# Assessing the hydrological changes to flood plain wetland inundation caused by river regulation

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**Abstract** Flood plain wetlands are crucial to the ecological functioning of Australian lowland rivers. River regulation has resulted in major changes to riverine flow regime and consequently the inundation regimes of flood plain wetlands. This paper presents a procedure for assessing the hydrological changes to flood plain wetland inundation as a result of river regulation. Three simple hydrological measures have been developed which assess the change to the number of times flood plain wetlands are inundated as well as the length and timing of inundation. Testing these on seven key flood plain wetland systems along the Murray–lower Darling River system indicates substantial changes to inundation patterns, particularly the number of times the flood plain wetland is inundated and seasonality of inundation. In contrast median inundation period has changed little. The procedure presented has the advantage of being a repeatable measure of change and may also be used to assess the potential impact of environmental flow options. The procedure would be greatly enhanced by the use of modelled daily flow data, more comprehensive areal inundation data and correlation of inundation regime changes with ecological consequences.

**Key words** flood plain wetland; hydrological assessment; inundation; regulation; River Murray; lower Darling River

## INTRODUCTION

Flood plain wetlands have simultaneously been described as the "kidneys of the landscape" and as "biological supermarkets" (Mitsch, 1995) illustrating the importance of their role in the ecological functioning of most river systems. Australian flood plain wetlands are no exception, being crucial for the breeding of native fish and bird species (Kingsford, 2000) and for the delivery of carbon and nitrogen to the river (Robertson *et al.*, 1998).

The flow regime of rivers drives a host of ecological processes, not least of which are those driven by lateral connections with the flood plain (Junk *et al.*, 1989). River regulation in Australia has resulted in major changes to the flow regime, including changes to the timing and duration of small to medium sized floods and alteration of the seasonal pattern of flooding. Such changes have altered lateral connections between the river and its flood plain and are known to affect plant community structure (Casanova & Brock, 2000), macroinvertebrate community composition (Quinn *et al.*, 2000), bird breeding (Briggs *et al.*, 1997), fish populations (Boulton & Lloyd, 1992) and nutrient cycling (Baldwin & Mitchell, 2000) in flood plain wetlands. As the river and its flood plains are inextricably linked, such change to the flood plain wetlands magnifies the effects of flow regulation on the ecological integrity of Australian rivers.

