Figure 3 **River flows from 1 January 2012 to 30 June 2023 for the (a) lower Lachlan floodplain; (b) Lowbidgee floodplain and (c) Millewa Forest (mid Murray)**

3.2 Trends in inundation extent across floodplains and in different vegetation types

All monitored wetlands across the MDB experienced annual inundation extents below the long-term average for 7 out of the 10 years (mid-2013 to mid-2023). This is mainly due to a prolonged dry period that affected most of NSW up until 2020. Wetlands in the northern MDB (Narran Lakes, Gwydir Wetlands and Macquarie Marshes) were severely affected during this time, with extents being well below the long-term median for most years, up to 2019–20. Wetlands across the southern MDB were also affected by this dry period, with annual inundation extents recorded below the long-term median for several years.

The effects of this dry period on annual inundation extents were more severe in the northern MDB, particularly in 2019. Flows into Narran Lakes, Gwydir Wetlands and Macquarie Marshes were extremely low (Figure 2, Table 7). In some instances, flows in these areas completely ceased with areas of core wetlands drying out completely. Narran Lakes had only one hectare (ha) of wetland floodplain inundated between 2013 and 2019. By mid-2019, this had fallen to zero. Similarly, Macquarie Marshes had only 7 ha (<1%) of the floodplain inundated by late 2019. The Gwydir Wetlands only had 57 ha (<1%) of its floodplain inundated during this time. Significant flows arrived in early 2020, breaking dry conditions. Effects of the dry conditions for 2020 are not well represented in Figure 4 as the inundation extent was calculated across the water year, not the calendar year.

In the southern MDB, the lower Lachlan floodplain experienced the greatest impact of the dry period. Inundation extent across the floodplain declined to ~690 ha (<1%) by 2020. The Lowbidgee floodplain and Millewa Forest were also affected, however areas of core wetlands remained inundated (Figure 5). By 2019, inundation extent across the Lowbidgee floodplain was ~2,000 ha (<1%) and Millewa Forest was ~1,000 ha (3%). These levels were relatively stable until mid to late 2020. Inundation extent during the 2013–20 dry period was low in all wetland regions, remaining below long-term average inundation extent (Figure 4 and Figure 5). However, relief was provided in 2016–17 with above average inundation extent for all wetland regions except Narran Lakes, which remained below the long-term median (Figure 4 and Figure 5). All southern MDB wetlands and Macquarie Marshes experienced much larger rainfall events in 2016–17, when compared with Narran Lakes and the Gwydir Wetlands (Figure 4 and Figure 5).

The dry period ended in early 2020 due to La Niña climatic conditions. These conditions continued through to 2022–23, progressively contributing to increasing annual inundation extents across all wetland regions. In the northern MDB, the annual inundation extents began increasing towards the long-term average during 2019–20, as a consequence of natural flows entering the system. In Narran Lakes, these extents lingered around the long-term average during 2019–20 and 2020–21. In the Gwydir Wetlands, by 2020–21, the extents exceeded the long-term average. Macquarie Marshes experienced an increase in extent from 2019–20 but did not exceed the long-term average until 2021–22. All 3 northern wetlands experienced an extreme increase in annual inundation extents during 2022–23, exceeding all reported long-term metrics.

The increases in magnitude of inundation extent lagged in the southern MDB, with all the wetlands remaining below the long-term average until 2021–22. In late 2022, high rainfall was experienced across NSW. This caused significant flooding through all 6 wetland regions. This set new long-term maximum inundation extent records for the 2022–23 water year for all 6 wetland regions.

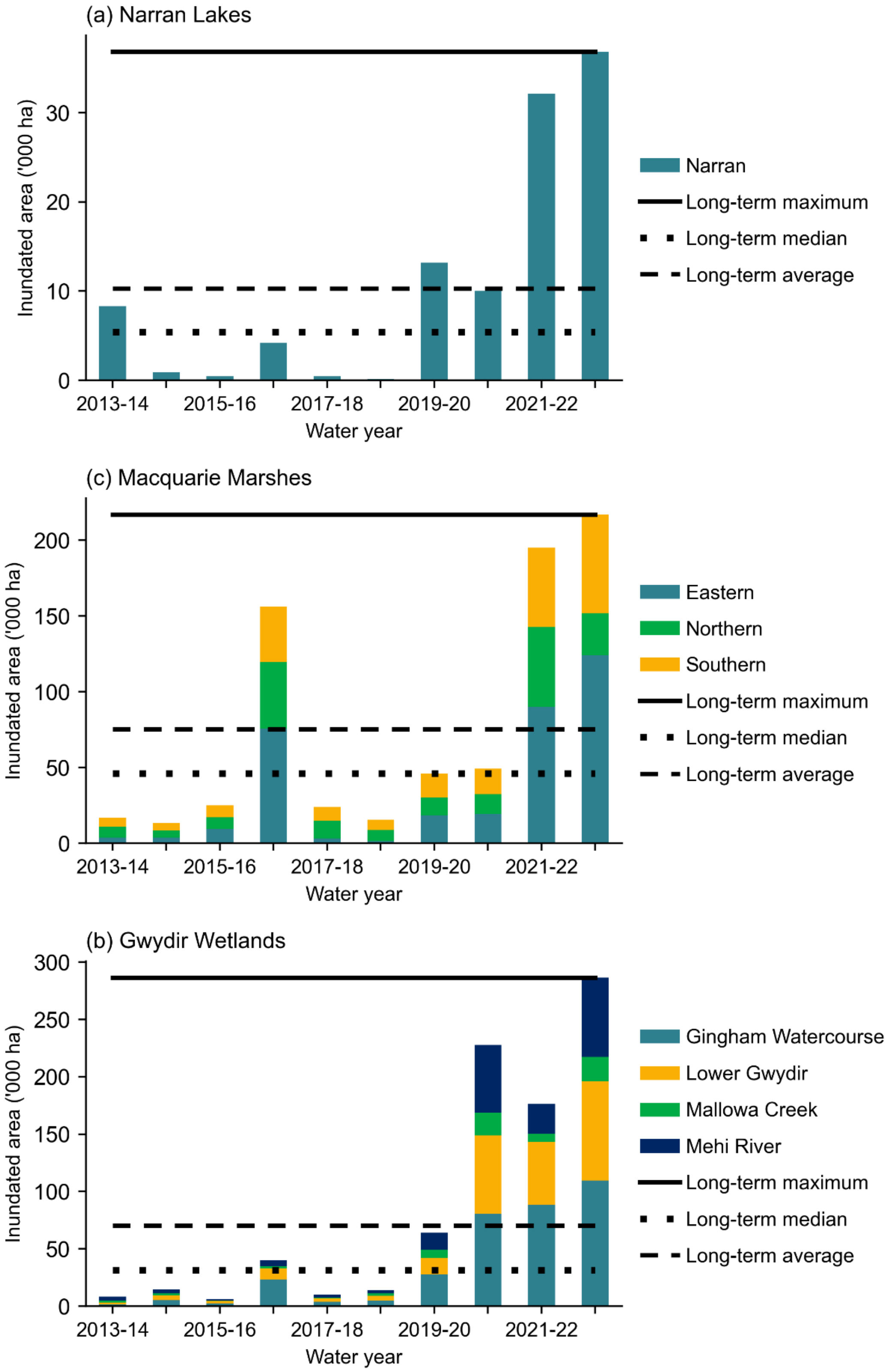

Figure 4 **Annual inundation extents for each water year in (a) Narran Lakes; (b) Gwydir Wetlands; (c) Macquarie Marshes. Long-term metrics of inundated area were calculated from the available time-series data, Narran Lakes: 2002–23; Gwydir Wetlands: 1988 to 2023; Macquarie Marshes: 1988 to 2023**

