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An unsustainable level of take: on-farm storages and floodplain water harvesting in the northern Murray–Darling Basin, Australia

Patrick Brown[1], Matthew J. Colloff[2], Maryanne Slattery[1] and William Johnson[1]

[1]Slattery and Johnson PLC Ltd., Canberra, Australian Capital Territory 2603, Australia

[2]Fenner School of Environment and Society, Australian National University, Canberra, Australian Capital Territory 2601, Australia

Corresponding author:

Abstract

Water resources for irrigation in the Murray–Darling Basin have been heavily over-allocated, with major detrimental effects on wetlands and rivers. The Murray–Darling Basin Plan is intended to return water from irrigated agriculture to the environment but requires comprehensive, accurate water accounting to achieve this objective. Floodplain harvesting – the diversion and storage of overland flows into on-farm dams – is widely practised by irrigators in the northern Basin. By reducing volumes of river flows, floodplain harvesting has negative effects on downstream water users and the environment. The volume of diversions is not known, creating a major source of uncertainty over water availability and use. We focussed on floodplain harvesting in northern New South Wales (NSW) catchments (Border Rivers, Gwydir, Namoi, Macquarie and Barwon-Darling) because the NSW government is attempting to licence and regulate the practice. We found in 2019-20 there were 1,833 storages in these catchments with a total surface area of 42,650 ha. Storage capacity has risen from 557 GL in 1993-94 to 1,067 in 1999-2000, 1,225 in 2008-09 to 1,393 GL in 2019-20, a 2.5-fold increase in 26 years. We estimated mean annual floodplain harvesting take (2004-2020) in northern NSW was 778 GL (range 632-926 GL). For context, this volume represents half of the mean volume of held environmental water released annually for the entire Basin between 2009-10 and 2018-19 (1,576 GL) and six times that for the northern NSW Basin (125 GL). The volume of take from floodplain harvesting is not sustainable and in breach of legislation on water use and management. We discuss the negative impacts of floodplain harvesting on downstream communities and flow-dependent ecosystems and their social justice implications.

Key words: water resource development; water reform policy; water accounting; upstream-downstream effects; remote sensing; Landsat detection of water

Introduction

Contestation over water use and availability has intensified globally as demand has increased, driven by population growth, irrigated agricultural production and the negative effects of climate change (Grafton et al. 2014). For trans-boundary river basins (including those traversing State borders within federal nations) such as the Colorado, Mekong, Ganges–Brahmaputra, Indus and Murray–Darling rivers, a major source of contestation is created by so-called 'upstream–downstream effects', whereby negative impacts on livelihoods, communities and the environment occur because of altered flow regimes due to upstream water resource development and use. Declines in the ecological condition and integrity of wetlands rivers threatens the important ecosystem services that freshwater ecosystems provide to people, including vital hydrological services of water supply, purification and water security (Vörösmarty et al. 2010). For example, reduced flows in the lower Indus River and its delta caused by upstream irrigation and hydropower dams has caused saline incursions, damage to crops and pastures and decline in condition and extent of mangrove ecosystems, restricting the supply of ecosystem services that support livelihoods of over two million people (Archer et al. 2010; Memon and Thapa 2011).

Another transboundary river basin in which upstream-downstream effects are a major source of contestation is the Murray–Darling Basin in south-eastern Australia (hereafter, 'the Basin'). The Basin includes parts of the States of Queensland, New South Wales, Victoria, South Australia and the Australian Capital Territory (Figure 1), each with their own water governance systems and rules on use. Historically, water has been managed by the Basin States in their own interests for consumptive use, though with various attempts to bring water resources under the control of the Commonwealth Government (Connell 2007). Between 1950 and 1980 there was a sharp rise in irrigation water use due to the construction of headwater dams on most of the major rivers and irrigation water is now over-allocated, accounting for ca. 46% of surface water use (CSIRO 2008, p. 32). Many rivers and wetlands are in poor ecological condition (Davies et al. 2010, 2012) and inflows have apparently declined markedly over the last two decades (MDBA 2020a, p. 21). Attempts at water reform since the 1980s culminated in the *Water Act* (Cth. 2007) and the Murray–Darling Basin Plan (Cth. 2012; hereafter, 'the Basin Plan'), a $AU 13 billion initiative aimed at addressing over-allocation in order to maintain the ecological condition of rivers and wetlands and ensure water diversions are limited to an 'environmentally sustainable level of take' (Commonwealth of Australia 2012).

In the northern Basin of Queensland and New South Wales (NSW), river flows have been reduced by the practice of floodplain harvesting, which involves the interception and storage of overland flows from the vast network of creeks and rivers surrounding the main channels (Steinfeld and Kingsford 2011; Steinfeld et al. 2012). Floodplain harvesting is defined in the Basin Plan as: 'the taking of water from a floodplain, including after it leaves a watercourse during a flood' (Commonwealth of Australia 2012, p. 7). This definition includes harvesting of rainfall runoff and overbank flow (Weber and Claydon 2019, p. 12). Water from floodplain harvesting is captured within on-farm storages and used for irrigation of broadacre crops, mostly cotton. Harvested floodplain water has been regarded as an unlicensed 'freely-available bonus' to a landholder's licensed entitlement (NSW Legislation 2018, Appendix 3, S2[3]). In order for the Basin Plan to achieve the objective of limiting irrigation diversions to an environmentally sustainable level of take, comprehensive water accounting, metering and monitoring is required, involving a principle-based conceptual and operational framework that includes accountability, independent assurance and comprehensive reporting to allow users to assess compliance with externally-imposed requirements (Water Accounting Standards Board 2009). Yet the volume of water harvested from floodplains has never been adequately monitored or accounted for under the Basin Plan (Slattery and Johnson, 2021), even though the *Water Act* states that the MDBA has the function of measuring, monitoring and recording interception activity (Commonwealth 2012, S172), a power that the MDBA has failed to exercise and the consequenses of which 'will prevent the achievement of the objects and purposes of the Water Act' (Walker 2019, p. 695).

The Murray–Darling Basin Cap was introduced in 1995 with the intent of limiting diversions to the level of development at 30 June 1994. The Basin Plan aims to achieve a sustainable diversion limit (SDL) for consumptive water use, informed by the setting of an ecologically sustainable level of take (ESLT). The Cap includes floodplain harvesting in principle, but limiting floodplain harvesting was not the primary aim of the policy measure (MDBC 1998, p. 13). Subsequent to the implementation of the Cap, there was a rapid growth in storage capacity as farmers built new storages before State government restrictions were enacted (Sinclair Knight Mertz et al. 2010, p 11). A moratorium on new storages in Queensland in 2000 was replaced by restrictions in the water resource plans on floodplain harvesting works. In NSW, regulation and licencing of floodplain harvesting was not proposed until 13 years after the Cap was introduced (DWE 2008) but has still not been implemented (cf. below). Considerable growth in on-farm storages has occurred in the meantime.

A major concern regarding floodplain harvesting is its legality. The NSW Department of Planning, Industry and Environment (DPIE) received internal legal advice in October 2020 that the practice was 'most likely illegal' without an access licence (Alexander 2021) and that use of a storage without a water supply work approval to capture and store water is unlawful under the *Water Management Act 2000* (NSW).[1] Advice from the NSW Crown Solicitor indicates the legal status of floodplain

[1] The DPIE legal advice of 2 October 2020 (document 544) is available here: https://drive.google.com/drive/folders/1k13W2LMEQ-kMGreH1Ov7gYD33kfRMPM1

harvesting is ambiguous (Parliament of NSW 2020a, 2020b). Attempts to licence, regulate and monitor floodplain harvesting and on-farm storages through legislation are underway in NSW (DPIE 2018a; Weber and Clayton 2019; NSW Legislative Council 2020). In Queensland, floodplain harvesting is required to be licenced under the *Water Act 2000* (Qld.) and in accordance with the applicable Water Resource Plans and River Operations Plans. Accordingly, our focus in this paper is on floodplain harvesting in the NSW portion of the northern Basin. The Basin Plan allows for a long-term average take of 46.3 GL yr^{-1} from floodplain harvesting in the northern NSW catchments (NSW Border Rivers, Gwydir, Namoi, Macquarie, Barwon-Darling) (MDBA 2020b). In most catchments, floodplain harvesting considerably exceeds the legal limits of diversions (DPIE 2021a).

A key reform process in the Basin Plan is the implementation of SDLs through the mechanism of Water Resource Plans (WRPs), which requires Basin States to account for and calculate the maximum permitted take for consumptive use (Productivity Commission 2018, p. 177). Improved water accounting is critical to the process of transitioning from Cap compliance to the implementation of SDLs, including the identification and determination within WRPs of permitted and actual annual water take from floodplain harvesting.

The relationship between growth in capacity of on-farm storages and the volume of take from floodplain harvesting is well-established (Bewsher Consulting 2006; DPIE 2018b, 2020a). However, estimates of annual take have been grossly underestimated in the past (Slattery and Johnson 2021, p. 15), including in official water accounts for Cap and SDL compliance (e.g. MDBA 2017, 2020c). There are few assessments of changes in on-farm storage capacity over time. This high degree of uncertainty and lack of monitoring of floodplain harvesting hinders attempts to achieve a comprehensive and transparent water accounting system, undermining attempts at water reform and the implementation of the Basin Plan (Grafton and Williams 2019).