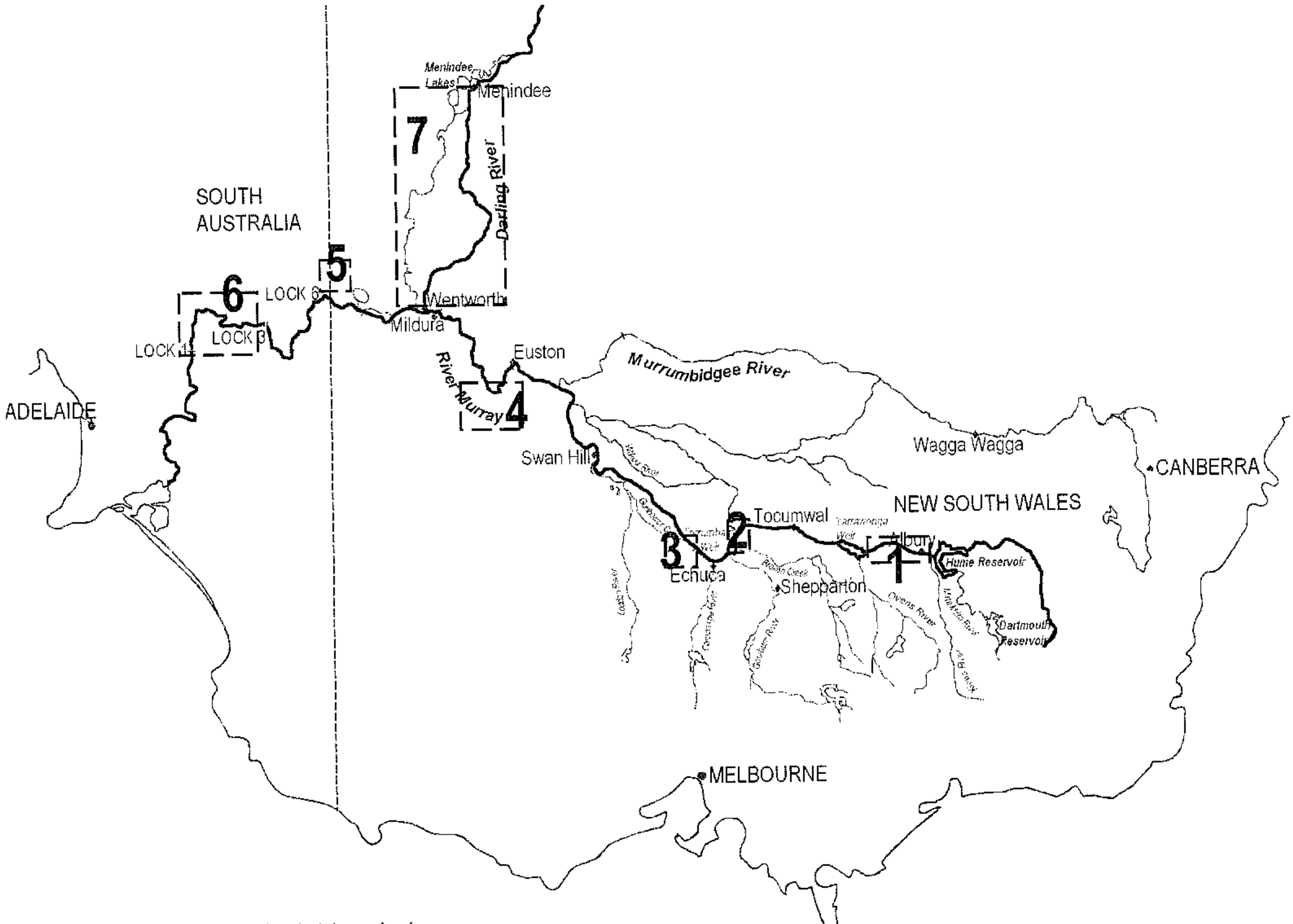


**Fig. 1** Location of the assessed flood plain wetlands.

As part of the "snapshot of river health" (Norris *et al.*, 2001a) a procedure was developed to assess the changes to flood plain wetland inundation caused by river regulation. This paper describes the procedure and illustrates its use and interpretation by presenting the assessment of seven key wetland systems along the Murray–lower Darling river system, Australia.

## STUDY SITE

The Murray–Darling river system is located in southeastern Australia (Fig. 1) and is the fourth longest river system in the world (Twidale, 1973). Almost the entire length of the Murray–Darling river system is impacted by regulation (i.e. dams and weirs) of either the main channel or tributaries (Thoms et al., 2002). Wetlands are an integral feature of these rivers with recent mapping identifying more than 7000 wetlands along 2500 km of the River Murray (Green & Alexander, 2002). Seven flood plain wetland systems were chosen along the River Murray and the lower Darling River for assessment (Fig. 1) based on available inundation data and relative importance of the wetlands (e.g. Ramsar listing).

## THE ASSESSMENT PROCEDURE

The assessment procedure developed is based on an auditing approach (Norris *et al.*, 2001b), where current inundation patterns are compared with natural or pre-regulation inundation patterns.

### Data

To assess the change to flood plain–wetland inundation, data indicating area inundated at various flows are required. Because each flood plain wetland has an individual flooding regime (Young, 2001), such data are sparse, with heavy reliance on anecdotal evidence or substantial extrapolation from known points. At present, standard inundation data sets are not available for each of the chosen wetlands along the Murray –Darling river system. Areal inundation data were collated from a variety of sources (Table 1) for use in this analysis. For most sites three threshold flows, chosen on the

**Table 1** Flood plain wetlands analysed and the threshold flows used for inundation spell analysis.

| Site | Flood plain/wetland | Threshold flow in Ml day$^{-1}$, (% inundation) | | | Data source |
|---|---|---|---|---|---|
| 1 | Flood plain from Albury to Yarrawonga | 26 000 (CTF) | 40 000 (14%) | 65 800 (75%) | MDBC |
| 2 | Barmah-Millewa forest* | 12 000 (CTF) | 16 400 (50%) | 30 400 (75%) | MDBC |
| 3 | Gunbower* | 13 700 (CTF) | | 40 000 (75%) | MDBC |
| 4 | Hattah lakes* | 36 700 (CTF) | 48 900 ("most") | 73 000 (100%) | MDBC |
| 5 | Chowilla flood plain* | 33 110 (CTF) | 80 000 (50%) | 100 000 (75%) | MDBC |
| 6 | Flood plain from lock 3–lock 1 | 28 000 (CTF) | 60 000 (25%) | 80 000 (30%) | MDBC |
| 7 | Flood plain from Menindee to Darling junction | 7 000 (20%) | 13 000 (50%) | 28 900 (93%) | Green *et al.* (1998) |