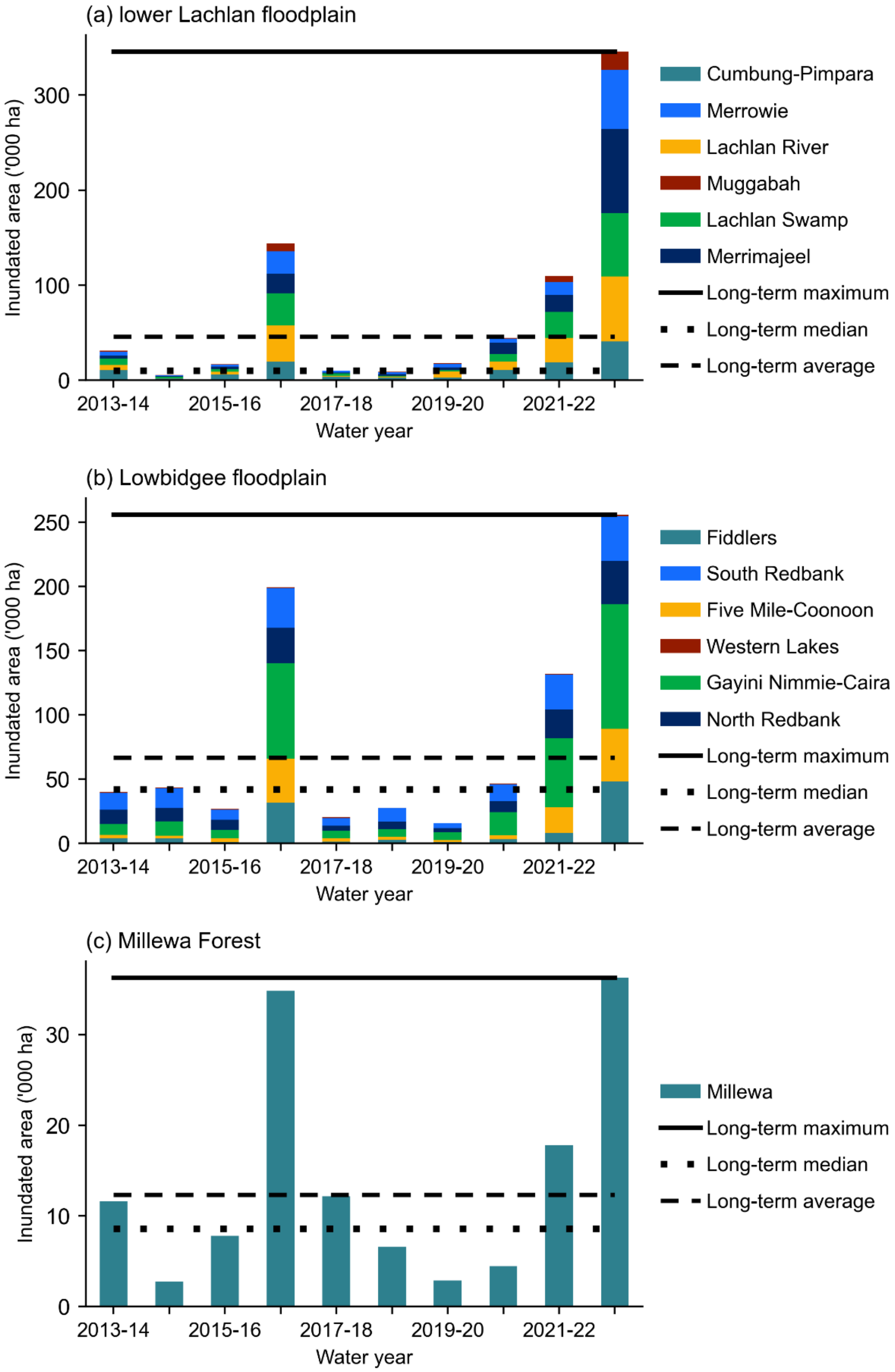

Figure 5 **Annual inundation extents for each water year in (a) lower Lachlan floodplain; (b) Lowbidgee floodplain; (c) Millewa Forest. Long-term metrics of inundated area were calculated from the available time-series data, lower Lachlan floodplain: 2002 to 2023; Lowbidgee floodplain: 1988 to 2023; Millewa Forest: 2002 to 2023**

Inundation extent over the 2013 to 2023 period was evaluated across all flood-dependent vegetation communities in each wetland floodplain. Non-woody wetland (NWW) vegetation communities are a small but important component of the wetlands assessed. They account for less than 5% of the total area of flood-dependent vegetation in each wetland region, except for the Macquarie Marshes (17.5%) and Gwydir Wetlands (6.3%). NWW have a high water-dependency and require inundation every 1 to 2 years (Roberts and Marston 2011). They are typically distributed in frequently flooded areas along flow paths.

During the extensive dry period, NWW had the highest proportion of total area inundated for most wetlands, relative to other vegetation types (Figure 6 and Figure 7). The proportion of river red gum forest (RRGF) inundated in the Macquarie Marshes and lower Lachlan floodplain was greater than NWW. While RRGF are found in frequently flooded areas, they cover a much smaller area and total inundation extent of NWW remains higher than RRGF in these regions.

The Gwydir Wetlands had the lowest proportion of NWW extent inundated during the dry period. Less than 2% of NWW was inundated in 5 out of 7 years, between 2013–14 and 2019–20 (Figure 6). During the same period, the proportion of NWW inundated remained above minimums set in 2019–20 for the Lowbidgee floodplain (71%) and Millewa Forest (52%). New minimum extents were experienced in 2014–15 for the lower Lachlan floodplain (5%) and Macquarie Marshes (28%). Narran Lakes experienced its driest year in 2018–19 when less than 1% of NWW was inundated, with all other years above 33%. It must be noted that these percentages do not represent fluctuations in areas throughout each year. In the Macquarie Marshes, by late 2019 the NWW inundation extent declined to zero, before increasing again early in 2020. These results demonstrate that some portions of NWW across all wetlands were inundated at least once annually during a water year, even in dry periods.

River red gum forest covers a large proportion of the Lowbidgee floodplain and Millewa Forest (Figure 7). River red gum woodlands (RRGW) are more prevalent in the lower Lachlan floodplain and Macquarie Marshes (Figure 6 and Figure 7). In dry years, only a relatively small proportion of RRGW areas were inundated across all wetland regions. Less than 1% was inundated in the lower Lachlan floodplain during 2014–15. Inundation extent in the Macquarie Marshes declined to 11% in 2018–19 (Figure 6). RRGF experienced similar contractions in inundation extent, which dropped to as low as 3% in the Millewa Forest and 8% in the Lowbidgee floodplain during 2019–20. Inundation extent was typically >20% during dry years in the Lowbidgee floodplain (Figure 7). The extent of RRGF is much smaller in the Gwydir Wetlands and Macquarie Marshes compared to what is found in the Lowbidgee floodplain. However, inundation extent was maintained between 14% and 22% in the Gwydir Wetlands during dry years and between 70% and 77% in the Macquarie Marshes. Significant flow events seen in 2016–17 and 2022–23 saw the proportion of RRGF inundated grow to more than 80% across all wetland regions. However, during the 2016–17 flow event, RRGF in Narran Lakes and Gwydir Wetlands were only partially inundated at 39% and 33%, respectively. RRGW also had large proportions of their extent inundated during these flow events (Figure 6).

Flood-dependent woodlands (FDW), such as black box and coolibah woodlands, and lignum- dominated flood-dependent shrublands (FDS), cover a large proportion of many of the wetland floodplains. The exception was Millewa Forest which is dominated by RRGF. During dry years, only a small proportion of these vegetation types were inundated, ranging between <1% to 11% across all wetlands in the reporting period. The exceptions were during 2016–17, 2021–22 and 2022–23 when most wetland regions had extensive flooding (Figure 4 and Figure 5). However, there was variability in inundation extent during these years. In the Macquarie Marshes in 2016–17, 85% of FDW and 90% of FDS were inundated. In the lower Lachlan floodplain, <1% of FDW were inundated compared to 29% of FDS. During 2022–23, >74% of FDS and FDW were inundated across most wetland floodplains. The exceptions were the Gwydir Wetlands, where only 58% of FDS were inundated, and Millewa Forest where only 11% of FDW were inundated.

During dry years, inundation of some areas of NWW and RRGF was maintained across all wetland regions. Only very small proportions of other flood-dependent vegetation communities, if any, were inundated during these years. Years of high wetland inflows were seen in 2016–17 and from 2020 onwards. This saw high proportions of flood-dependent vegetation inundated, except in the Narran Lakes and Gwydir Wetlands. In the Narran Lakes, elevated inundation extent in all flood-dependent vegetation was observed from 2019–20 onward (Figure 6). For wetlands in the southern MDB, extensive inundation of flood-dependent vegetation was not seen until 2021–22 (Figure 7).

Figure 6 **Percentage (%) of inundated area of flood-dependent vegetation groups during each water year at (a) Narran Lakes, (b) Gwydir Wetlands and (c) Macquarie Marshes (refer to Table 4 for vegetation map dates). NWW = non-woody wetland, RRGF = river red gum forest, RRGW = river red gum woodland, FDS = flood-dependent shrublands, FDW = flood-dependent woodlands**

