AMBIO
DOI 10.1007/s13280-014-0495-x

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PERSPECTIVE

Water Planning and Hydro-Climatic Change in the Murray-Darling Basin, Australia

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Received: 19 August 2013 / Revised: 15 December 2013 / Accepted: 7 February 2014

Abstract More than a third of humanity lives in regions with less than 1 million liters of fresh water per person per year. Population growth will increase water demand while climate change in arid and semi-arid areas may reduce water availability. The Murray-Darling Basin in Australia is a region where water reform and planning have been used to reduce consumptive extraction to better sustain river ecosystems under climate variability. Using actual data and previously published models that account for climate variability and climate change, the trade-off between water extractions and water essential to the long-term ecological function of river systems is analysed. The findings indicate that better water planning and a more complete understanding of the effects of irrigation on regional climate evapotranspiration could: (1) increase the overall benefits of consumptive and non-consumptive water use; (2) improve riparian environments under climate variability; and (3) be achieved with only small effects on the profits and gross value of food and fiber production.

Keywords Water planning · Climate variability · Irrigated agriculture · River ecosystems

INTRODUCTION

Projected effects of climate change and hydro-climatic shifts induced by irrigation (Destouni et al. 2013) affect water availability at a basin-scale. At a global level, per capita water availability is declining in many countries (WWAP 2012). If water availability continues to fall, it will exacerbate underlying tensions between extractive and non-consumptive uses of fresh water and, with business as usual, result in environmental decline (Vorosmarty et al. 2010).

The Murray-Darling Basin (MDB), Australia offers insights about how to undertake water reform and planning in a region with highly variable and declining water availability. Planned MDB reforms have been undertaken to improve aquatic ecosystems without damaging the value of agricultural production. This basin is noteworthy as one of the world's most variable regions in terms of streamflows (McMahon et al. 2007) and precipitation (see Fig. 1), the large size of its water extractions relative to inflows (Grafton et al. 2012), and the relative importance of irrigated agriculture in terms of both its diversions and value added. Further, the MDB is a "test case" of water reform (Connell and Grafton 2011) because of the size of the proposed reductions in water extractions within a basin-wide water planning framework and the extensive use of markets for water reallocation (Grafton et al. 2011b; Grafton and Horne 2014).

Our evaluation provides insights about how to manage the trade-offs between consumptive and non-consumptive water in the MDB and also other locations, such as the Colorado Basin in the US, where current water management imposes major environmental costs (Glenn et al. 1996). Our review of the MDB: (1) assesses the ecosystem impacts of current water reform; (2) considers the costs and benefits of reallocating an increased share of the available surface water to environmental flows; and (3) provides insights about how to improve basin-wide water management.

KEY FEATURES OF THE MURRAY-DARLING BASIN: HYDROLOGY AND WATER EXTRACTIONS

The MDB encompasses about 1 million km^2, some 14 % of the Australian continent, and stretches across extensive floodplains of the Murray River and its tributaries to the Great Southern Ocean (see Fig. 2). The basin includes riverine floodplains of 200 m or less in elevation, with meandering river systems, but due to high natural losses and anthropogenic extractions, its discharges are small compared to other similar-sized basins. Natural flood and drought cycles connect the river channels to the floodplains where processes have evolved to derive ecological function from climate variability. The floodplains supply nutrients that support the basin's photosynthetic activity (Overton and Saintilan 2010), are places where aquifers are recharged (Williams 2011), and are important locations for bird, amphibian, reptile, and fish breeding (Kingsford et al. 2004; Beesley et al. 2010).

The annual potential evapotranspiration in the basin ranges from 700 mm in the South East to over 2000 mm in the North West (Kirby et al. 2006). Almost half the runoff and transfers into the basin are diverted for consumptive use while a similar proportion is evaporated from open water and as evapotranspiration (Kirby et al. 2006). On average, a little more than 10 % of the basin runoff is discharged at the Murray mouth.

Around 90 % of the water extracted in the basin, including water losses and conveyance, is diverted for irrigation (Australian Bureau of Statistics, Australian Bureau of Agricultural and Resource Economics-Bureau of Rural Sciences 2009, pp. 1–2, 9–11, 57–58), primarily from just two rivers, the Murray and Murrumbidgee. Both the proportion of total runoff that is extracted and the relative importance of irrigation are large even when compared to agriculturally dependent river basins with large diversions, such as the Orange River in South Africa (Mare 2007).