In an attempt to address this uncertainty, and to understand the effects that floodplain harvesting take may have on downstream communities and ecosystems, we investigated the number and capacity of permanent on-farm storages in the northern NSW Murray–Darling Basin, including a compilation of all previous published estimates relating to floodplain harvesting. Our motivation for this study was to determine the growth in storages since 1994. DPIE has repeatedly asserted floodplain harvesting diversions have increased above the legal limits set under Water Sharing Plans and the Basin Plan and that they were bringing floodplain harvesting within the Cap, but have failed to supply evidence of this (DPIE 2018a, 2021a). Accordingly, we went ahead and did the assessment work ourselves. We had four main objectives: (1) develop a method to identify on-farm storages on the floodplain; (2) calculate the capacity of on-farm storages; (3) assess the change in total storage volume between 1993-94 and 2019-20 and (4) estimate the magnitude of floodplain harvesting take.

Methods

Study area

The study area includes the floodplains of five catchments in the northern NSW Murray–Darling Basin, covered by the NSW Floodplain Management Plan, with floodplain management areas (FMAs) detailed by DPIE (2019, Figure 1 therein): the Barwon-Darling, NSW Border Rivers, Gwydir, Namoi (lower and upper) and Macquarie (Figure 1). The FMAs cover an area of 52,745 km^2 (Table 1).

Analysis of satellite imagery

Permanent on-farm storages were identified using the Water Observations from Space product (WOfS, version 2.1.5; NCI, 2018). We did not attempt to identify temporary storages (e.g. surge areas and low-lying sites in paddocks where water is channelled and accumulates and can then be pumped to the crop or to permanent storages). The WOfS product is based on data derived from Landsat 5, 7 and 8 images and provides an analysis-ready water map for mainland Australia and Tasmania at 25 m resolution, at 16-day intervals, from 1986 to the present. A number of remote sensing algorithms are available for detecting surface water using Landsat imagery and are effective at detecting water bodies such as storages, as assessed in Australia (Fisher et al. 2016; Mueller et al. 2016) and internationally (Olthof et al. 2017; Lefebvre 2019; DeVries 2020). Details of the water detection algorithm for WOfS are given by Mueller et al. (2016).

WOfS data is provided in NC file format and the GDA94 Australian Albers projection. The size of each scene is 100 × 100 km (4000 × 4000 pixels). Images were downloaded and processed using scripts written with Matlab software and used to read the rasters, apply all the masks and extract all pixels covering areas that contained surface water. A raster consists of a matrix of pixels organized into a grid, whereby each pixel contains a value representing information. The following base layers were prepared: 1) *data availability raster*: this raster counted the cumulative number of days that clear (cloud free) data was available for each pixel during the water year, regardless of whether surface water was present; 2) *water availability raster*: this raster counted the cumulative number of days that water had been detected in each pixel during the water year and 3) *water availability proportion raster*: this raster was produced by dividing water availability by data availability rasters and provides the percentage of times water was detected for the cloud-free images.

Water availability proportion rasters were compared to aerial images to determine a threshold for detection of waterbodies. This process was required because WOfS classifies highly-irrigated terrestrial areas (such as sports fields) as surface water. We eliminated these commission errors by applying a threshold of ≥6% of water availability on the water availability proportion raster maps. Raster maps were converted to vector format and water body polygons created to produce five shapefiles (one for each modelling year plus one to represent the total). An unique identification number was assigned to each water body detected in each year. We merged each shapefile and an artificial water storage layer, published by Geoscience Australia, into a single shapefile to determine the maximum extent of each water body in order to harmonise waterbody identifications with WOfS water years.

Natural waterbodies (rivers, lakes, wetlands and swamps) were removed by clipping out the areas that intersected with the Australian National Aquatic Ecosystem (ANAE) geodatabase layer (for lacustrine, palustrine, and riverine wetland layers). In some cases, ANAE layers were incomplete or did not cover the full extent of the natural waterbody. Accordingly, we applied manual validation using high-resolution imagery to select and eliminate waterbodies that were not on-farm irrigation storages. Dark objects, such as black soils, shadows from buildings and steep slopes were another source of commission errors. These anomalies were manually digitised and eliminated. We also imposed a buffer of 100 m on each side of each riverine shapefile to ensure removal of wetlands and tributaries. In cases where on-farm storages were within the 100 metre buffer, we manually edited the shapefile to incorporate the storage. Figure 2a shows an example of manual identification of a waterbody with on-farm storages connected to an irrigation channel (right-hand side, blue outline), rather than a wet paddock (left-hand side, red outline), that might otherwise be mistakenly interpreted as a storage. We also eliminated storages smaller than 75 x 75 m (0.56 ha) from the results.

Calculation of on-farm storage volume

Landsat-based satellite imagery cannot detect depth of on-farm storages. To overcome this issue, we downloaded digital elevation models from the Foundation Spatial Data Elevation and Depth portal (ICSM, 2021). This online platform contains publicly-available spatial datasets and digital elevation models derived from LiDAR surveys undertaken between 2008–2017 that produce a regular grid of ground heights with resolutions of 1, 2 and 5 metres.

The digital elevation models were processed using the geographical information system software program QGIS. We generated elevation contours at 0.2 m intervals to determine the highest possible water level in a given storage (Figures 2b, 2c) and used the 'Raster Surface Volume' tool in QGIS to calculate the storage volume below this level. Where the LiDAR survey did not map the bottom of the storage (due to the presence of water at the time of survey), a storage invert level was inferred from the surrounding ground level to enable calculation of the storage volume.

We calculated the volume of 406 storages based on the digital elevation models. The volumes calculated with the digital elevation models comprise 76% of the total surface area of storages. Where the storage capacity of a particular dam was not calculated based on a digital elevation model, a depth was assumed based on storages of a similar surface area in the same FMA.

To assess changes in on-farm storages, the number and capacity of storages were calculated for the water years 1993-94, 1999-2000, 2008-09 and 2019-20 (1 July to 30 June). We also compiled all available published data on numbers of on-farm storages, storage capacity and estimates of floodplain harvesting take in the entire northern Basin, covering a period from 1973-2020.

Estimation of annual floodplain harvesting take

To estimate the volume of take from floodplain harvesting in the NSW FMAs we collated annual data on the area of cotton grown in the relevant FMA catchments from 2004-05 to 2020-21, based on data provided by the Cotton Research and Development Corporation to Senate Estimates (Parliament of Australia 2021a; 2021b). Because the data for Border Rivers included both Queensland and NSW portions, to obtain an estimate for NSW Border Rivers only we used a figure of 47% of the total, based on the average of total Border Rivers diversions taken by NSW between 2012-13 and 2017-18, from MDBA Cap compliance reports (MDBA 2020c).

To calculate the volume of irrigation water required to grow the cotton crop, we used a low estimate, based on that by Roth et al. (2013) of 6.9 ML ha^{-1} plus 30% on-farm losses prior to application (9.86 ML ha^{-1} in total) and a high estimate of 12.12 ML ha^{-1} (Tennakoon and Milroy 2003). We expressed these estimates as upper and lower ranges around the mean (11 ML ha^{-1}). We then collated data on licensed water take for the FMAs, including all surface and groundwater take for the period, except take against domestic and stock and local water utility licenses, from the NSW Water Register (WaterNSW 2021) as well as held environmental water use (DPIE 2021b; Chen et al. 2021). Because data on annual licenced water usage for the Barwon–Darling FMA is not available from the NSW Water Register before 2012-13, and that for the Border Rivers before 2009-10, we calculated the mean values for these FMAs for the years of complete record as a percentage of the total for Gwydir, Namoi, and Macquarie FMAs and used these percentages to estimate the missing values.

We calculated the deficit between the volume of licenced water take and the volume of water required to grow the crop. Licenced water in each FMA is used predominantly to irrigate cotton, but in dry years (e.g. 2006-07 to 2009-10, 2014-15 to 2016-127 and 2019-20) and in some FMAs licenced water may be used to grow other crops or pastures and the proportion of licenced water used for cotton falls accordingly. To take account of this temporal and spatial variation, we adjusted licenced water use in each year and each FMA by the proportion of water use on cotton to total irrigation water use, using data from the *Water Use on Australian Farms* statistical series (ABS 2021). We then used the adjusted licenced water take (equivalent to licenced cotton water use) to calculate the adjusted water deficit. The volume of the adjusted deficit was considered equivalent to the take from floodplain harvesting used for cotton production.

Results

Distribution of storages

Figure 3 shows the distribution of on-farm storages in the FMAs, outside the FMAs and also, for context and completeness, along the rivers of the southern Queensland part of the Basin. Storages in the Gwydir FMA are concentrated to the north and west of Moree and along the lengths of the Mehi River and Moomin Creek to the south-west. Storages are distributed throughout the upper Namoi FMA along the Macintyre between Mungindi and Goondiwindi, in the more upstream portions of the lower Namoi and Macquarie FMAs and scattered in relatively low numbers in the Barwon-Darling FMA between Bourke and Walgett. The highest concentrations of storages in NSW FMAs are in the Macquarie between Narromine and Warren and in the lower Namoi north and west of Narrabri. However, there are high concentrations in Queensland along the lower Balonne, the Border Rivers between the Macintyre and the Weir rivers and the upper Condamine between Chinchilla and Warwick, which has the highest concentration in the northern Basin with some 621 storages.

Number, surface area and volume of storages

The total number of on-farm storages in 2019-20 was 1,833 (Table 1). The storages have a total surface area of 42,650 ha. The Gwydir FMA accounts for 40% of the total surface area of storages and the Namoi (upper and lower) for 22%. We divided the storages into three size classes: small, comprising 60% of storages by number (0.56-12 ha); medium, comprising 20% of storages (>12-34 ha); and large, comprising 20% of storages (>34-949 ha). The upper Namoi, Barwon–Darling and Macquarie FMAs had the highest proportion of small storages (82%, 72% and 69% of total storages respectively; Table 1) and the Border Rivers and Gwydir had the highest proportion of large storages (35% and 32% respectively).