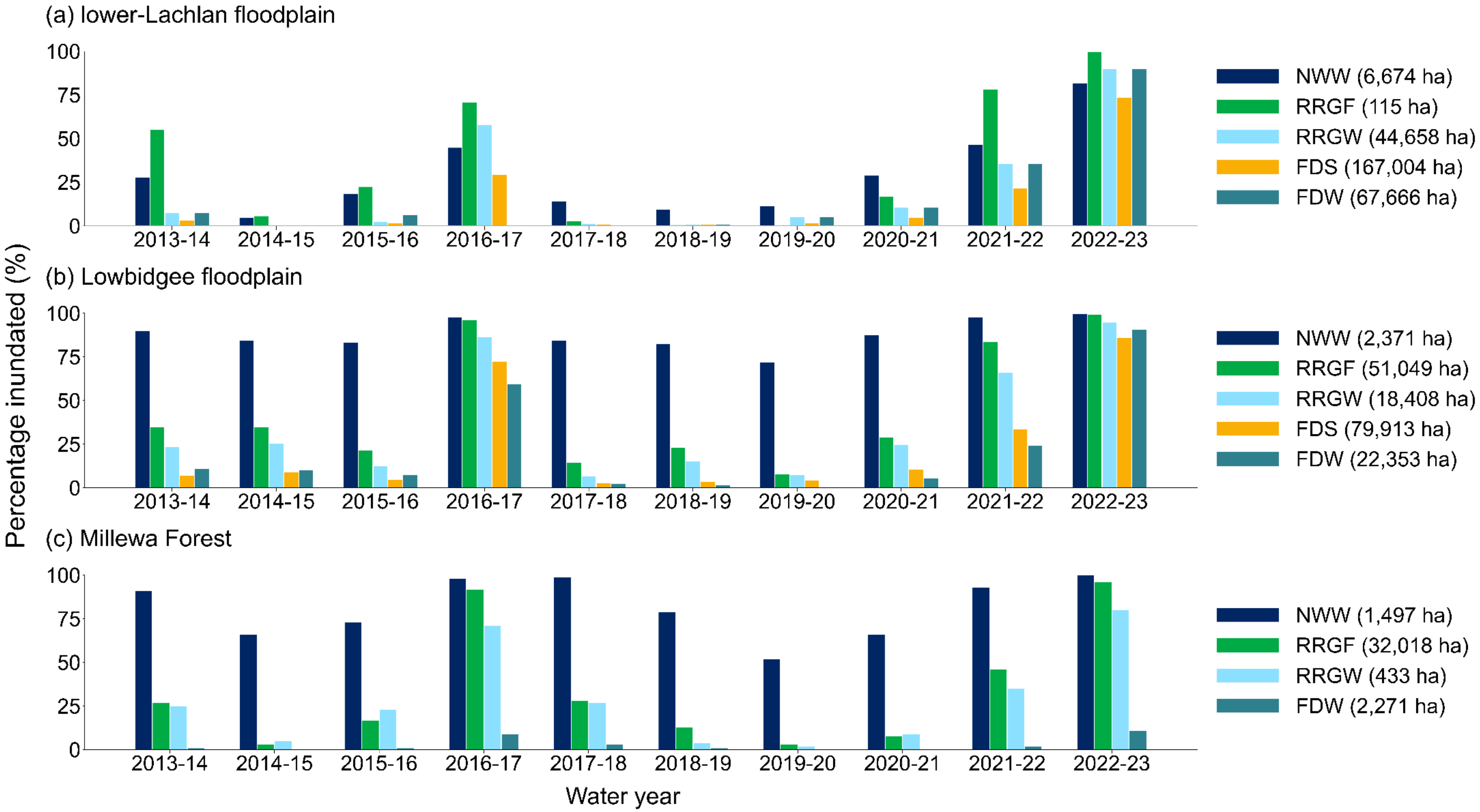

Figure 7 **Percentage (%) of inundated area of flood-dependent vegetation groups during each water year at (a) lower Lachlan floodplain, (b) Lowbidgee floodplain and (c) Millewa Forest (mid Murray) (refer to Table 4 for vegetation map dates). NWW = non-woody wetland, RRGF = river red gum forest, RRGW = river red gum forest, RRGW = river red gum woodland, FDS = flood-dependent shrublands, FDW = flood-dependent woodlands**

3.3 Inundation regimes across the landscape

Varying extents of inundation were seen over the 10-year flood frequency mapping period (2013 to 2023). During this time, different frequencies of inundation were experienced across all monitored floodplain wetland landscapes (Figure 8). The most frequently flooded areas (classified as values 5 to 10; Figure 8) indicated that inundation occurred every 1 to 2 years and predominantly in river channels and connected wetland areas. More than 10% of the landscape in each wetland floodplain experienced such frequencies, apart from the Gwydir Wetlands (5%) and lower Lachlan floodplain (4%). Millewa Forest had the highest percentage of area flooded every 1 to 2 years at 26%. This was followed by Narran Lakes at 17%, Lowbidgee floodplain at 15% and Macquarie Marshes at 14%. Regions more frequently inundated were confined to locations containing core wetland areas, that is, areas considered habitable for water-dependent vegetation species. Examples include the Central Gingham–Gwydir (22%), Great Cumbung Swamp–lower Lachlan (26%) and Nap Nap Swamp–Lowbidgee Floodplain (54%).

The largest proportion of spatial variability and inundation extent occurred where inundation frequency was <3 times in the 10-year period (Figure 8). A large proportion of these were likely attributable to natural flood events rather than environmental water delivery (Figure 8). These less frequent events were encountered within 70% of the Macquarie Marshes and Narran Lakes, 60% of Gwydir Wetlands, 59% of Millewa Forest, 49% of lower Lachlan floodplain and 48% of Lowbidgee floodplain. Under this low frequency regime parts of the landscape received no water over the 10-year period. This was evident in the lower Lachlan floodplain, with 44% of the landscape obtaining zero inundation during this period.

Across all wetlands, at least 56% of the floodplain landscape was inundated at least once during this 10-year period (Figure 8). Narran Lakes had 94% of its landscape inundated at least once. This was the largest proportion of landscape inundation observed. However, Narran Lakes is the smallest wetland floodplain of the 6 monitored wetlands. Millewa Forest had 92% of its landscape inundated at least once and Macquarie Marshes had 91%. The Gwydir Wetlands and Lowbidgee floodplain were similar with 76% and 73% inundated at least once, respectively. The lower Lachlan floodplain only had 56% of its landscape inundated. These results show the spatial variability of inundation across the 6 monitored wetlands.

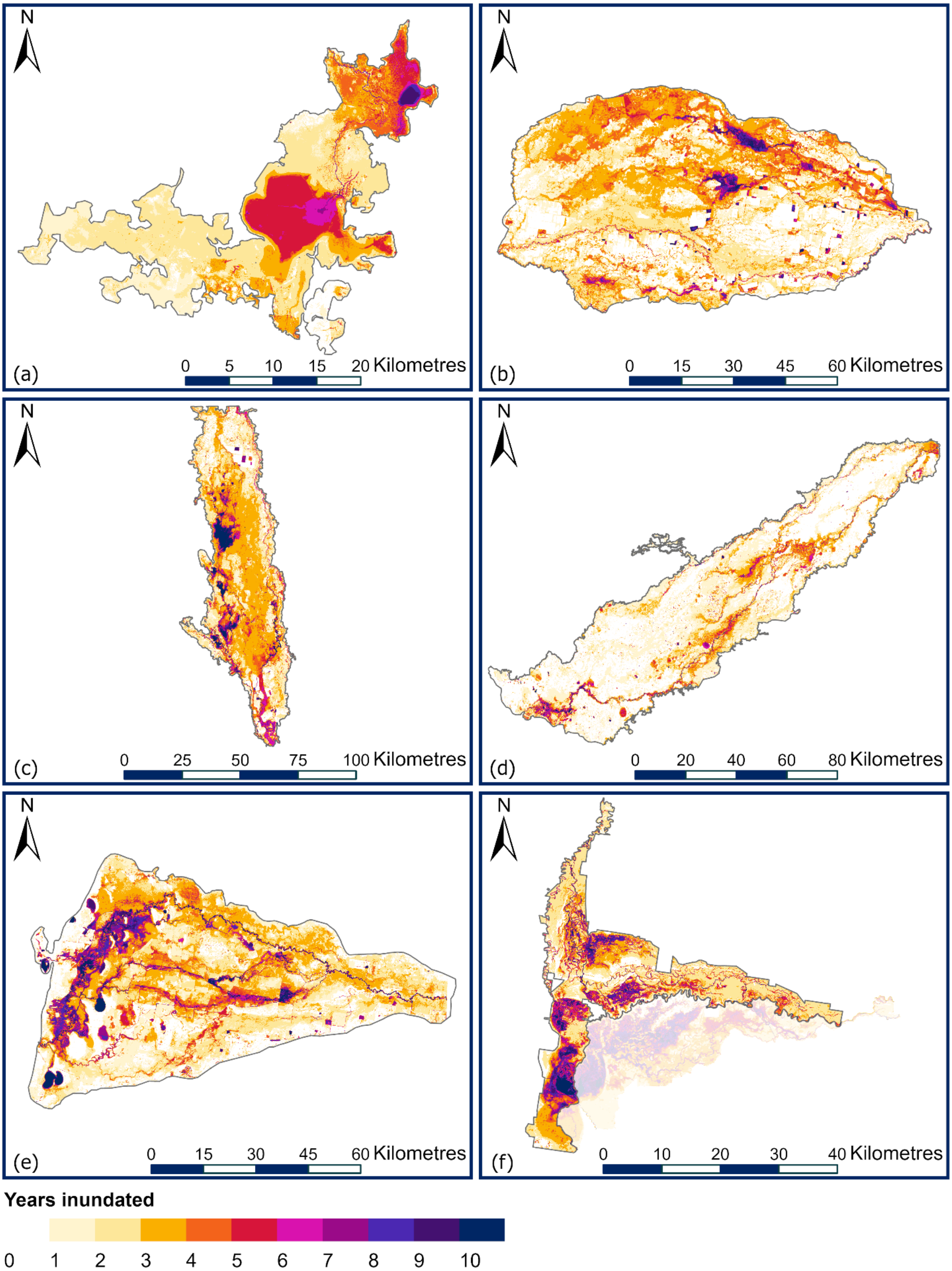

Figure 8 The 10-year inundation frequency for (a) Narran Lakes, (b) Gwydir Wetlands, (c) Macquarie Marshes, (d) lower Lachlan floodplain, (e) Lowbidgee floodplain and (f) Millewa Forest (mid Murray). The scale above represents the number of years inundated in the 10-year window of 2013 to 2023