Over 98 % of the MDB surface area is devoted to rainfed agriculture. Less than 2 % of the basin area is in irrigated agriculture or horticulture. The principal features of irrigated crops and regions (Meyer 2005; Kirby et al. 2006) in the basin include:

(1) Irrigated pastures for dairy, beef, and sheep occur in the southeast of the basin. Flood irrigated for much of the year, about 550–750 mm of water is diverted per crop in locations where the rainfall varies from 700 mm year^{-1} in the east to less than 400 mm year^{-1} in the west;

(2) Rice production in the Murray and Murrumbidgee River systems is based on paddy rice. Water diversions average more than 1000 mm per crop and occur in highly variable rainfall environments of between 200 and 400 mm year^{-1};

(3) Grapes, citrus, and perennial horticulture dominate the lower basin with water mostly applied by sprinkler or microsystems. Water diversions vary by crop and location, but average 600 mm and are located in highly variable rainfall environments of between 200 and 400 mm year^{-1}; and

(4) Cotton dominates the northern basin where water use is around 700–800 mm year^{-1} that takes place in rainfall locations of about 400–550 mm year^{-1}.

The diversity of soils under irrigation means that soil water storage to 1.5 m is some 90 mm in light-textured

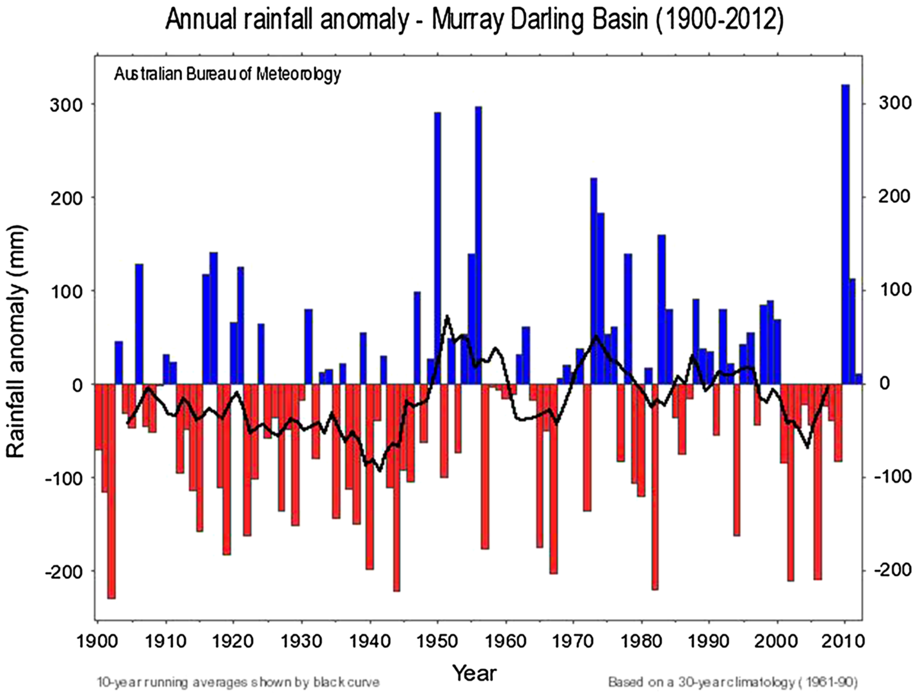

Fig. 1 Annual rainfall anomaly, Murray-Darling Basin

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Fig. 2 Map of the Murray-Darling Basin

soils to 250 mm in heavy-textured cracking clays (Williams 1983). During the Millennium Drought, there was rapid drying of soil moisture and depletion of surface water storages that occurred by early 2003, some 7 years before the drought ended (Leblanc et al. 2009).

Rainfall and extraction of soil water storage during an irrigation cycle is highly variable (Humphreys et al. 2003) and can range from 20 to 60 % of crop water use. For example, rainfall and extraction of soil water storage can vary from about half to more than 60 % of the 800 mm water used in a cotton crop in the northern basin, to between 15 and 30 % for water use of 900–1500 mm in a pasture forage crop in the south west basin (Humphreys 2003).

ECOSYSTEM IMPACTS OF PAST WATER PLANNING AND MANAGEMENT

Concerns about environmental degradation led to the imposition of a policy known as "the cap" in the mid-1990s which limited average annual surface water extractions to what they would have been given the infrastructure that existed in 1993–1994, assuming the same hydrological and climactic conditions. The overall limit of surface water extractions set by the cap was intended to prevent further deterioration in the environment, but was not established to provide for agreed-to-environmental outcomes. Simultaneous with the establishment of the cap, the states in the basin that manage water resources agreed to encourage water trading that separated rights to land and water. Thus, while total diversions were capped, individual irrigators could increase their extractions if they purchased water entitlements.