The total storage capacity in 2019-20 was 1,392 GL (Table 2). Some 72% of storage capacity was calculated directly from measurements taken from digital elevation models, with the remainder based on the average depth of similar sized storages from the same FMA (Supplementary Material, Table S1). The Gwydir, Border Rivers and Barwon-Darling FMAs contain 71% of the total storage capacity, with the Gwydir alone accounting for 40%, followed by 18% for the Namoi (upper and lower) and 16% for the Border Rivers (Table 2). Despite comprising only 18% of the total number, storages greater than 1 GL account for 78% of the total capacity. Storages greater than 5 GL comprise 2.5% of the number of storages but account for 32% of the total capacity.

Change in on-farm storage capacity over time

There has been a major increase in on-farm storage capacity in the northern NSW FMAs, from 557 GL in 1993-94 to 1,393 GL in 2019-20; a 2.5-fold increase in 26 years (Figure 4; Table S2). This increase is highest in the Gwydir FMA, where storage capacity has tripled, from 188 GL to 559 GL (Table S2). Although storage capacity in the upper Namoi and Macquarie is markedly lower than in the Gwydir, these two FMAs have the highest growth rates: 4.1 and 3.6-fold respectively, with 2.4 fold for Barwon-Darling, 2.1 for the Namoi and 1.7 for the Border Rivers.

Historical estimates of rates of growth in storage capacity (Table S3) include a 1.2-fold increase in storage capacity the NSW Border Rivers and the Macquarie between 2002-2014 (DPIE 2020a; 2021c); a 1.8-fold increase in the Gwydir between 1994-2020 (DPIE 2021d); a 3.3-fold increase in numbers of storages in the upper Namoi between 1973-1990 (Beavis et al. 1997) and a 6.5-fold increase in storage capacity in the Barwon–Darling between 1987-2003 (Figure S1; Stazic et al. 2006, cited by Brewsher Consulting 2006). In the upper Condamine in Queensland, on-farm storage capacity grew 2.1-fold, from 89 to 190 GL between 1997-2004 (Porter and Delforce 2000; Brewsher Consulting 2006).

Estimation of annual floodplain harvesting take

We estimated the difference between the total volume of water required to grow the cotton crop in all FMAs (based on the area harvested and the mean volume of water, 11 ML, required to produce a hectare of cotton) and the estimated licenced cotton water use. The deficit was considered equivalent to the floodplain harvesting take for cotton production. Between 2004-05 and 2020-21, deficits were recorded in all years for the region (Figure 5), but not for all FMAs (Table S4). The mean total estimate of take was 778 GL (range 132–1,669 GL). Low and high estimates, based on figures of 9.86 ML ha^{-1} and 12.12 ML ha^{-1}, were 632 GL (range 53-1,421 GL) and 926 GL (range 197-1,918 GL) (Table S4). Negative values of take (e.g. in the Barwon–Darling (-63 GL in 2006-07, -10 GL in 2019-20, both dry years with little or no cotton production), indicate that licenced cotton water use was greater than total cotton water use (though less than total licenced irrigation water use), highlighting an inconsistency between the cotton production figures and the ABS data on irrigation water use for those years (ABS 2021). Floodplain harvesting take was highest in the Namoi FMA (312 GL), followed by the Gwydir (196 GL) and Border Rivers (141 GL) and lowest in the Barwon–Darling (48 GL) and the Macquarie (40 GL) (Table S4).

Low volumes of deficit occurred even in the driest years in the region (2006-08, 2018-20; Figure 5), indicating the use of water from on-farm storages that had been harvested during the previous year, and that some floodplain harvesting may still have occurred in some of the FMAs where rainfall was above the regional average (e.g. Macquarie and Barwon–Darling during 2007-08; Table S5). Regarding the use of water harvested during the previous year, Figure 5 shows clear lags in the decline of mean total cotton water use after periods of high rainfall, with water use remaining high in 2005-06, 20012-14 and 2017-18, even though rainfall had declined markedly during those years. On-farm storages containing water were detected in satellite images even in 2019-20, the driest year, in the Border Rivers, Gwydir, Namoi and Macquarie FMAs, but not in the Barwon–Darling.

The estimated mean annual floodplain harvesting take of 778 GL for all FMAs corresponds well with the total on-farm storage capacity of 1,392 GL. However the relationship between storage capacity and mean annual take varies markedly between FMAs and over time. Figure 6 shows the change in the proportion of storage capacity to floodplain harvesting take for each FMA for two periods: 2004-05 to 2008-09 and 2009-10 to 2019-20. We could not compare storage capacity at earlier periods (1993-94 and 1999-2000; Figure 4) with take because data on licenced water use (required to estimate take) only extends back to 2004-05. For the two periods, take increased more rapidly than storage capacity in the Border Rivers and Barwon–Darling FMAs, stayed the same in the Macquarie and declined in the Gwydir, even though storage capacity increased in both FMAs. In the Namoi, take exceeded capacity for both periods. Water can be captured more than once in a water year, resulting in a larger estimate of take than total storage capacity. The marked disparity between high storage capacity and low take in the Gwydir, compared with other FMAs, may be due to the under-estimation in industry figures of the extent of cotton production in that FMA (Parliament of Australia 2021a, 2021b).

There is a statistically significant positive correlation between floodplain harvesting take and mean annual rainfall for the NSW northern Basin (R^2 = 0.446, $F_{1,15}$ = 12.07, p = 0.0034; Figure 7; Tables S4 and S5), based on reduced major axis regression with analysis of variance to test for the statistical significance of the regression line (Fowler et al. 1998). As derived from the regression equation ($y = 2x - 176$), for every 100 mm in mean annual rainfall, there is an equivalent increase in mean annual floodplain harvesting take of 100 GL across all FMAs (200 mm ≡ 24 GL, 800 mm ≡ 624 GL).

Discussion

Our intent in this paper was to assess the magnitude and extent of floodplain harvesting in the northern NSW Murray–Darling Basin in order to understand the effects that the take may have on downstream communities and ecosystems. The estimation of the average annual volume of take from floodplain harvesting we used is based on an assessment of the volume of water required to grow the cotton crop in each year in the FMAs in which we mapped permanent on-farm storages. Estimating volumes of water harvested from particular overland flow and flood events is beyond our present scope. It would involve calculation of the height of water in each of the on-farm storages in relation to their total height following a particular event, requiring LiDAR data for the relevant dates of the event. A possible source of inaccuracy in our estimations is that some storages may have been modified since the LiDAR survey was completed. If this is the case, it is more likely that the storages would have been enlarged rather than made smaller. We did not account for temporary storages. These have been mapped by DPIE (2018b) but their distribution and extent and the volume of take have not been fully reported. An estimated 27 GL was harvested in March 2012 in temporary storages in the Gwydir FMP area following flooded flows and 1.5 GL in January 2011 in the NSW Border Rivers FMP area (DPIE 2018b).

The number and capacity of on-farm storages reported herein generally accords with current estimates by DPIE (Table S3). The total storage capacity we reported was 1,393 GL compared with DPIE estimates of between 1,291 and 1,450 GL, depending on the source document. DPIE reported between 1,213 and 1,419 storages, whereas we found 1,491. However, our figure for annual floodplain harvesting take of 778 GL is twice the DPIE estimate of 395 GL (Slattery and Johnson 2021, Table 2). This volume of take is not in compliance with the long-term Murray–Darling Basin Cap on diversions, which remains in force until it is formally superseded by the SDL, which requires legislative change. Based on total areas of dams and mean annual rainfall in each FMA (Tables 1, S5), rainfall interception alone would account for 218 GL yr^{-1} of take. This volume is almost five times greater than the MDBA estimate for all floodplain harvesting in these catchments in 2019-20 and only slightly lower than the estimate of 251 GL for all floodplain harvesting in the entire northern Basin (MDBA 2019). It is clear that the magnitude of floodplain harvesting has previously been vastly underestimated by agencies responsible for implementing the Basin Plan (Slattery and Johnson 2021, Table 2 therein).

The data on changes in numbers of storages over time indicate that the 1995 Murray–Darling Basin Cap on diversions and subsequent rules had no effect in halting growth in storage construction, despite assertions to the contrary, e.g.: ‘Floodplain harvesting is not likely to expand;

there are moratoriums in place in the relevant river basins to restrict construction of new storages' (Sinclair Knight Mertz et al. 2010, p. 11).

Our estimates of storage capacity were focused on NSW catchments because of the proposal by the NSW government to licence, regulate and monitor floodplain harvesting. In Queensland, under the *Water Act* (Qld. 2000), floodplain harvesting may require a licence and can be freely undertaken unless there is a moratorium notice or a water plan that limits take. Floodplain harvesting there is concentrated in the Condamine–Balonne and Queensland Border Rivers catchments, where the estimated capacity of on-farm storages was 1,582 GL in 2006 (Webb, McKeown and Associates 2007, p. 17). Some 1,241 GL of on-farm storage capacity was estimated for the Lower Balonne floodplain, inferred from volumes and numbers of storages at nodes in Integrated Water Quality and Quantity (IQQM) models and maps of storages from an undefined source (Sinclair Knight Mertz 2012, p. 15). However, these figures are likely to be under-estimates. Based on growth in storages in NSW between 1993-94 and 2019-20 of ca. 32 GL yr^{-1}, the current capacity for the entire Condamine–Balonne catchment would be at least 2,000 GL. Thus the on-farm storage capacity for the entire northern Murray–Darling Basin is in the order of 3,375 GL.