3.4 Inundation frequency trends across vegetation types

The status and trend of the 10-year inundation frequency across vegetation types is shown in Figure 9 and Figure 10. Changes in flood frequency were assessed by evaluating the rolling 10-year periods, beginning with the 2004 to 2014 period to the current 2013 to 2023 period (figures 11 to 16). Of the vegetation communities evaluated, NWW require the most frequent flooding. NWW communities, consisting of species such as the common reed, require inundation every 1 to 2 years. Flooding is required once every 1 to 3 years for NWW communities consisting of sedgeland (Roberts and Marston, 2011). Significant proportions of NWW were inundated in 9 out of 10 years in the Lowbidgee floodplain (69%) and Millewa Forest (52%). This was lower for Narran Lakes (29%), Gwydir Wetlands (29%) and Macquarie Marshes (32%). In the lower Lachlan floodplain, only 8% of NWW was inundated at this frequency, mostly in the Great Cumbung Swamp. More than 60% of NWW wetlands met the lower estimate of inundation frequency requirement of 5 years in 10 for all wetland regions (Table 8), except the lower Lachlan floodplain (30%). For all wetland floodplains, the median and upper quartile of flood frequency classes in figures 11 to 16 indicate an increase in frequently flooded areas of NWW over time. Much of this increase appeared to stabilise after 2008 to 2018, likely due to earlier periods having a larger proportion of years affected by the Millennium Drought (2000 to 2009). The exception to this trend was Narran Lakes where flood frequency of NWW has remained relatively consistent across all periods evaluated (Figure 11).

RRGF can tolerate periods of dry conditions but require regular watering to maintain individual tree health and promote regeneration. They have a higher water requirement (1 to 3 years) compared with woodland (RRGW) communities (2 to 4 years; Roberts and Marston, 2011). The Lowbidgee floodplain and Millewa Forest contain the largest areas of RRGF and had 86% and 51% of RRGF inundated respectively for 3 out of 10 years; which is the lower estimate of flood frequency requirement. Other wetland regions had between 61% (Gwydir Wetlands) and 98% (Macquarie Marshes) of RRGF inundated at this frequency (Table 8). More than 93% of Macquarie Marshes was inundated in 4 out of the 10 years, compared to 32% in Millewa Forest and 73% in Narran Lakes. In the Lowbidgee floodplain and Millewa Forest, peaks in inundation extent in 2016–17, 2021–22 and 2022–23, indicate that many areas had 4 years with no inundation, although the flood return interval was not quantified.

In contrast, RRGF in Macquarie Marshes did not have this extended dry period, with 55% inundated annually. Similar intervals of peaks in extent are also observed with RRGW but with lower proportions inundated relative to RRGF (Figure 9 and Figure 10). RRGW are more prevalent in the Macquarie Marshes and lower Lachlan floodplain relative to RRGF, with 95% and 82% respectively inundated in 2 out of 10 years. For the Lowbidgee floodplain and Millewa Forest, 88% and 74% respectively were inundated at this frequency (Figure 10). This indicates that almost all Macquarie Marshes and more than three-quarters of the lower Lachlan floodplain and Lowbidgee floodplain met the water requirements of RRGW.

Trends in inundation frequency for RRGW and RRGF vary between wetland floodplains. In the lower Lachlan floodplain, median flood frequency of both vegetation communities was once every 10 years in 2004 to 2014 increasing to 3 out 10 years by 2021–22 (Figure 14). In other wetland communities there is no clear trend in flood frequency for RRGW and RRGF (figures 9 to 16).

FDS and FDW have a lower inundation frequency requirement compared to NWW, RRGF and RRGW communities. Lignum shrublands can maintain condition when inundated in 2 out of 10 years (Roberts and Marston, 2011). Annual inundation promotes vigorous growth and regeneration for these communities. FDWs, such as black box and coolibah woodlands, require between 3 and 7 year and 10-year return intervals, respectively (Roberts and Marston, 2011). Given the lower inundation requirements relative to NWW and RRG communities, it is unsurprising FDW and FDS have the lowest inundation frequencies. More than 61% of FDW were inundated at least twice, and more than 88% at least once, in all wetland floodplains during the reporting period, except for Millewa Forest at 68% (Figure 9 and Figure 10). This means the majority of FDW met the minimum estimated requirements. There are no clear trends in inundation frequency for FDW (figures 11 to 16). However, the current reporting period (2013 to 2023) had the highest median inundation frequency for FDW. This is likely due to extensive flooding in 2016–17 and again in 2021–22 and 2022–23 (Figure 9 and Figure 10). More than 72% of FDS were inundated at least twice during the reporting period across all wetland regions, meeting their minimum water requirements (Table 8). The exception was the lower Lachlan floodplain, where only 34% of FDS were inundated at this frequency. Only small proportions of FDS were inundated at more regular intervals. Between 2% (lower Lachlan floodplain) and 11% (Narran Lakes) were inundated in 5 out of 10 years. Although the Gwydir Wetlands had the lowest extent of FDS, more than 42% were inundated at this frequency. As with FDW, there are no clear trends in inundation frequency over time (figures 11 to 16).

Table 8 **Proportion of mapped vegetation groups that meet lower estimates of flood frequency requirements to maintain condition (Roberts and Marston, 2011). Some species within vegetation groups may require higher frequencies, while regeneration and expansion of vegetation groups require higher frequencies**

Group	Frequency	Narran Lakes	Gwydir Wetlands	Macquarie Marshes	Lower Lachlan floodplain	Lowbidgee floodplain	Millewa forest
NWW	5 in 10 years	68%	75%	61%	30%	91%	96%
RRGF	3 in 10 years	81%	61%	98%	74%	86%	51%
RRGW	2 in 10 years	–	–	95%	82%	88%	74%
FDW	1 in 10 years	97%	88%	99%	91%	90%	68%
FDS	2 in 10 years	91%	93%	96%	34%	72%	–

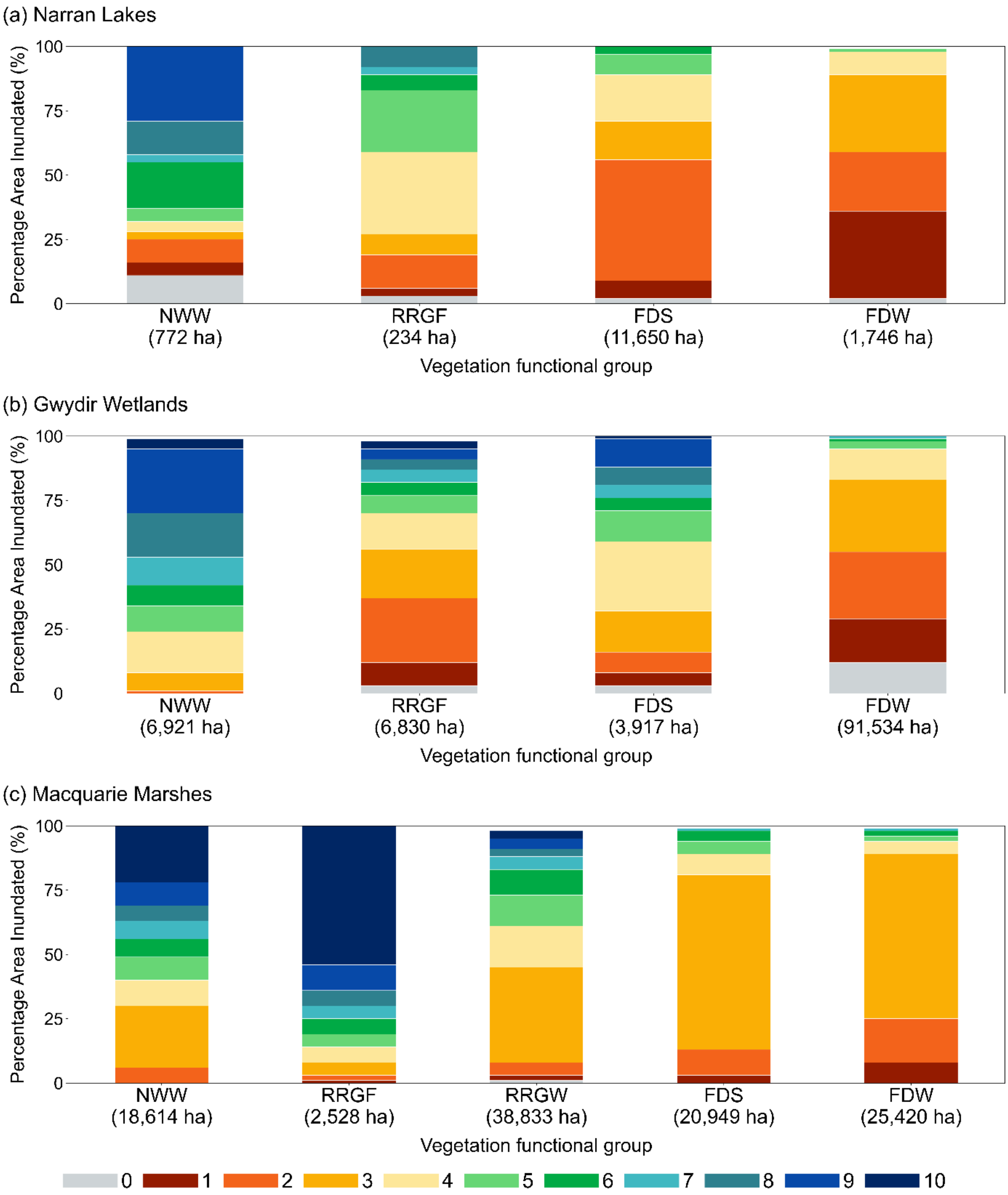

Figure 9 **Percentage (%) area of floodplain vegetation groups inundated in the 10-year period (2012–13 to 2022–23) at (a) Narran Lakes, (b) Gwydir Wetlands and (c) Macquarie Marshes. The scale above represents the number of years inundated in the 10-year window. NWW = non-woody wetland, RRGF = river red gum forest, RRGW = river red gum woodland, FDS = flood-dependent shrublands, FDW = flood-dependent woodlands**