* Ramsar wetlands (Convention on Wetlands, Ramsar, Iran, 1971).

basis of the reliability of the corresponding areal inundation data, were assessed. Two of these thresholds are considered ecologically important:

- *Commence to flow (CTF)* represents the flow (Ml day$^{-1}$) at which a range of in-channel structures, riparian vegetation communities, lowlying wetlands, primary flood runners and anabranches begin to receive water.
- *Significant flood plain inundation (SFI)* represents flows (Ml day$^{-1}$) that result in a significant degree (typically 50–75%) of flood plain wetland inundation and connection with association flood plain structures.

Modelled monthly flow data for a *c.* 100-year period under "current" and "natural" conditions for sites along the River Murray and lower Darling River were supplied by the Murray Darling Basin Commission (MDBC). Modelled monthly data were used as modelled daily data were not available for all sites. Thus, one of the additional difficulties in assessing the change in flood plain wetland inundation was marrying the flow thresholds, measured in Ml day$^{-1}$ with the monthly flow data available. This was achieved using a spell analysis program (see below), which divides the monthly flows by the number of days in each month to give "average" daily flows.

## Data analysis

The modelled natural and current flow data were analysed using a spell analysis program "GetSpells" (Donald *et al.*, 1999). This program defines a spell as being the period of time when flows are continuously above or below a nominated threshold flow and can therefore provide information related to the frequency, duration and interval between events exceeding selected thresholds. "GetSpells" was used to determine the change in the number of times the flood plains are inundated, the length of inundation and the timing of the inundation, for the CTF, SFI and an intermediate inundation threshold. It is recognized that drying of the flood plain is equally important ecologically as wetting (Baldwin & Mitchell, 2000), but it was found that the median length of dry periods was highly correlated with the number of times the flood plain is inundated and so analysis of dry periods was not used as a separate component of the assessment.

## Assessment

Three indicators of change to the flood plain wetland inundation regime were calculated as follows:

**Change in event frequency (*N*)** This indicator was based on the ratio of current to natural flows and assumes that an increase in the number of inundation times is equally detrimental to the flood plain as a decrease. This assesses the change to the number of times in 100 years that the flow is above a threshold flow. It was calculated according to the following equation:

$$N = \frac{n_c}{n_n}$$

where $n_c$ and $n_n$ are the number of times/100 years above threshold for current and natural conditions respectively. In situations where $n_c > n_n$, the inverse of the index was used. A value of 1 indicates no change from natural conditions and 0 a complete change.

**Change in median event duration (*D*)** The assessment was based on a ratio of current to natural flows and assume that an increase in median event duration is equally detrimental to the flood plain as a decrease. This indicator was calculated according to the following equation:

$$D = \frac{d_c}{d_n}$$

where $d_c$ and $d_n$ are median event durations under current and natural conditions respectively. Again, where $d_c > d_n$ the inverse of the index was used, and a value of 1 indicates no change from natural conditions and 0 a complete change.

**Change to the frequency that floods commence in each month (*S*)** This index was designed to indicate change to seasonal pattern and is based on the change to the number of times the flow threshold commenced a period of exceedance for each month over a 100-year period. It was calculated as the sum of the difference between current and natural conditions for each month, with the month with the maximum number of times the flow commenced to exceed the threshold flow scaled to 1 for both natural and current conditions. This allowed a change in the total number of exceedances between current and natural with no change to the pattern of exceedances to score as no change. In the absence of evidence to the contrary, this assessment assumes that a change in the number of times the flow commenced to exceed the threshold flow in any month is, ecologically, of equal importance.