The mean annual floodplain harvesting take from the Condamine–Balonne catchment reported in MDBA Cap compliance reports (2006-07 to 2018-19) is 333 GL. Given that 420 GL was harvested on the lower Balonne in a single flood event between February and March 2020 (DNRME 2020), the real figure is likely to be markedly higher. With our estimate of mean annual take of 778 GL from floodplain harvesting in the northern NSW Basin, the figure for the entire northern Basin is likely in the order of 1,200-1,500 GL. To place this volume in context, the volume of water to be recovered for the environment under the Basin Plan was set at 2,750 GL yr^{-1} (later reduced to 2,100 GL yr^{-1}). Between 2012-13 and 2018-19, the mean annual volume of held environmental water released in the Basin was 1,905 GL and only 218 GL in the northern Basin (Chen et al. 2020); 5-7 times less than the estimated floodplain harvesting take. So what effect does floodplain harvesting have on downstream communities and ecosystems?

Upstream-downstream effects

DPIE acknowledges the environmental importance of accounting for floodplain harvesting take, as follows: 'Accurately measuring floodplain harvesting take is critical to understanding the relationship between floodplain harvesting and habitats for aquatic organisms, the health of rivers downstream and whether any adjustments are needed to better manage environmental flows' (DPIE 2020b, p. 94). There is a direct correlation between on-farm storage development and decreased inflows and catchment water yield. Neal et al. (2002) found that for every 1 ML of farm dam storage capacity there was a decrease in streamflow of 1–1 .3 ML. Based on our estimates of floodplain harvesting take for the NSW FMAs, this would translate into an annual average reduction in streamflow in the Macintyre, Gwydir, Namoi, Macquarie and Barwon–Darling rivers of between 1,393 and 1,811 GL.

The main impact of floodplain harvesting in the northern Basin has been reduced flows in the Darling River south of Bourke (Figure 1), with greater frequency of no flow or very low flow events. Following catastrophic fish kills caused by de-oxygenation following cyanobacterial (blue-green algal) blooms in the lower Darling river at Menindee in the summer of 2019-20, two enquiries found that excessively high irrigation diversions in the northern Basin were a major contributing factor (AAS 2019; Vertessy et al. 2019). The former report concluded 'The root cause of the fish kills is that there is not enough water in the Darling system to avoid catastrophic decline of condition through dry periods…the findings point to serious deficiencies in governance and management, which collectively have eroded the intent of the Water Act and implementation of the Murray-Darling Basin Plan (2012) framework' (AAS 2019, p. 2). The latter report stated: ' it is clear that historic patterns of extractions in the northern Basin over the last two decades…have reduced the resilience of riverine ecosystems in the lower Darling. Maintaining the present pattern of water extractions into the future will further weaken the resilience of the riverine ecosystem and make it more vulnerable to fish death events. As such, water access and water sharing arrangements in the Barwon–Darling should be reviewed and modified' (Vertessy et al. 2019a, p. 9).

In 2018-19, the water year before the fish kills at Menindee and during the height of the 2016-2020 drought, it was estimated that for the northern Basin cotton crop: 'at least 845 and perhaps as much as 1,135 gigalitres of water will be applied to this crop and a further 1,000 GL likely evaporated while in storage before irrigation use. In the meantime, only 40 GL flowed down the Barwon–Darling past Bourke and a little over 11 GL reached Wilcannia in all of 2018' (Slattery et al. 2019, p. 3). Further, changes by NSW government to the model used for calculation of Cap limits has left the Barwon–Darling 'owing' 635 GL of water to irrigators (Slattery et al. 2019).

Communities on the lower Darling rely on the river as a source of domestic water. Water quality has been consistently below minimum safety standards due to low flows and the risk from toxic blue-green algae, particularly during the 2016-17 to 2019-20 drought (Davies 2019). Drinking water has had to be delivered in bottles and by tanker. Maintaining water quality is a requirement under the Basin Plan and the *Water Management Act* to ensure requirements are met for environmental, social, cultural and economic benefits. Water quality targets in the lower Darling have not been met for turbidity, salinity, cyanobacteria and nutrients, with particularly high nitrogen and phosphorous concentrations at Menindee (DPIE 2020c).

Access to safe, reliable drinking water is recognised by the United Nations as a basic human right (UN 2021). Governments of member States bear the duty of providing safe water to their citizens. Accordingly, the reduction in flows in the Darling River system due to upstream floodplain harvesting not only reveals serious deficiencies in governance and management of the Basin Plan but represents a major failing of water justice for Australia.

Issues of water justice affects other water users in the Basin beyond the Darling and its northern Basin tributaries. Victorian Water minister Lisa Neville demanded an explanation as to why NSW and Queensland irrigators have been allowed to harvest floodplain waters during the 2016-2020 drought, a decision described by the Victorian government as 'reckless' (Neville 2020). With reduced flows to the southern Basin from the Darling, there has been increased pressure on Victorian rivers to deliver more water, resulting in high flows in the Goulburn River that have caused environmental damage. Extra demands on the River Murray and its tributaries to meet the annual entitlement of 1,850 GL to South Australia under the Murray-Darling Basin Agreement (MDBA 2021) have disadvantaged irrigators in the southern Basin. Neville (2020) stated: 'We need consistent application of rules across the Basin to get fair outcomes – this includes for irrigators, communities and the environment.'

One aspect of floodplain harvesting where issues of water use and management intersect with water justice is in regard to losses from storages. If a high rainfall or flood event occurs during the period between when the crop has been harvested (March/April) and the planting season (September/October), water harvested and held within on-farm storages is subject to considerable evaporative and seepage losses. Such losses from on-farm storages in the NSW Border Rivers FMA were estimated at 48 GL annually or 26% of total on-farm storage capacity (DPIE 2020d, p. 58) and in the Gwydir as 188 GL or 30% of storage capacity (DPIE 2020e, p. 51). For all northern NSW FMAs, these estimates would translate to annual losses in the order of 400 GL a year. It is claimed that water-use efficiency for cotton has increased dramatically in recent decades and that Australian cotton is 'three times more efficient than the global average' (DAWE 2019). Such assessments refer only to water applied to the crop and do not take into account losses from evaporation and seepage from on-farm storages and are therefore misleading. On-farm losses account for 30-42% of irrigation water use (Tennakoon and Milroy 2003; Roth et al. 2103). Losses from evaporation are not counted as take under either the Cap or the SDL. Irrigators would argue that they bear the cost of on-farm losses, which for floodplain harvesting is not the case, since the water harvested represents a free good from a common pool resource and the intercepted water, by definition in the *Water Act*, 'would otherwise flow, directly or indirectly into a watercourse, lake, wetland, aquifer, dam or reservoir that is a Basin water resource' (Commonwealth of Australia, 2007, S4).

Losses in the order of 400 GL a year represent a major injustice and opportunity cost foregone for downstream water users, resulting in negative impacts on their communities and the environment. In the Murray–Darling Basin Royal Commission report, Walker (2019, p. 589) noted: ‘The issue of floodplain diversions was frequently raised before the Commissioner as a significant concern for many communities…large unaccounted volumes of water being extracted from flows over floodplains… raises serious concerns about compliance with the long-term cap on diversions (Cap), the assessment of sustainable diversion limits (SDLs), and the achievement of environmental and community outcomes.’

Mitigating the risks from floodplain harvesting

Licencing and regulation of floodplain harvesting in NSW requires measures to be legislated for that mitigate negative impacts on downstream communities and the environment and ensure rules on floodplain harvesting are applied fairly and equitably. Such measures include ensuring volumes of water harvested are legal and compliant with limits under the Basin Plan, as well as the setting and enforcement of downstream flow targets to be met before floodplain harvesting can commence. In addition, far greater effort is required in the monitoring and transparent reporting of the extent and magnitude of floodplain harvesting if there is to be any prospect of developing an accurate, comprehensive Basin water accounting system and adapting in a fair and just manner to a future under climate change with more variable and unpredictable rainfall.

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Table 1. Number, surface area and depth of on-farm storages greater than 0.56 ha. by floodplain management areas (FMAs) in northern Basin catchments that were surveyed for storages. Where the volume of a storage was not calculated from a digital elevation model, a depth was assumed based on the average depth of storages in the same size class

	Extent of FMA	Small storages (>0.56-12 ha)			Medium storages (>12-34 ha)			Large storages (>34-949 ha)			Total	
FMA & catchment	Area (km²)	No.	Mean depth	Area (ha)	No.	Mean depth	Area (ha)	No.	Mean depth	Area (ha)	No.	Area (ha)
Border Rivers	5,576	95	1.6	190	30	3.7	711	66	4.1	4,849	191	5,750
Gwydir	11,471	182	1.7	523	112	3.0	2,566	140	3.4	14,076	434	17,164
Lower Namoi	6,881	200	3.0	816	109	2.7	2,257	64	2.6	3,703	373	6,775
Upper Namoi	5,394	265	2.5	702	44	3.5	942	13	2.0	757	322	2,401
Macquarie	12,457	235	1.6	659	58	3.3	1,088	49	2.8	3,434	342	5,181
Barwon–Darling	10,966	123	2.1	207	13	2.7	286	35	3.6	4,886	171	5,379
Total	52,745	1,100		3,096	366		7,850	367		31,705	1,833	42,650

Table 2. Total storage capacity (GL) by NSW floodplain management area (FMA) in catchments in relation to class of storage volume

	0-1 GL		>1-5 GL		>5-55 GL		Total		
FMA & catchment	No.	Capacity (GL)	No.	Capacity (GL)	No.	Capacity (GL)	No.	Capacity (GL)	% of total capacity
Border Rivers	122	22	61	135	8	65	191	222	16.0
Gwydir	302	87	109	265	23	207	434	559	40.1
Lower Namoi	329	98	43	81	1	9	373	187	13.5
Upper Namoi	309	47	13	18	0	0	322	65	4.7
Macquarie	298	47	42	79	2	19	342	145	10.4
Barwon–Darling	135	10	25	59	11	145	171	214	15.3
Total	1,495	311	293	637	45	445	1,833	1,393	