The cap was implemented with the water management rules that operate separately in each state, and provided for a greater proportion of inflows to irrigators in dry years than in wet periods. These rules were justified on the basis that the environment would get its "fair share" of the water during floods, and this would mimic the natural system of droughts and flooding events to which the basin's ecosystems had evolved.

Under the Australian federation, the state and territory governments have held primary responsibility for water resources management and allocated water, applying different types of entitlements and accounting standards. In the basin, the cap was agreed by consensus between the

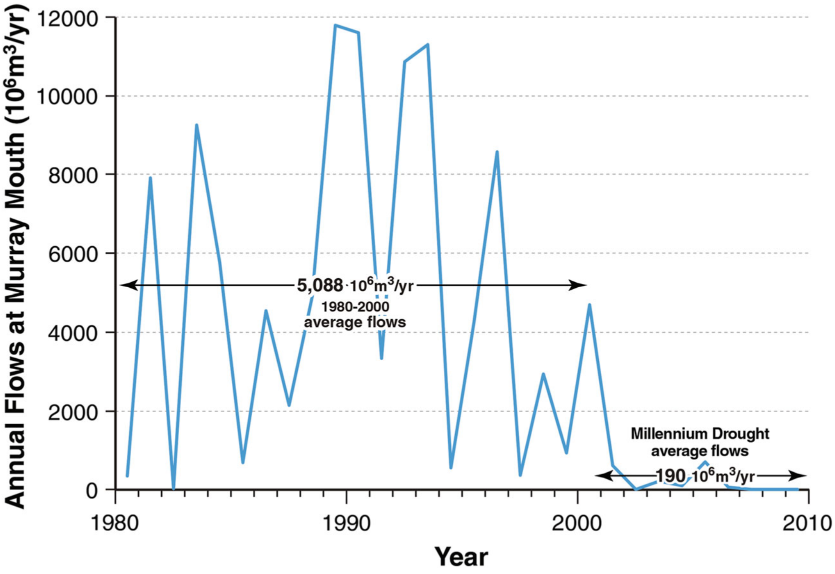

Fig. 3 Annual flows at Murray Mouth

state and federal governments, requiring harmonization of entitlements and reporting. The water available in each state was then allocated by state government institutions, often informed by multi-stakeholder (sub-basin) catchment management authorities. In 2007, the federal government drew on its constitutional powers to regulate corporations and implement environmental treaties under the Water Act 2007, to direct water governance in the basin through a plan that will primarily be implemented by states (Connell and Grafton 2011).

A drying trend in the southern part of the basin began shortly after the implementation of the cap in 1995 (Vernon-Kidd and Kiem 2009). The drought reduced water availability to such an extent that the maximum levels of extraction under the cap were not achievable even with reductions in environmental flows. To provide additional water to irrigators during the drought, the state governments in New South Wales and Victoria suspended water sharing plans that had previously provided for environmental flows (NWC 2009). More generally, environmental flows were treated as a residual claim, to be met after allocations of water for extractive uses. As a result, during the 2002–2010 Millennium Drought, environmental flows across the basin declined by about four times as much as reductions in surface water extractions by irrigators (CSIRO 2008, p. 59).

The frequency of zero or low-flow years at the mouth of the Murray River has increased from about 1 % prior to European settlement to over 40 % (CSIRO 2008). During the 2002–2010, Millennium Drought flows at the Murray Mouth were close to zero (see Fig. 3). By 2030, some climate change modeling scenarios predict that these low-flow events may be expected 70 % of the time (Young and Chiew 2011, p. 456). The federal government's basin plan, adopted in 2012 after several years of negotiation and study, has as a key goal keeping the Murray Mouth open through freshwater flows 9 out of 10 years, on average.

While the biggest impact of water stress is observed at the Murray Mouth, riparian ecosystems and floodplain vegetation throughout the basin have significantly declined (Overton et al. 2009; Pittock et al. 2010). Observed ecological decline at or close to river mouths as a result of high levels of water extraction occurs in other mid-latitude rivers globally (Grafton et al. 2012). In the case of the MDB, Fig. 4 shows that water extraction is the principal cause for reduced flows at the end of the system. Based on the historical climate (1895–2006), water extractions have resulted in a mean reduction in end-of-system flows of over 60 % compared to what would have flowed in the absence of irrigation.