Initially, this index gives a value of 0 where there is no change to the number of times per month the threshold is exceeded and although numerically this approach gives a maximum possible value of 12, practically it has been found that a complete reversal of the seasonality or the removal of any seasonal pattern results in scores of the order of 7. To enable easy comparison and combination of the three indicators, this index was adjusted so that a value of 1 indicates no change and 0 a complete reversal of the seasonal pattern.

## Combining the indicators

The three components assessed are key to the normal operation of riverine–flood plain ecology. Therefore, compromising any one of these measures compromises flood plain–river processes. Consequently, the assessment given for each flow threshold was the lowest score of the three measures. For example, if the scores of *N*, *D* and *S* for a CTF threshold at a site are 0.4, 0.8 and 0.7 respectively, then the numerical assessment for the CTF threshold will be 0.4.

## RESULTS

The inundation regimes of the flood plain wetlands along the entire length of the River Murray from Hume Dam to the Barrages and the lower Darling River have been substantially modified as a result of flow regulation (Table 2). The greatest modification has been to the number of times the flood plain is inundated—with many flow thresholds currently being exceeded fewer than 50% of the times (and some sites have observed an increase) that would occur under natural flow conditions. Additionally, the number of times the significant inundation thresholds (inundation of 50–75% of the flood plain wetland) are exceeded has been modified far more than the CTF threshold. In particular, inundation of 75% of the Chowilla flood plain and the flood plain from Lock 3 to Lock 1, now occurs fewer than one third of the times it would under natural flow conditions.

The seasonal pattern of wetland inundation has also been modified for most of the river length (Table 2). The most substantial effect is on the lower Darling River with large changes to the seasonal pattern of small floods (those floods represented by the inundation of 20% of the flood plain). The area between Yarrawonga and Torrumbarry has also had the seasonal pattern of flood plain inundation modified—particularly at the CTF and 50% inundation thresholds.

While the number of times the flood plain is inundated and the seasonal pattern of inundation have changed substantially, the duration of inundation has not changed to

**Table 2** Flood plain wetland inundation assessment for seven sites along the Murray–Darling river system. For each of the indicators, a value of 1 indicates no change and a value of 0 a complete change.

| Site | Threshold | *N* | *D* | *S* | Assessment |
|---|---|---|---|---|---|
| 1 | CTF | 0.42 | 1.00 | 0.77 | 0.42 |
| | 14% | 0.47 | 1.00 | 0.74 | 0.47 |
| | 75% | 0.55 | 1.00 | 0.88 | 0.55 |
| 2 | CTF | 0.89 | 0.40 | 0.59 | 0.40 |
| | 50% | 0.77 | 0.50 | 0.69 | 0.50 |
| | 75% | 0.43 | 1.00 | 0.76 | 0.43 |
| 3 | CTF | 0.62 | 0.67 | 0.76 | 0.62 |
| | 75% | 0.63 | 0.67 | 0.77 | 0.63 |
| 4 | CTF | 0.49 | 0.60 | 0.76 | 0.49 |
| | "most" | 0.41 | 0.75 | 0.74 | 0.41 |
| | 100% | 0.30 | 1.00 | 0.84 | 0.30 |
| 5 | CTF | 0.55 | 0.67 | 0.77 | 0.55 |
| | 50% | 0.32 | 1.00 | 0.83 | 0.32 |
| | 75% | 0.30 | 0.83 | 0.66 | 0.30 |
| 6 | CTF | 0.62 | 0.57 | 0.88 | 0.62 |
| | 25% | 0.34 | 0.75 | 0.78 | 0.34 |
| | 30% | 0.29 | 1.00 | 0.87 | 0.29 |
| 7 | 20% | 0.72 | 1.00 | 0.36 | 0.36 |
| | 50% | 0.49 | 0.80 | 0.54 | 0.49 |
| | 93% | 0.40 | 0.67 | 0.53 | 0.40 |

*N* change in event frequency;
*D* change in median event duration;
*S* change to the frequency that floods commence in each month.

the same extent (Table 2). Little modification has occurred to the duration of the larger floods with data for the flood plain between Albury and Yarrawonga, the Barmah Millewa forest and the flood plain between locks 1 and 3 showing no change to the duration of floods which inundated greater than 75% of these flood plain wetlands. The greatest modification to the duration of flood plain inundation occurs for small floods into the Barmah Millewa forest, with a substantial increase in the duration of events which begin to inundate this site (Table 2).