Figure 1. The Murray-Darling Basin showing major tributaries of northern and southern basins and proximity between major wetlands or floodplains and irrigation districts. Note major headwater dams on most rivers which supply irrigation water and environmental flows. Dashed rectangle indicates the area in Figure 3 containing northern NSW floodplain management areas and catchments that were assessed for permanent on-farm storages

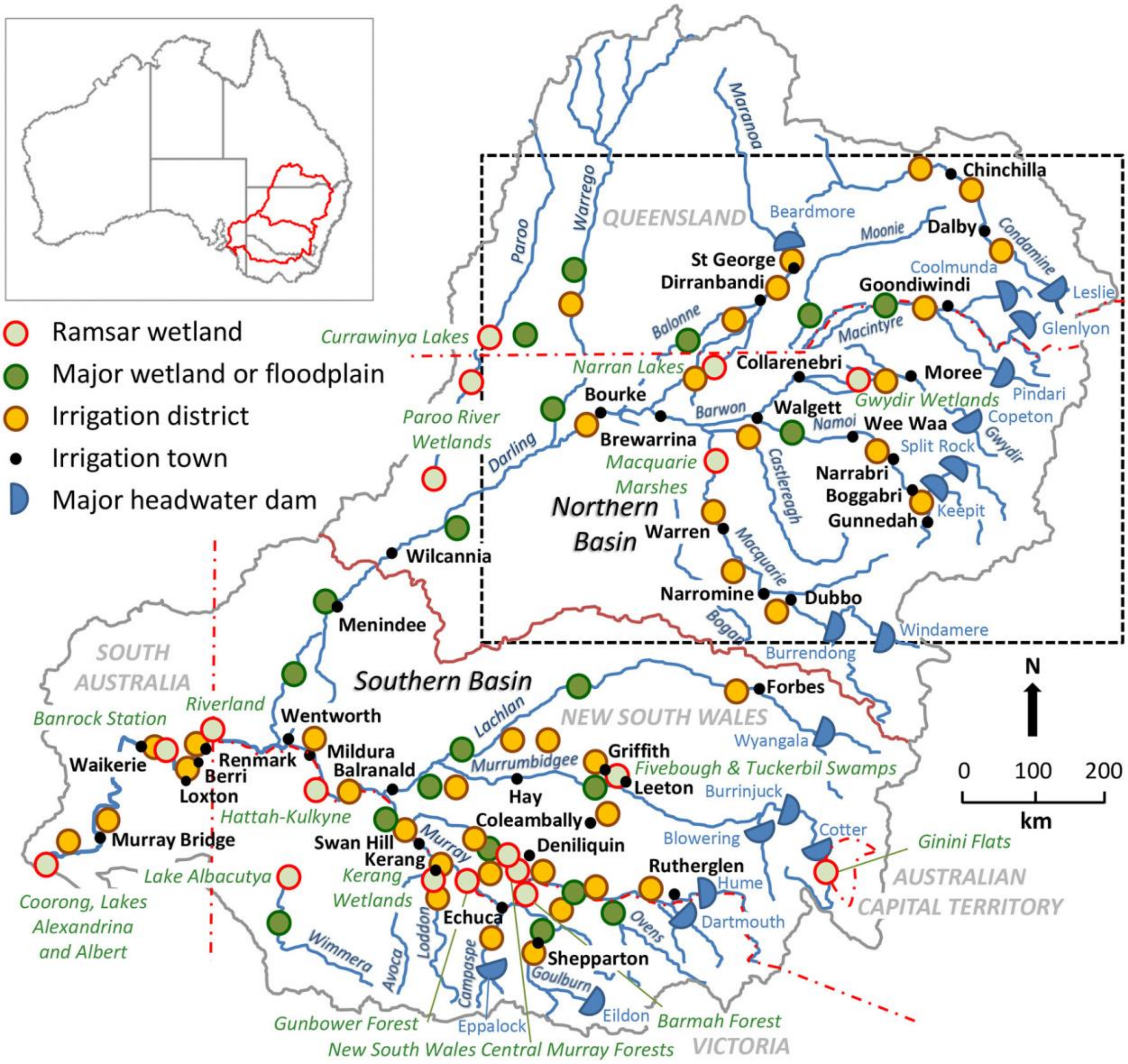


Figure 2 (a) An example of manual inspection to remove non-storage bodies from the assessment of permanent on-farm storages; (b) a digital elevation model image of an on-farm irrigation storage. Blue outline shows storage, as detected using Water Observations from Space data. Red line (A to B) indicates location of cross section; (c) cross section of the storage (A to B)

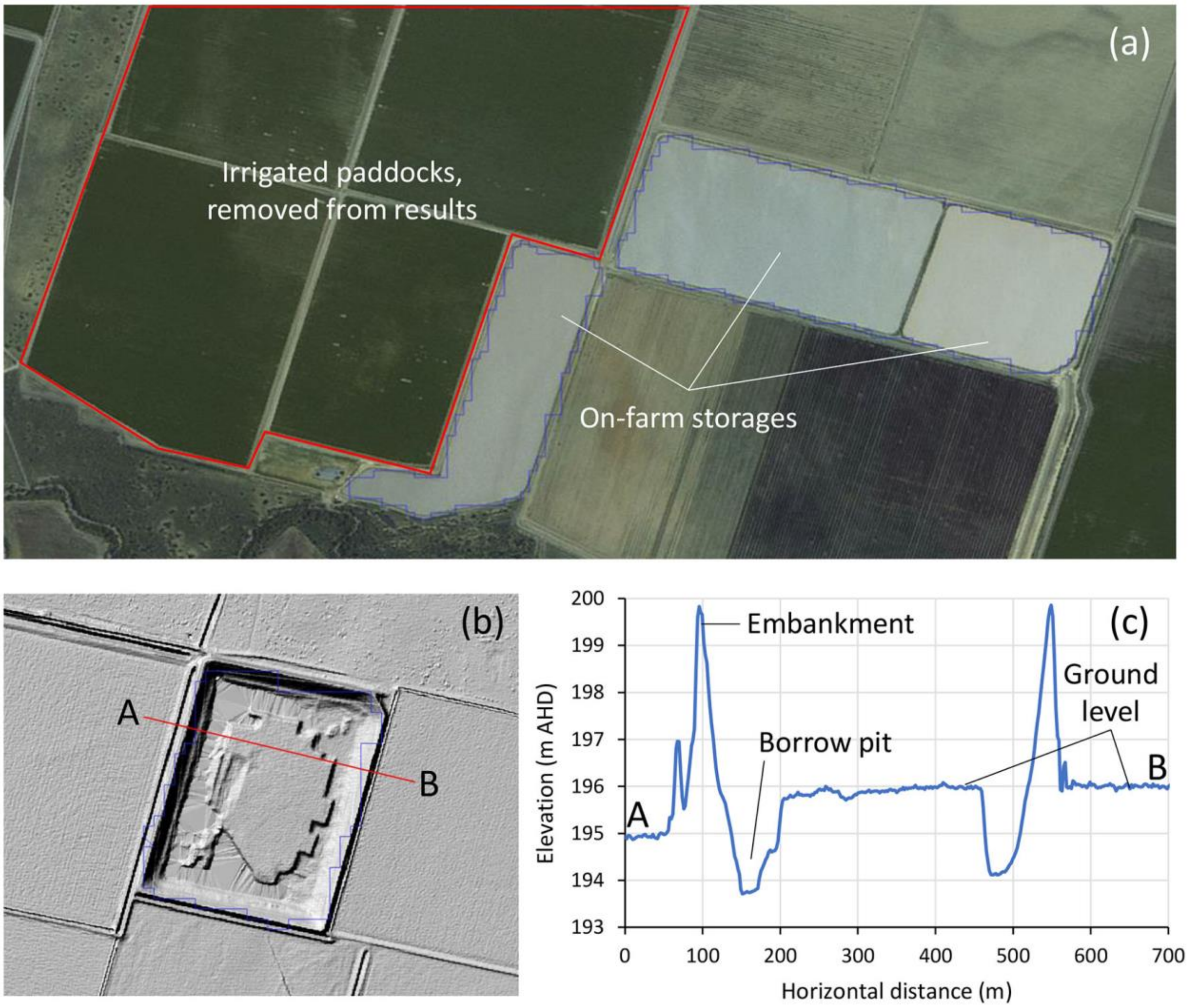


Figure 3. Distribution of permanent on-farm storages greater than 0.56 ha in the Murray–Darling Basin of northern New South Wales and southern Queensland in relation to major wetlands. Blue circles = storages within northern NSW floodplain management areas (FMAs; indicated by red outline). Maroon circles = storages outside FMAs