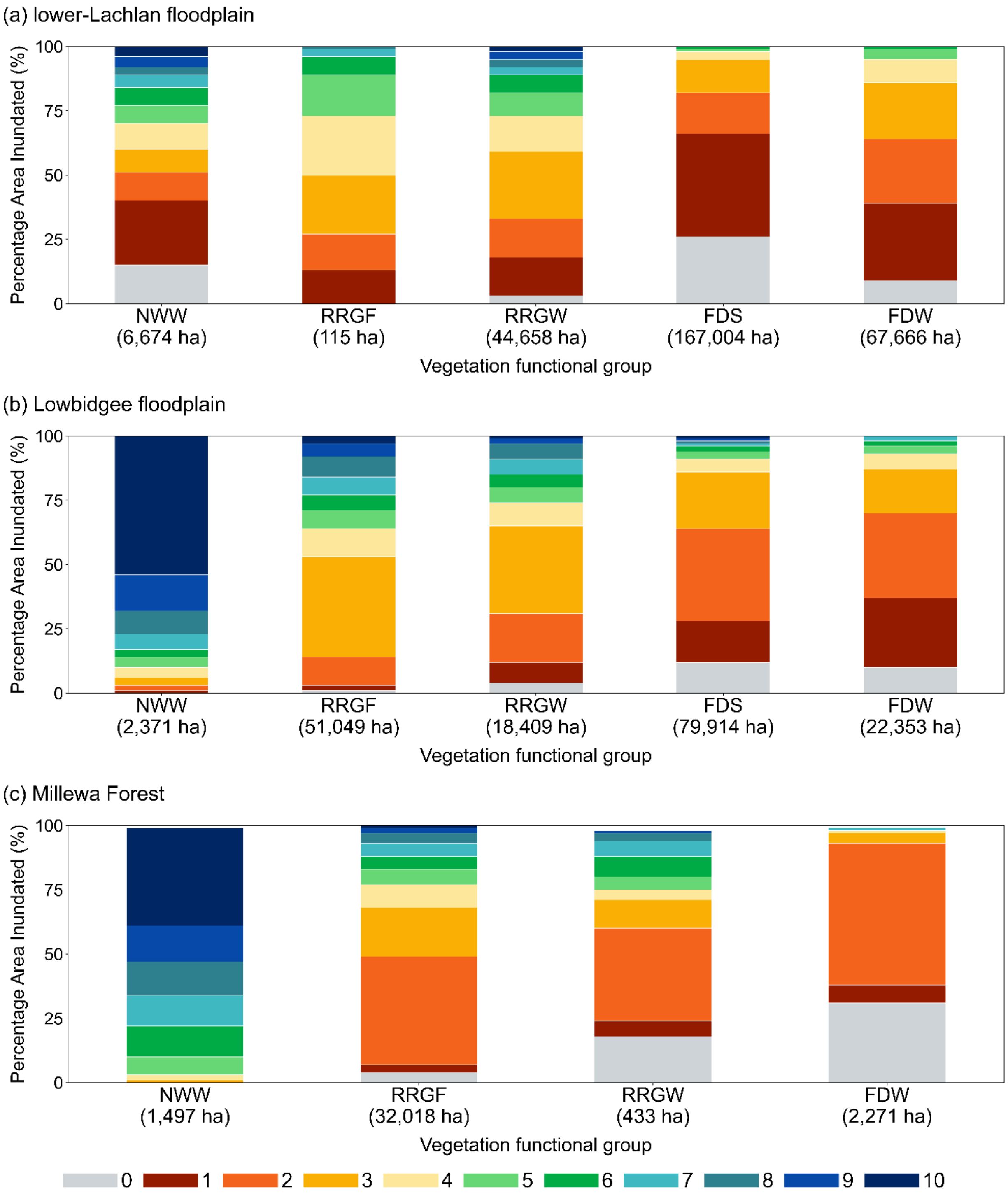

Figure 10 **Percentage (%) area of floodplain vegetation groups inundated in the 10-year period (2012–13 to 2022–23) at (a) lower Lachlan floodplain, (b) Lowbidgee floodplain and (c) Millewa Forest (mid Murray). The scale above represents the number of years inundated in the 10-year period (2012–13 to 2022–23). NWW = non-woody wetland, RRGF = river red gum forest, RRGW = river red gum woodland, FDS = flood-dependent shrublands, FDW = flood-dependent woodlands**

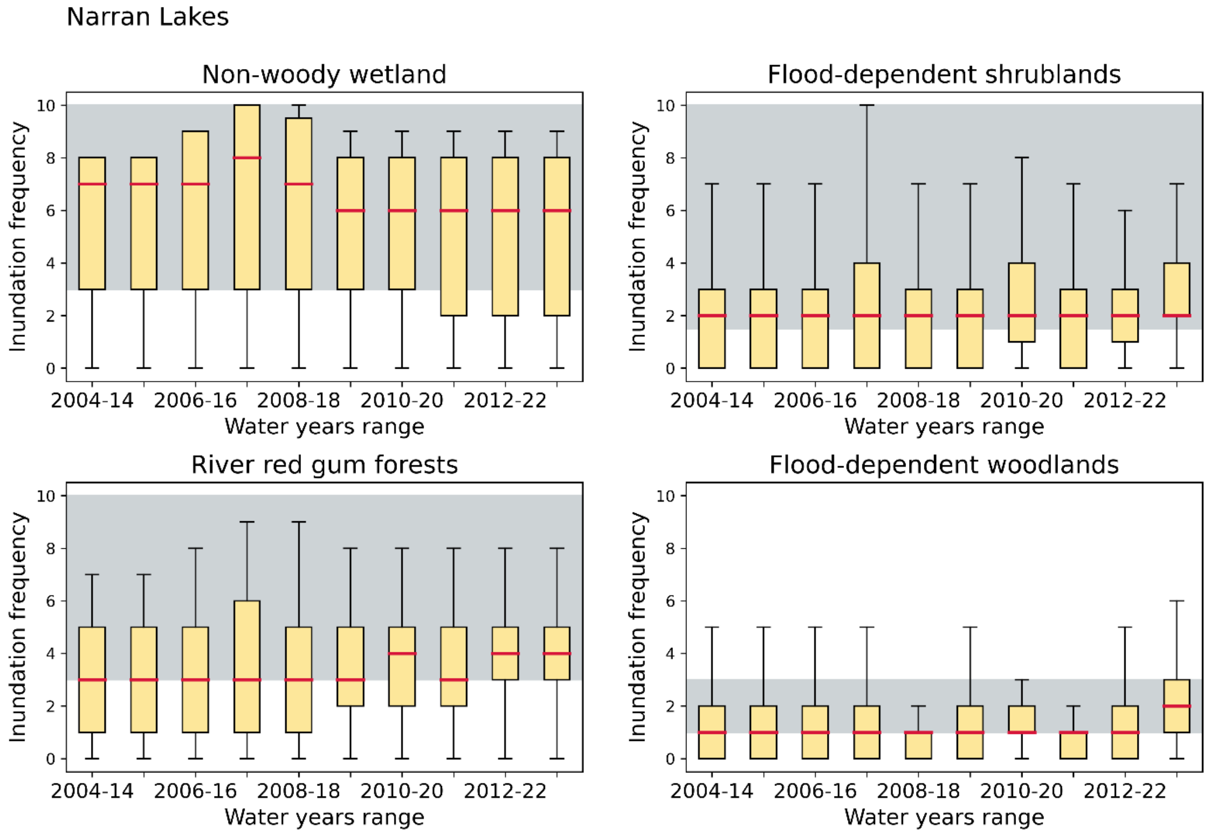

Figure 11 **The 10-year inundation frequency for Narran Lakes for wetland vegetation functional groups in relation to the range of known flood frequency water requirements (grey band). The number of years inundated in each 10-year window shifted forward annually. Red line indicates the median 10-year inundation frequency**