## DISCUSSION

This assessment indicates substantial changes to the inundation patterns of the flood plain wetlands along the Murray–lower Darling river system. The River Murray and its major tributaries are managed to provide reliable water supply—particularly to meet irrigation demands. This has caused substantial alteration to the number of times the flood plain wetlands is inundated as well as some modification to the seasonal pattern of inundation (Table 2). Only minor modification to the duration of events that inundate particular flood plain wetlands were revealed by this analysis (Table 2).

The capture and storage of water by dams and the release of water during the irrigation season changes the number of times the flood plain wetlands are inundated by removing the mid-range floods from the flow regime (Close, 1992). These effects are reflected in the first of the tested indicators, $N$, which shows substantial changes to the number of times the flood plain wetlands are inundated. At some sites, the release of high flows during the irrigation season has increased the number of times the flood plain commences to be inundated, e.g. Barmah Millewa forest. While the change is reflected in the indicator $N$, the direction of change is not. It may be valuable for the ecological use of this indicator that the direction of change be provided with the number as a plus or minus sign. Additionally, drying may be a relevant analysis for specific wetlands that are inundated during the periods of extended regulated flow as these wetlands often fail to receive adequate drying periods.

The storage of water in large dams along the River Murray (and its major tributaries) and its release during the irrigation season has also had the effect of reversing the natural seasonal pattern of flows in the channel, which were low in summer under natural conditions (Close, 1992). Many studies show that the changed seasonal pattern of flows is most severe in areas immediately below the main regulating structures, with effects dissipating downstream (Maheshwari *et al.*, 1995; Close, 1992). This is not reflected in the indicators presented in this analysis, with the change in seasonality of flooding greater through the Barmah-Millewa forest (site 2, Table 2) than immediately downstream of Hume Dam (site 1, Table 2). This is a function of the differences in the nature of the indicators used. Typically, analyses which assess the hydrological changes caused by river regulation analyse the whole of the flow duration curve (e.g. Maheshwari *et al.*, 1995; Close, 1992), but the analysis presented in this paper assesses that part of the flow duration curve which relates to inundation of the wetlands. It should also be noted that the flow thresholds assessed are specific to each flood plain wetland system and are thus a function of the varying geomorphic character of the river. For example, the CTF value downstream of Hume Dam is 26 000 Ml day$^{-1}$, whereas for the Barmah Millewa forest it is 12 000 Ml day$^{-1}$.

Consequently, this method of assessment allows a more appropriate interpretation of the effects of river regulation on the changes to seasonal pattern of wetland flooding than does the more traditional assessment of change to overall river hydrology.

While there have been substantial changes to the number of times the flood plain wetlands are inundated and the seasonal pattern of flooding has also been modified, once the flood plain wetlands are inundated, many of them remain inundated for a relatively "natural" period of time (i.e. $D$ values of >0.8, Table 2). There are three explanations for this. The first is that the use of monthly flow data may be masking some of the change in inundation duration and the second is that while we have decreased the number of times the flood plain is inundated, when it is inundated, it goes under for a "natural" period of time. The third is that the index may be demonstrating that while large floods pass through relatively unchanged and small floods have been removed from the system, the median length of inundation has not changed.

The assessment undertaken is limited by the use of modelled monthly data and comparisons between sites are limited as there are not consistent areal inundation data available. A more comprehensive assessment requires modelled daily data and more areal inundation data. Interpretation of the assessment output, and validation of the indices used, is also limited by a lack of information that correlates inundation patterns with ecological function. More information is required regarding the critical flow patterns for ecological functioning of the flood plain wetlands and the impact these wetlands have on the main stem of the river e.g. Is there a critical time of the year when the flood plain should be dry or inundated? Is there a critical duration of inundation that should/should not be exceeded?

The advantage in the assessment approach adopted is that it can be used to compare the extent of changes to sites varying in natural inundation regime. The application of such a standard assessment procedure at a wider scale provides policy makers and managers with an overview of where change has occurred. A particular benefit is that the measures can be included as standard output in comparison of model runs, as is currently done for measures of consumptive use. This will assist managers in considering ecological effects in their decision making, as they currently do for effects on consumptive use. Changes to flood plain wetland ecosystems are driven primarily by changes to the hydrological regime, and the method presented not only quantifies this, but provides a repeatable measure for use in comparing environmental flow options.

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