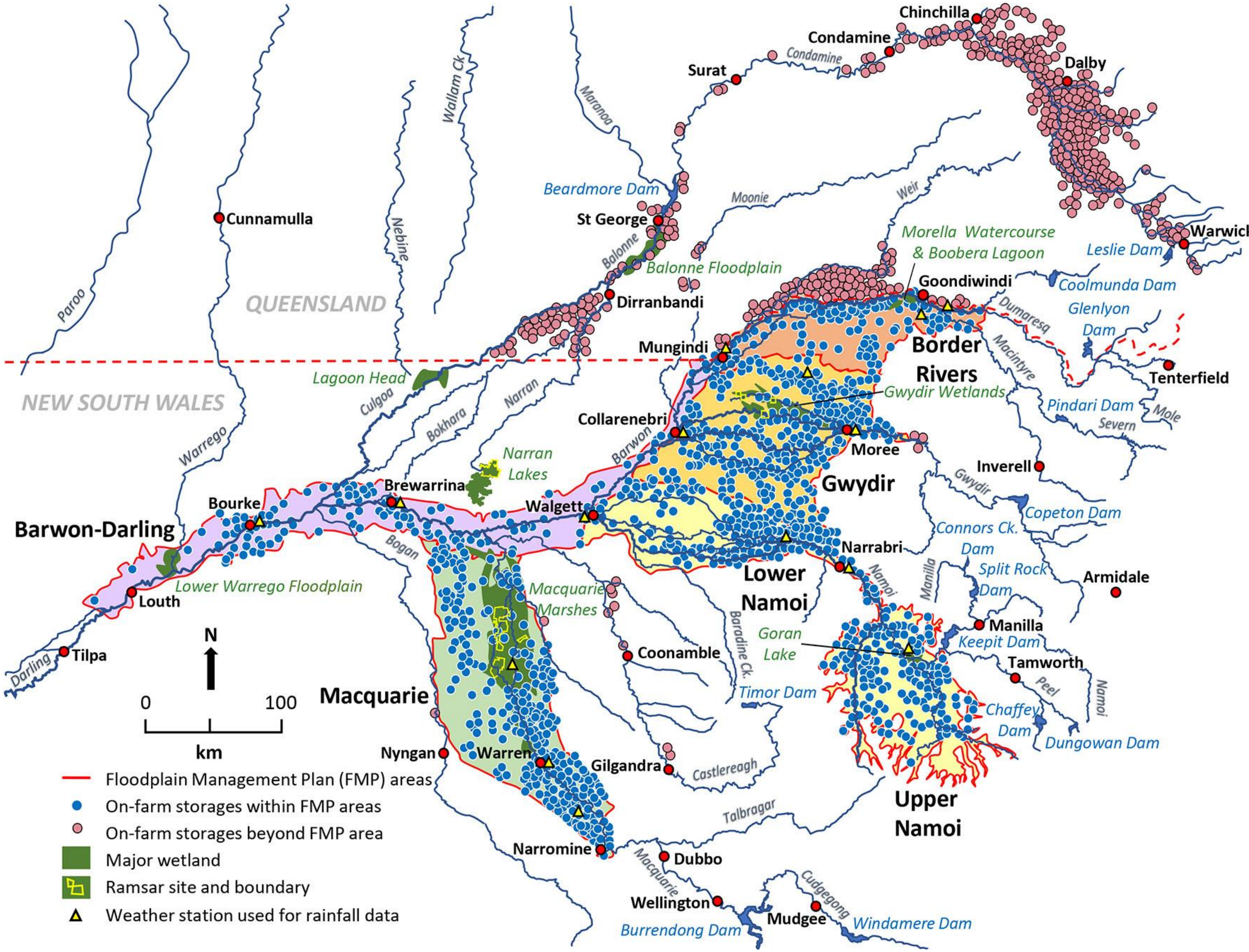


Figure 4. Change in permanent on-farm storage capacity over time in each floodplain management area (FMA) (histograms, left-hand *y*-axis) and total for all FMAs (line graph, right-hand *y*-axis) in the northern NSW Murray–Darling Basin from 1993-94 to 2019-20 (cf. also Table S2)

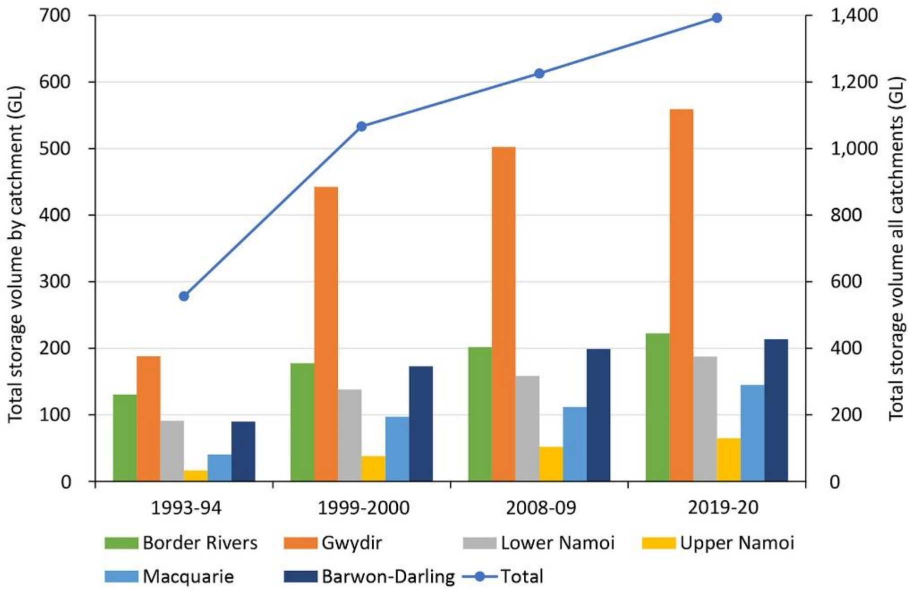


Figure 5. Estimation of mean annual floodplain harvesting take from all floodplain management areas in the northern NSW Murray–Darling Basin in relation to mean annual rainfall for the region (Table S5). The cotton water deficit, equivalent to the take from floodplain harvesting, is the total volume of irrigation water used for cotton minus the estimated licensed water use for cotton. Error bars on total cotton water use = maximum and minimum values; error bars on rainfall = standard error. Dashed black line = mean annual rainfall for the region of 487 mm (2004-2020)

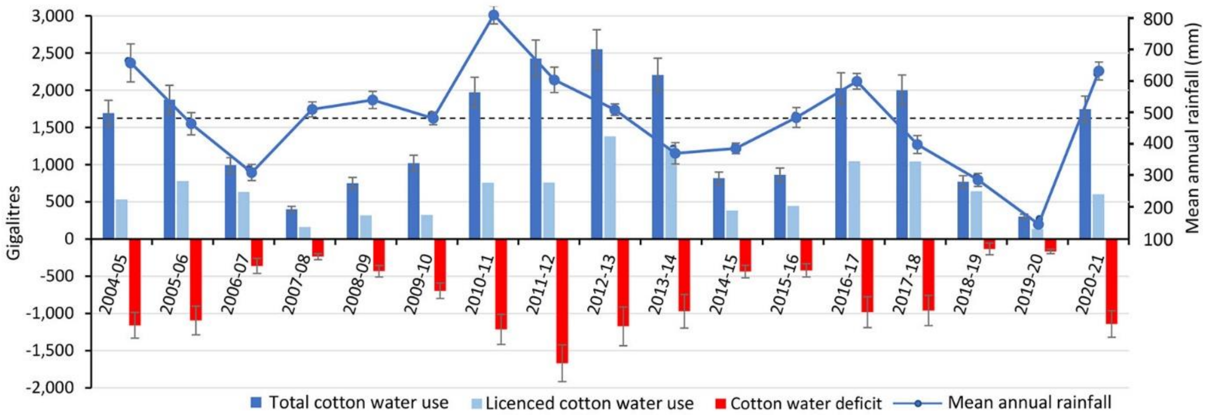


Figure 6. Change in the proportion of on-farm storage capacity to the mean annual floodplain harvesting take in each floodplain management area (FMA) between 2008-09 and 2019-20. The data is based on the capacity of storages in each FMA in 2008-09 and 2019-20 (Table S2) and the mean annual take from floodplain harvesting between 2004-05 and 2008-09 and between 2009-10 and 2019-20 (Table S4)

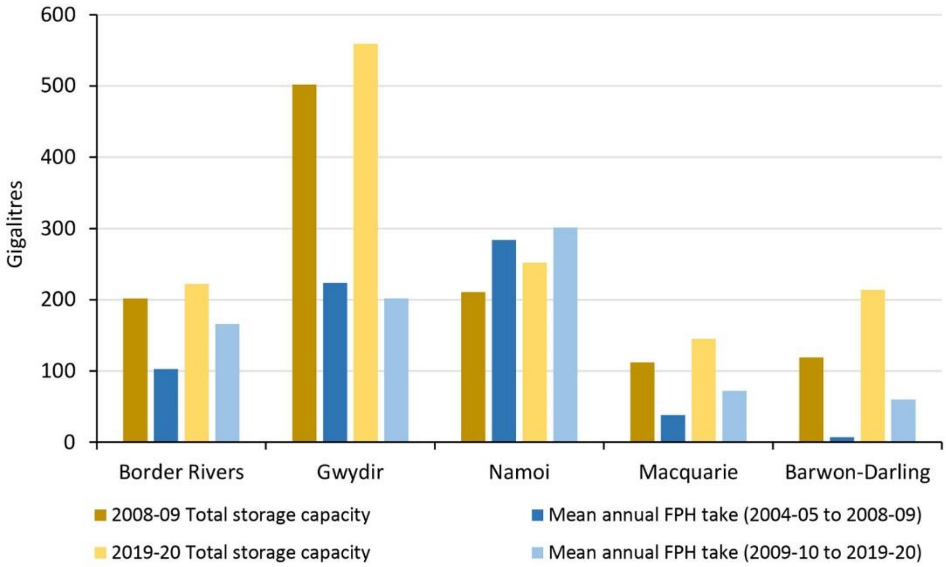
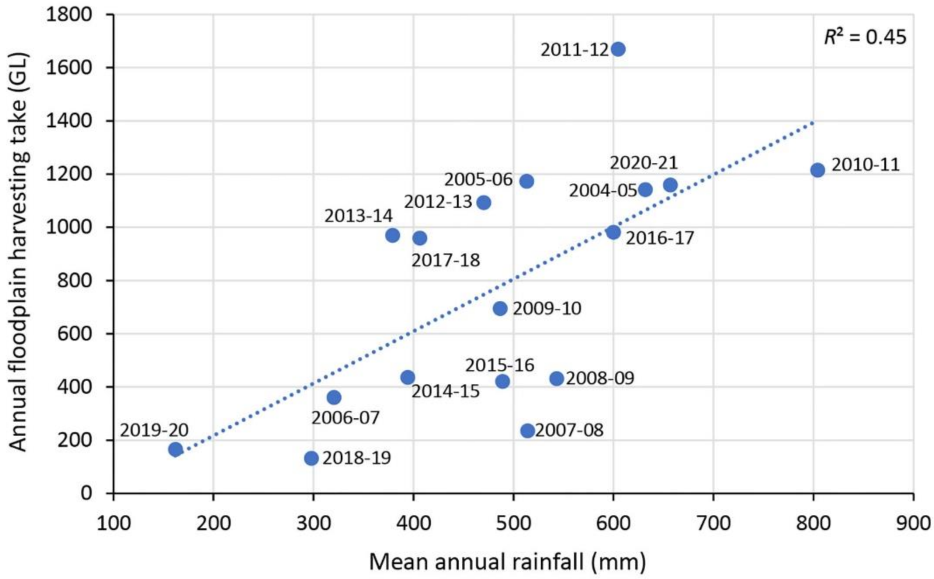