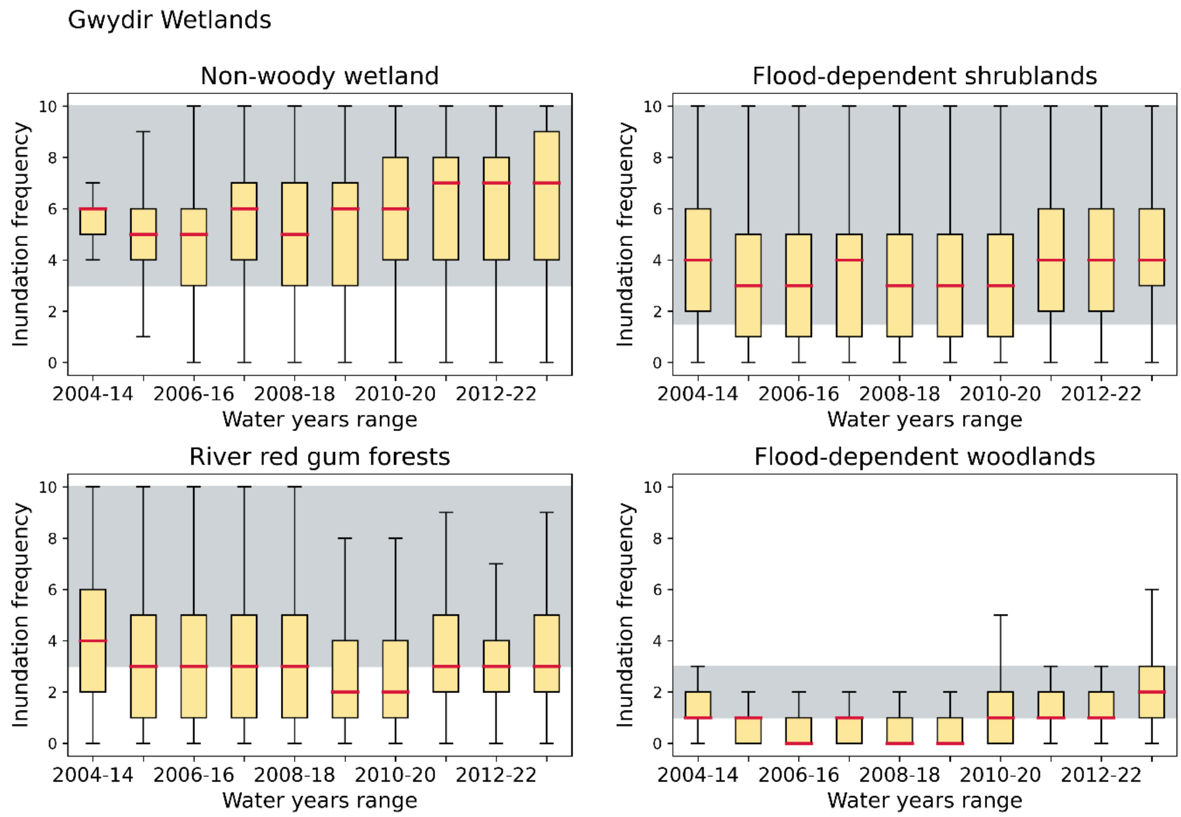

Figure 12 **The 10-year inundation frequency for the Gwydir Wetlands for wetland vegetation functional groups in relation to the range of known flood frequency water requirements (grey band). The number of years inundated in each 10-year window shifted forward annually. Red line indicates the median 10-year inundation frequency**

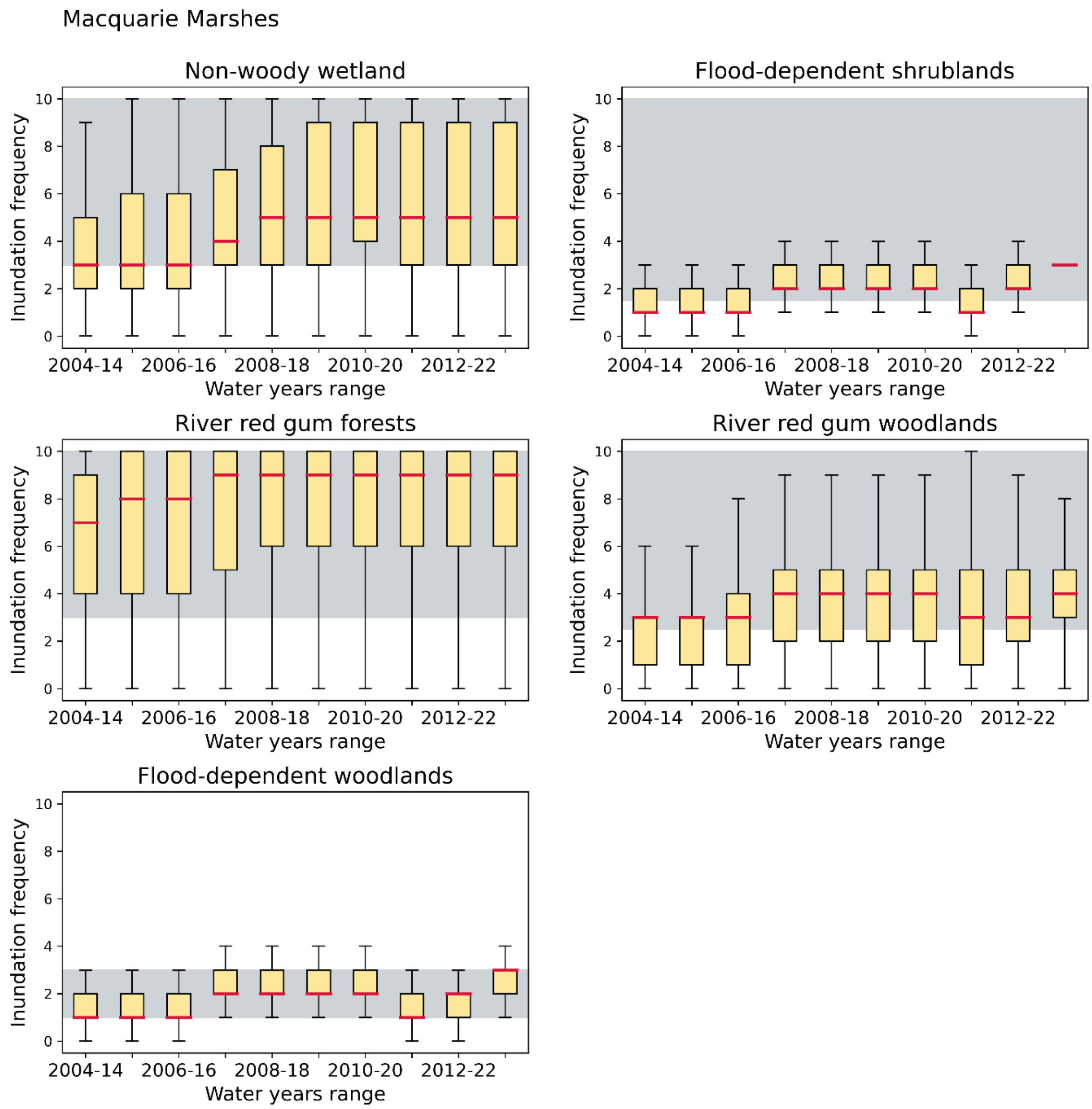

Figure 13 **The 10-year inundation frequency for Macquarie Marshes for wetland vegetation functional groups in relation to the range of known flood frequency water requirements (grey band). The number of years inundated in each 10-year window shifted annually. Red line indicates the median 10-year inundation frequency**

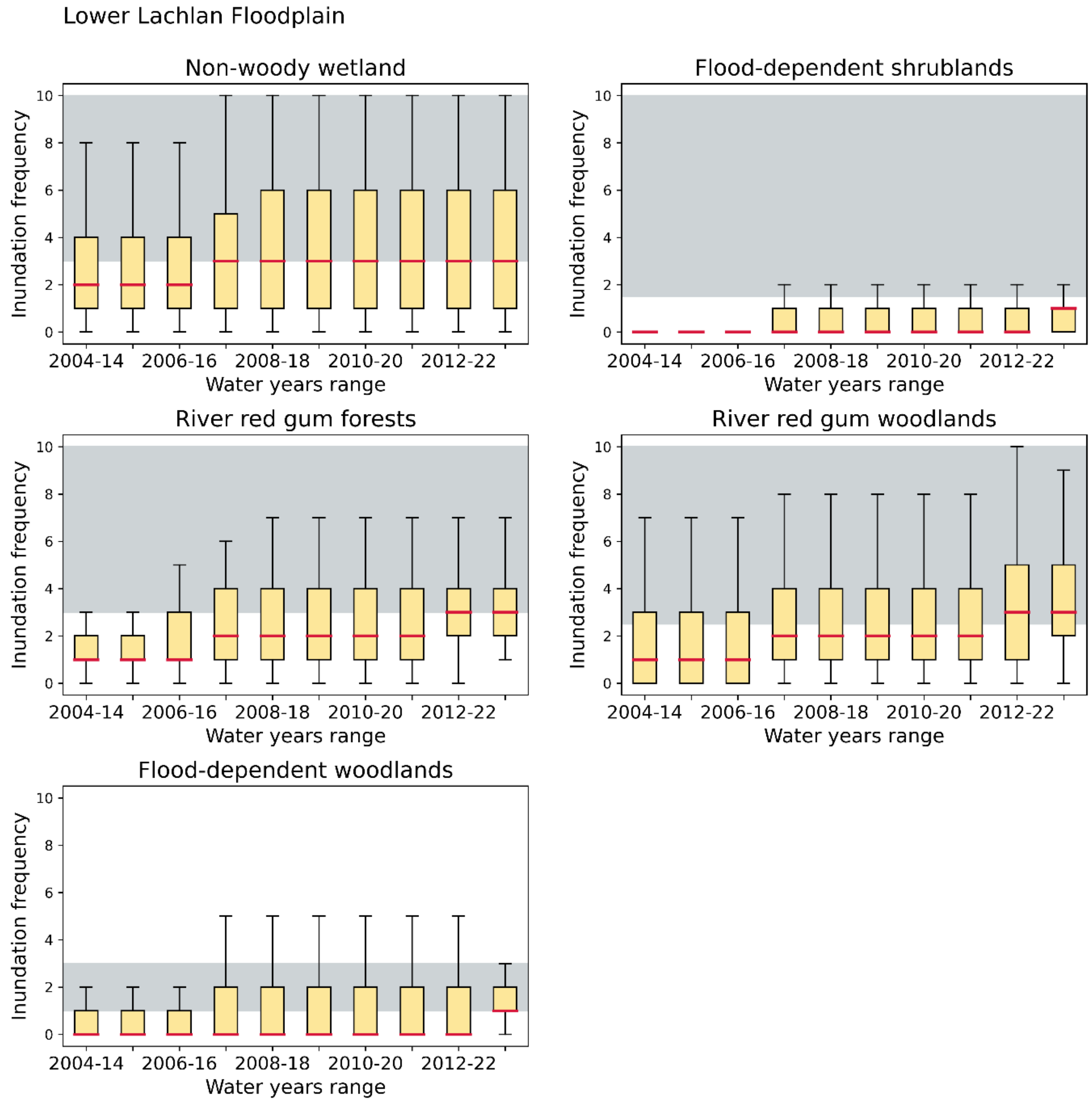

Figure 14 **The 10-year inundation frequency for the lower Lachlan floodplain for wetland vegetation functional groups in relation to the range of known flood frequency water requirements (grey band). The number of years inundated in each 10-year window shifted annually. Red line indicates the median 10-year inundation frequency**

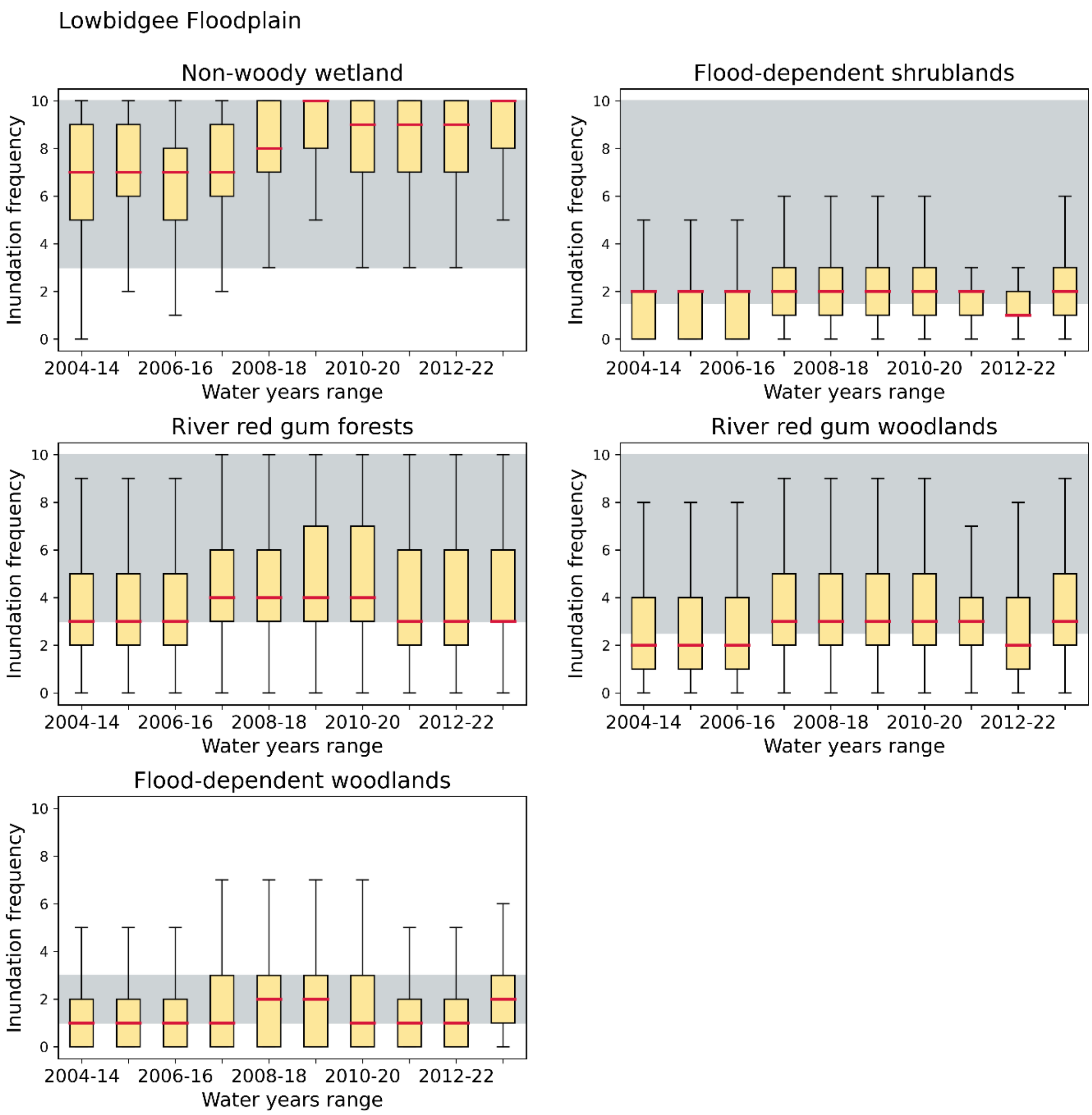

Figure 15 **The 10-year inundation frequency for the Lowbidgee floodplain frequency for wetland vegetation functional groups in relation to the range of known flood frequency water requirements (grey band). The number of years inundated in each 10-year window shifted forward annually. Red line indicates the median 10-year inundation frequency**

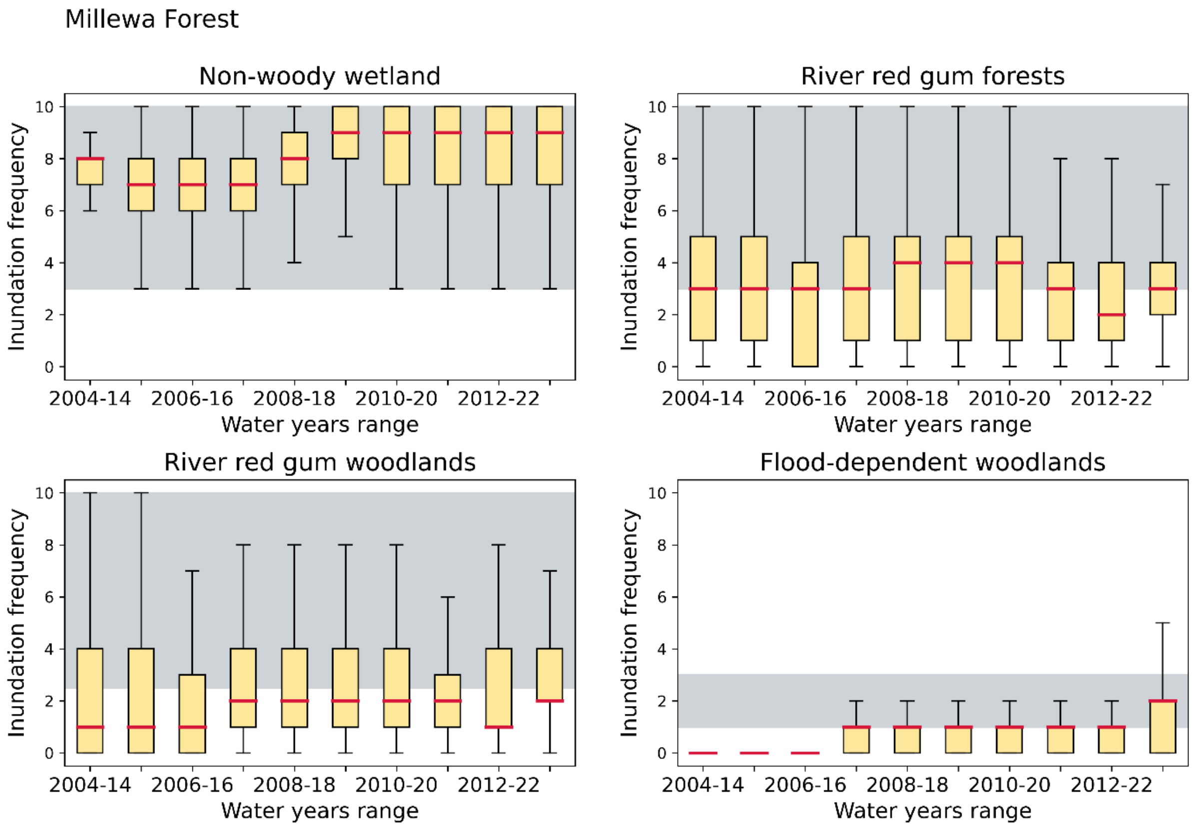

Figure 16 **The 10-year inundation frequency for Millewa Forest (mid Murray) for wetland vegetation functional groups in relation to the range of known flood frequency water requirements (grey band). The number of years inundated in each 10-year window shifted forward annually. Red line indicates the median 10-year inundation frequency**

4. Discussion

4.1 Is this result expected and why are we seeing these outcomes? How has environmental water contributed?

Climatic conditions fluctuated across all 6 wetland regions during the 10-year evaluation period. Wetlands became extremely dry, with no tributary flows and minimal to no environmental water available for delivery to the system during the severely dry period (2013 to 2020). Narran Lakes became significantly dry by 2018–19 due to lack of tributary flows from Queensland. The extent of inundation across the Gwydir Wetlands and Macquarie Marshes decreased due to hot, dry conditions, with a few small water delivery events throughout the water years between 2013 and 2023. The annual inundation extent of NWW vegetation declined to as low as 1% in the Gwydir Wetlands and 16% in Macquarie Marshes during the prolonged dry period. However, these percentages are based on water years. Macquarie Marshes experienced inundation areas of less than 1% in NWW vegetation by late 2019 but were replenished in early 2020 due to heavy rainfall. In the Macquarie Marshes, 50% of RRGF was inundated, while in the Gwydir Wetlands only 4% was inundated.