Figure 7. Relationship between estimated mean annual floodplain harvesting take for all five floodplain management areas (Table S4) and mean annual rainfall for the northern NSW Murray–Darling Basin between 2004-05 and 2020-21 (Table S5)



Supplementary Material

Table S1. Number of storage volume calculations undertaken, based on digital elevation models, and average derived depths of on-farm storages by floodplain management area in each catchment

	No. volume calculations based on digital elevation models				Average depth of storage (m)		
Catchment	Small storages (0.56-12 ha)	Medium storages (>12-34 ha)	Large storages (>34-949 ha)	Total	Small storages (0.56-12 ha)	Medium storages (>12-34 ha)	Large storages (>34-949 ha)
Border Rivers	9	10	50	69	1.6	3.7	4.1
Gwydir	10	14	116	140	1.7	3.0	3.4
Lower Namoi	8	16	39	63	3.0	2.7	2.6
Upper Namoi	14	13	9	36	2.5	3.5	2.0
Macquarie	11	10	34	55	1.6	3.3	2.8
Barwon-Darling	8	8	27	43	2.1	2.7	3.6
Total	60	71	275	406	2.1	3.2	3.1

Table S2. Changes over time in permanent on-farm storage capacity by floodplain management area in each catchment (GL)

Catchment	1993-94	1999-2000	2008-09	2019-20
NSW Border Rivers	131	178	202	222
Gwydir	188	443	502	559
Lower Namoi	91	138	159	187
Upper Namoi	16	39	52	65
Macquarie	40	97	112	145
Barwon-Darling	90	173	199	214
Total	557	1,067	1,225	1,393

Table S3. Estimates of floodplain harvesting take in the northern Murray–Darling Basin. Figures separated by commas = estimates for more than one year. Shaded areas = comparison of estimates from present study with those of Department of Planning, Industry and Environment (DPIE)

Catchment	Year	No. storages	No. properties	Storage area (ha)	Fold-increase	Storage capacity (GL)	Annual take (GL)	% of total diversions	Reference
Warrego	1998-2003						0.4		Brewsher Consulting (2006)[1]
	2019						3.0	3.7	MDBA 2019
Condamine-Balonne	1995						144	21.1	Brewsher Consulting (2006) (cf. also Webb McKeown, 2007)[2]
	1997-2003						50		Brewsher Consulting (2006)[2]
	1999-2004					820, 1,350			Brewsher Consulting (2006)[3]
	2005	1,582							Agrecon (2005), cited by Webb McKeown (2007)[4]
	2010					1,340			SKM, CSIRO & BRS (2010)[5]
	2012-2015						135		MDBA (2017 pp. 69-72)*
	2019						147	14.4	MDBA (2019)
Upper Condamine	1997-1999	197, 310			1.57	89, 143			Porter & Delforce (2000)
	1999-2004					140, 190			Brewsher Consulting (2006)[3]
	2020	621							Present study
Moonie	2000						4	11.8	Brewsher Consulting (2006) (cf. also Webb McKeown, 2007)[2]
	2010					31	10		SKM, CSIRO & BRS (2010)[6]
	2019						4	4.4	MDBA (2019)
Border Rivers (Qld. & NSW)	1997-1999							39.3	Tennakoon & Milroy (2003)[7]
	2005	459							Agrecon (2005), cited by Webb McKeown (2007) [4]
	2007						13	2.9	Webb McKeown (2007)[8]
	2010					426	150		SKM, CSIRO & BRS (2010)[6]
Qld. Border Rivers	1999-2003						10		Brewsher Consulting (2006)[1]
	1999-2004					197, 360			Brewsher Consulting (2006)[3]
	2000						26	12.2	Brewsher Consulting (2006)[2]
	2012-2015						43		MDBA (2017 pp. 69-72)*
	2019						50	13.2	MDBA (2019)
NSW Border Rivers	2003-04						>3	>20	Brewsher Consulting (2006)[9]
	2002, 08, 14					166, 190, 202			DPIE (2020a, p. 48)
	2019						3		MDBA (2019)
	2019						3		Moroka (2019) (cf. also Slattery & Johnson 2021)[10]
							43.6		DPIE (2020b, p. 16)
	2020	132				179			DPIE data, cited in NSW Parliament (2020, p. 4)
	2020	111		5,000		176			DPIE (2020c, p. 58)
	2020	191		5,750		222	141		Present study
Gwydir	'94, '99, '09, '20					291, 398, 508, 523			DPIE (2021a, p. 44)
	1996-1998							12.8	Tennakoon & Milroy (2003)[7]
	1999-2000						>114	>27	Brewsher Consulting (2006)[9]
	2005	351							Agrecon (2005), cited by Webb McKeown (2007)[4]
	2007						97	21.8	Webb McKeown (2007)[8]
	2010					429	150		SKM, CSIRO & BRS (2010)[5]
	2019						118		Moroka (2019) (cf. also Slattery & Johnson 2021)[10]
	2020	403				553			DPIE data, cited in NSW Parliament (2020, p. 4)
	2020	327	130	20,600		472	150	~33	DPIE (2020d, pp. 50-51, Fig. 20)
	2020					523	174		DPIE (2021b, pp. 13, 15)
	2020	434		17,164		559	196		Present study

Catchment	Year	No. storages	No. properties	Storage area (ha)	Fold-increase	Storage capacity (GL)	Annual take (GL)	% of total diversions	Reference
Namoi	1996-1998							14.5	Tennakoon & Milroy (2003)[7]
	2005	190							Agrecon (2005), cited by Webb McKeown (2007)[4]
	2006						>94	>22	Brewsher Consulting (2006)[9]
	2007						88	16.7	Webb McKeown (2007)[8]
	2010					171	60		SKM, CSIRO & BRS (2010)[6]
	2019						94		Moroka (2019) (cf. also Slattery & Johnson 2021)[10]
	2020	554				312			DPIE data, cited in NSW Parliament (2020, p. 4)
	2020	445		10,400		251	42	~25	DPIE (2020e, pp. 72, 144)[11]
	2020	695		9,176		252	312		Present study
Upper Namoi (Peel River)	1973-1990	118, 392							Beavis et al. (1997)
Macquarie	1996-1998							8.6	Tennakoon & Milroy (2003)[7]
	2005	110							Agrecon (2005), cited by Webb McKeown (2007)[4]
	2005	54		1,900					Steinfeld & Kingsford (2013)[12]
	2010					24	8		SKM, CSIRO & BRS (2010)[6]
	2020	213				167			DPIE data, cited in NSW Parliament (2020, p. 4)
	2020		75					13	DPIE (2020f, p. 64)
	2004, '08, '20					125, 144, 153			DPIE (2021c, p. 51)
	2020					153	39		DPIE (2021d, pp. 13, 16)
	2020	342		5,181		145	40		Present study
Barwon-Darling	1987-2003					50, 325			Stazic et al. (2006), cited by Brewsher Consulting (2006)
	2001						>43	>18	Brewsher Consulting (2006) (cf. also Webb McKeown, 2007)[9]
	2005	298							Agrecon (2005), cited by Webb McKeown (2007) [4]
	2010					151	50		SKM, CSIRO & BRS (2010)[6]
	2019						22		Moroka (2019) (cf. also Slattery & Johnson 2021)[10]
	2020	117				239			DPIE data, cited in NSW Parliament (2020, p. 4)
	2020	171		5,379		214	48		Present study
Qld. MDB	2010					1,625	570		SKM, CSIRO & BRS (2010)[13]
	2019						204	12.8	MDBA 2019
Northern NSW MDB	2001						254	4	Brewsher Consulting (2006)[9]
	2010					950	320		SKM, CSIRO & BRS (2010)[14]
	2019						46	2	MDBA 2019
	2019	1,450							DPIE data, cited in NSW Parliament (2020, p. 4)
	2020	1,833		42,650		1,393	738		Present study
Northern Basin	1996-1998							15.5	Tennakoon & Milroy (2003)[7]
	2010					2,600	880		SKM, CSIRO & BRS (2010)[6]

*Average for 2012-13 to 2015-16. [1]Annual Water Audit Reports submitted by Qld. to MDBC; [2]Estimates of Average Annual Diversions for Qld. from IQQM; [3]Figure 4.2 therein, on-farm storage capacity; [4]Estimated no. ring tanks, Table 5 therein; [5]Table 6 therein; [6]Table 8 therein; [7]Table 1 therein; [8]Table 5; includes floodplain harvesting & rainfall harvesting; [9]Estimates using IQQM; includes rainfall runoff; harvesting; [10]Table 2 in Slattery & Johnson (2021); [11]Mean annual take from Figure 45 therein; [12]Figures for off-river storages (>2 ha); [13]Table 9 therein; [14]Table 10 therein. Note: we did not include estimates of annual floodplain harvesting take for NSW catchments from MDBA Cap and SDL compliance reports because they used the same figures for every year (2012-13 to 2018-19: NSW Border Rivers 2.95 GL; Gwydir 17.8 GL; Namoi 13.99 GL; Macquarie) GL; Barwon–Darling 11.49 GL; Total NSW 46.2 GL). Prior to 2012-13 the Cap compliance reports included only incomplete estimates of floodplain harvesting from Queensland catchments.