The lower Lachlan floodplain was most affected during the prolonged dry conditions in the southern MDB. By 2018–19, less than 2% of NWW vegetation, RRGF and FDS, was inundated (Figure 10). These small areas were inundated from small environmental water flows delivered to the system. The delivery of environmental water flows resulted in the inundation of 40 to 70% of NWW vegetation in the Lowbidgee floodplain during the dry phase. However, by 2019–20 the extent of inundation dropped to only 8% of RRGF and RRGW, and 5% of FDS. This highlights the impact of the severe lack of larger flows in the system. In Millewa Forest, NWW vegetation was most affected during the dry period, with only 11% inundated in 2017–18, compared to other vegetation types (Figure 10). Management of priority water maintained inundation of NWW vegetation above 50% for the remainder of the dry period. However, because water management targeted NWW vegetation, less than 10% of RRGF and RRGW were inundated during this time.

For most wetlands, there was no expectation for wetlands to receive inundating flows for the 2019–20 water year. This was because of the extremely dry landscape that persisted after the prolonged dry period and the lack of available environmental water. However, widespread rainfall began across the northern MDB from early 2020, and in the southern MDB from mid-2020 causing a noticeable increase in the extent of inundation across all wetlands. Increased tributary flows and dam spills resulted in higher proportions of wetland vegetation being inundated. In some instances, wetland vegetation became 100% inundated – for example, in the Macquarie Marshes during the 2022–23 water year for both NWW vegetation and RRGF (Figure 9). However, it is important to note that this is based on historical vegetation mapping, which does not account for the expansion of NWW into new areas. Due to large overbank flows, environmental water was delivered to several wetlands after the high tributary flows to extend the lateral connectivity across and within these wetlands.

As inundation extent from one year to the next is spatially variable, it is expected that the inundation occurring at any one location will vary in the 10-year period between 2013–14 and 2022–23. Ideally, this occurrence should meet the water requirements of the different vegetation communities. Flows that inundate the wetlands have been delivered to a proportion of Macquarie Marshes every year. Therefore, the hydrological conditions for these areas are likely to be on track to meet the long-term 10-year ecological water requirements that maintain and protect most of the core wetland areas. It was not expected that all areas of wetland vegetation would have received their required 10-year inundation frequency. This is due to extended dry periods of up to 3 years before and after the 2016–17 flood, with 5 of the years having an inundation extent less than the long-term median (figures 4 and 5). Some areas did not experience inundation even during large flow events due to changes in flow paths. The inundation frequency of RRGF was expected as they are largely distributed along a major flow and flooding pathway.

4.2 How has the Basin Plan (environmental water) contributed?

Since the introduction of the Basin Plan in 2012–13, environmental water has been improving ecological outcomes for wetlands in NSW. This water has been delivered from both the NSW Government and the Commonwealth Environmental Water Holder, across all water resource planning areas of the MDB. Typically, environmental water delivery has been designed to maintain the current condition and extent of refugia habitat for breeding and dispersal opportunities, through the delivery of water to core vegetated wetlands. This has increased the frequency and duration of wetland vegetation inundated within channel, or within nearby wetland landscape habitats. This is evident in Millewa Forest (mid Murray), where water is predominantly delivered annually, from winter to spring, to improve connectivity within and across wetlands to support fauna breeding events. The delivery of environmental water to the Millewa Forest has enabled 100% of NWW vegetation to experience high frequency regimes and meet environmental watering requirements (EWR). In some wetlands, the contribution of environmental flows is limited due to system constraints that prevent inundation reaching certain areas of the landscape. Environmental flow delivery has been shown to support wetlands in times of natural flooding. These flow deliveries have been used to either extend the duration of inundation or increase the volume of water delivered to the system. This increases the total extent of inundation across the floodplain, enabling vegetation at higher elevation to be inundated more frequently, and potentially meet their EWRs (i.e. in FDW). For example, environmental water was delivered in the Gwydir Wetlands in early 2021. These flows were additional to increased natural flows from rainfall that supported recovery from preceding dry years. Similarly, in the lower Lachlan floodplain, translucent flows occurring in mid-to-late 2020 were complemented with environmental water. This supported sustained inundation in the wetlands of the lower Lachlan, particularly in the Great Cumbung Swamp.

4.3 What is being done to meet objectives in future and how will this be monitored?

To ensure the required inundation regimes are maintained within and across wetlands, water for the environment is essential, particularly for vegetation in core wetland areas such as NWW and RRG communities with high water requirements. Vegetation groups that sit higher on the floodplain are reliant on overbank and wetland inundating flows from all water sources . These may not occur with sufficient frequency to meet the water requirements of these vegetation groups. For example, a large proportion of FDS in the lower Lachlan floodplain has been inundated once in the last 10 years (Table 8) but to maintain health it is known to require at least two inundation events in 10 years (Figure 14). Monitoring and evaluating the extent of inundation under different watering scenarios, in collaboration with water managers, is crucial to provide evidence that EWRs are being met, and to better inform water management decisions.

The introduction of innovative technology to the inundation monitoring program will improve the accuracy of data captured. These new technologies will greatly assist water managers with future water planning and decision-making. For example, the use of drones to survey areas will improve inundation modelling because this technology provides better imagery to capture complex surfaces and topology. Also, the installation of a network of depth loggers across wetlands will help inform decisions around wetland hydrology (for example, cease-to-flow conditions) and improve monitoring of water levels. The monitoring of inundation also needs to broaden its geographical extent to other priority wetlands across the NSW MDB not reported in this program. These include wetlands along the Murray River such as Koondrook–Perricoota forests, as well as wetlands within the Namoi and Border Rivers catchments.

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Appendix A: List of long-term water plan objectives

Table 9 Summary table of NSW LTWP objectives assessed under the 4 monitored themes

Theme	Code	Objectives
Flows and connectivity	EF1	Provide and protect a diversity of refugia across the landscape.
Flows and connectivity	EF2	Create quality instream, floodplain and wetland habitat.
Flows and connectivity	EF3a	Provide movement and dispersal opportunities for water-dependent biota to complete lifecycles and disperse into new habitats within catchments.
Flows and connectivity	EF3b	Provide movement and dispersal opportunities for water-dependent biota to complete lifecycles and disperse into new habitats - between catchments.
Vegetation	NV1	Maintain the extent and viability of non-woody vegetation communities occurring within channels.
Vegetation	NV2	Maintain or increase the extent and maintain the viability of non-woody vegetation communities occurring in wetlands and on floodplains.
Vegetation	NV2a	Non-woody vegetation communities within semi-permanent, intermittent, temporal & ephemeral wetland & floodplain areas.
Vegetation	NV2b	Ephemeral understorey vegetation within forests, woodland & open floodplain areas.
Vegetation	NV3	Maintain the extent and improve the condition of river red gum communities closely fringing river channels.
Vegetation	NV4a	For river red gum forests, maintain or increase the extent and maintain or improve the condition of native woodland and shrubland communities on floodplains.
Vegetation	NV4b	For river red gum woodlands, maintain or increase the extent and maintain or improve the condition of native woodland and shrubland communities on floodplains.
Vegetation	NV4c	For black box woodlands, maintain or increase the extent and maintain or improve the condition of native woodland and shrubland communities on floodplains.
Vegetation	NV4e	For lignum shrublands, maintain or increase the extent and maintain or improve the condition of native woodland and shrubland communities on floodplains.

Theme	Code	Objectives
Waterbirds	WB1	Maintain the number and type of waterbird species.
Waterbirds	WB2	Increase total waterbird abundance across all functional groups.
Waterbirds	WB3	Increase opportunities for non-colonial nesting waterbird breeding.
Waterbirds	WB4	Increase opportunities for colonial nesting waterbird breeding.
Waterbirds	WB5	Maintain the extent and improve condition of waterbird habitats.
Other species (frogs)	OS1	Maintain species richness and distribution of flow-dependent frog communities.
Other species (frogs)	OS2	Maintain successful breeding opportunities for flow-dependent frog species.
Other species (frogs)	OS3a	Maintain and increase number of wetland sites occupied by threatened southern bell frog.
Other species (frogs)	OS3b	Maintain and increase number of wetland sites occupied by threatened Sloane's froglet.