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Table S4. Estimation of annual floodplain harvesting take (positive sign of the cotton water deficit) in each floodplain management area, based on the difference between mean total water use per hectare of irrigated cotton (mean of low and high estimates of 9.86 ML/ha and 12.12 ML/ha) and estimated licenced cotton water use. Cotton water use as a percentage of total irrigation water use is derived from the *Water Use on Australian Farms* statistical series (ABS 2021; see methods section for details)

	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	Mean
Border Rivers																		
Irrigated cotton production (ha)	30,080	24,440	12,944	2,538	8,460	16,215	33,840	49,664	45,367	43,150	7,428	13,253	33,753	30,774	11,050	785	12,711	22,144
Total cotton water use (GL)	331	269	142	28	93	178	372	546	499	474	82	146	371	338	121	9	140	243
Total licenced irrigation water use (GL)	90	121	115	65	58	100	163	134	199	173	44	94	224	137	148	18	105	117
Cotton water use as % of total irrig. water use	86.8	89.7	87.4	33.4	70.7	88.1	94.8	93.3	95.6	95.4	73.9	85.6	92.6	95.0	83.8	59.5	82.6	82.8
Licenced cotton water use (GL)	78	108	100	22	41	88	155	125	190	165	32	80	207	131	124	11	87	103
Cotton water deficit (GL)	-253	-160	-42	-6	-52	-91	-217	-421	-308	-309	-49	-65	-164	-208	3	2	-53	-141
Gwydir																		
Irrigated cotton production (ha)	50,000	60,000	31,100	10,500	25,600	26,000	52,200	43,877	71,386	62,709	20,948	19,500	46,400	47,800	10,500	4,540	40,300	36,668
Total cotton water use (GL)	549	659	341	115	281	285	573	482	784	689	230	214	509	525	115	50	442	403
Total licenced irrigation water use (GL)	154	435	160	115	173	82	255	222	408	422	141	111	332	310	99	58	215	217
Cotton water use as % of total irrig. water use	88.8	89.7	87.4	33.4	70.7	88.1	94.8	93.3	95.6	95.4	73.9	85.6	92.6	95.0	83.8	59.5	82.6	83.8
Licenced cotton water use (GL)	136	390	140	38	122	72	242	207	390	403	104	95	308	295	83	35	177	190
Cotton water deficit (GL)	-413	-269	-201	-77	-159	-213	-331	-275	-393	-286	-126	-119	-202	-230	-32	-15	-265	-212
Namoi																		
Irrigated cotton production (ha)	56,000	61,800	32,480	20,000	28,650	38,800	66,500	66,366	58,028	57,154	33,915	30,400	55,835	52,200	28,400	16,900	66,000	45,260
Total cotton water use (GL)	615	679	357	220	315	426	730	729	637	628	372	334	613	573	312	186	725	497
Total licenced irrigation water use (GL)	349	139	303	226	233	228	235	206	366	495	269	135	262	321	274	90	200	255
Cotton water use as % of total irrig. water use	73.2	77.7	69.1	40.4	42.8	52.0	84.0	80.2	79.3	74.3	57.7	73.4	92.6	95.0	83.8	59.5	70.8	70.9
Licenced cotton water use (GL)	256	108	209	91	100	119	197	165	290	368	155	99	242	305	229	54	142	184
Cotton water deficit (GL)	-359	-571	-147	-128	-215	-307	-533	-563	-347	-260	-217	-235	-371	-268	-82	-132	-583	-313
Macquarie																		
Irrigated cotton production (ha)	7,000	16,000	13,900	3,210	4,150	6,000	16,800	42,070	40,571	25,811	9,726	9,700	25,700	36,000	19,500	4,735	20,200	17,710
Total cotton water use (GL)	77	176	153	35	46	66	184	462	445	283	107	107	282	395	214	52	222	194
Total licenced irrigation water use (GL)	44	162	235	55	89	91	144	237	454	284	116	136	194	398	304	103	138	187
Cotton water use as % of total irrig. water use	52.1	63.8	50.9	22.8	39.5	37.1	71.7	84.7	79.2	85.6	54.5	75.2	79.0	79.7	68.3	20.5	60.3	60.3
Licenced cotton water use (GL)	23	103	120	12	35	34	103	200	360	243	63	102	153	317	208	21	83	128
Cotton water deficit (GL)	-54	-72	-33	-23	-10	-32	-81	-261	-86	-40	-44	-5	-129	-78	-6	-31	-139	-66.1
Barwon-Darling																		
Irrigated cotton production (ha)	11,000	8,500	0	125	1,580	6,000	10,300	19,171	17,142	12,124	2,516	6,000	22,900	15,525	900	580	19,700	9,063
Total cotton water use (GL)	121	93	0	1	18	66	113	236	188	133	27	99	376	275	18	7	216	100
Total licenced irrigation water use (GL)	61	82	78	0	55	25	69	74	163	63	28	69	275	3	0	234	182	86
Cotton water use as % of total irrig. water use	67.0	88.2	81.1	0.0	40.7	54.2	87.8	83.5	91.5	91.2	98.1	99.7	48.9	44.0	25.1	7.0	62.7	63.0
Licenced cotton water use (GL)	41	72	63	0	22	14	61	62	149	58	28	69	134	1	0	16	114	53
Cotton water deficit (GL)	-80	-21	63	-1	5	-52	-52	-149	-39	-75	0	3	-117	-169	-10	10	-102	-46
Total																		
Irrigated cotton production (ha)	154,080	170,740	90,424	36,373	68,440	93,015	179,640	221,148	232,494	200,948	74,533	78,853	184,588	182,299	70,350	27,540	158,911	130,846
Total cotton water use (GL)	1,692	1,875	993	399	752	1,021	1,973	2,429	2,553	2,207	818	866	2,027	2,002	773	302	1,745	1,437
Licenced cotton water use (GL)	533	781	632	164	320	326	758	759	1,380	1,237	382	445	1,045	1,049	645	136	603	658.6
Cotton water deficit (GL)	-1,159	-1,094	-361	-236	-431	-695	-1,215	-1,669	-1,173	-970	-437	-421	-982	-953	-128	-166	-1,142	-778

Table S5. Mean annual rainfall (mm) based on data from three weather stations in each catchment, 2004-05 to 2020-21 (± standard error, SE). Data from Bureau of Meteorology, http://www.bom.gov.au/climate/data/

Catchment	Weather Station & no.	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	Mean
Border Rivers	Mungindi Post Office 052020	761	474	357	455	558	362	776	648	511	312	439	405	679	358	338	154	565	480
	Croppa Creek 053018	904	520	434	544	537	524	756	884	539	510	381	563	552	512	340	148	738	552
	New Kildonan 041507	628	529	303	422	436	484	900	670	495	522	352	774	634	566	397	220	627	527
Gwydir	Collarenebri (Albert St.) 048031	856	546	415	563	539	392	800	587	453	297	351	377	652	259	224	121	598	472
	Garah Post Office 053011	951	530	365	492	701	570	813	768	666	516	366	592	628	398	353	117	664	558
	Moree Aero 053115	849	524	479	518	629	539	646	845	633	499	355	522	527	512	428	125	652	546
Namoi	Wee Waa (George St.) 053044	968	639	389	448	565	370	921	676	563	418	372	598	656	436	339	203	741	547
	Narrabri Airport 054038	891	715	425	552	617	483	617	612	445	591	458	584	709	585	376	206	771	567
	Gunnedah Airport 055202	620	511	353	622	671	420	912	665	583	478	562	538	580	555	377	233	844	560
Macquarie	Quambone Station 051042	555	376	288	660	444	617	880	389	448	263	431	391	598	330	216	160	612	450
	Warren (Mumblebone) 051034	388	390	220	492	568	534	989	559	494	327	420	426	632	374	207	102	612	455
	Trangie Research Station 051049	340	511	208	523	512	408	886	585	421	336	432	540	751	350	263	160	631	462
Barwon-Darling	Bourke Airport 048285	298	173	123	258	243	465	627	380	435	132	345	316	389	297	205	211	394	311
	Brewarrina Hospital 048015	356	230	202	598	563	558	722	417	503	239	378	368	405	248	208	144	474	389
	Walgett Airport 052088	487	385	243	562	561	570	815	382	508	248	270	341	608	314	195	123	554	422
Mean		657	470	320	514	543	486	804	604	513	379	394	489	600	406	298	162	632	487
SE		58	34	25	23	26	20	28	39	18	33	16	31	24	28	20	10	28	18

Figure S1. Growth in on-farm storage capacity on the Barwon-Darling (from Stazic *et al*. 2006, quoted by Brewsher Consulting 2006). Using the equation for the regression line (dotted line; second-order polynomial; $y = 0.293x^2 + 22.7x + 29.1$), estimated storage capacity increased from 51 GL in 1987-88 to 330 GL in 2003-04, an average annual increase of 16.4 GL for 17 years. Note the increased rate of growth in 1996-97, immediately after implementation of the Murray–Darling Basin Cap on diversions in June 1995