Current water planning allows for the removal of all of the small flood events that would have occurred without irrigation and greatly diminishes the size and frequency of overbank events that arise with larger-sized floods. As a result of past and current water use floodplains are much drier, the connectivity between floodplains and rivers is greatly reduced (NRC 2009, Chap. 8, pp. 102–199), and 20 of the 23 river valleys in the basin have been classified as either in poor, or in a very poor, state of ecological health (Davies et al. 2010).

The Water Act 2007 established the MDB Authority, an agency of the federal government, and charged it with preparing a basin plan that would set lower "sustainable diversion limits" for consumptive water users. While environmental flows are planned to increase as a share of

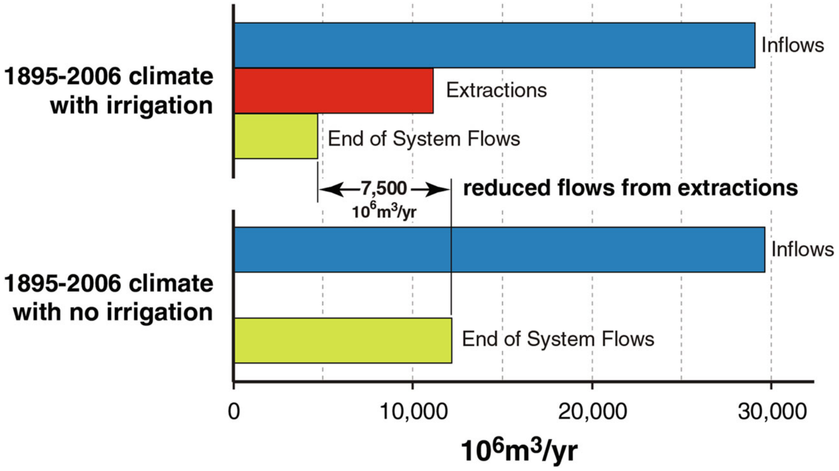

Fig. 4 Long-term average annual basin flows

stream flows, the state governments' water allocation rules that capture and abstract small flood events remain unchanged (Pittock 2013). The basin plan adopted in 2012 requires state governments to prepare new water management plans for their jurisdictions by 2019.

The water volume to be reallocated to environmental flows under the basin plan is equivalent to about one quarter of the average annual basin extractions. Some of the proposed increase in environmental flows will come from water entitlements held by the Commonwealth Environmental Water Office (CEWO 2013) that, as of 30 June 2013, equalled a little less than half equal the planned for increases in environmental flows by 2024, but only 30 % of the initially recommended reallocation of water to the environment (MDBA 2010a). About 80 % of the planned-for-increases in environmental flows in the southern part of the basin are expected to be achieved by supply measures that include infrastructure investments and on-use water efficiency rather than by purchases of water entitlements. These supply measures have uncertain benefits and possibly perverse impacts that can reduce water quality, fragment wetland ecosystems, and may lower resilience to climate change (Pittock 2013).

About half of the federal government's water entitlements used to generate environmental flows are classed as "high security" water. Typically, only high security water entitlements are allocated water in times of severe drought with low security entitlements receiving low or zero allocations of water. Almost all high security entitlements are held in storages in the southern MDB and, thus, are not deliverable to northern parts of the basin. An additional challenge to delivering the target volumes of environmental flows under the 2012 basin plan is that the New South Wales government has constrained the purchases of water entitlements by the federal government over a 10-year period to only 3 % of the total volume of entitlements in that state. This limit is intended to push the federal government to favor irrigation water efficiency and environmental "works and measures" projects to increase environmental flows.

CLIMATE VARIABILITY AND WATER USE

The rapid expansion of irrigation development in the MDB from the 1950s to 1980s was conducted without consideration of the climate variability. This peak period of expansion occurred during an observable wet period, with the exception of four dry years in the 1960s. Over this relatively wet, expansion period both the mean and variance of annual rainfall increased (Khan 2008) and were higher relative to the previous period 1900–1950, as shown in Fig. 1.

While further expansions in water allocations were capped in 1995, it was not until the decade-long Millennium Drought that ended in 2010 that water for irrigated agriculture systematically declined. This drought led to a 40 % decline in runoff from 1997–2008 in the southern MDB relative to the long-term mean (CSIRO 2009, p. 2). Over the period 2002–2007, average annual net inflows in the Murray River were the lowest ever recorded for a 5-year period. This translated into greatly reduced water diversions to irrigated farmers of between 30 and 50 %. The drought and water allocation rules also diminished flows at the Murray Mouth by about 96 % between 2002 and 2010 (see Fig. 3) relative to the average flows over the period 1980–2001. Under water planning rules within the MDB that favor extraction over environmental flows, this resulted in the proportion of inflows diverted for agriculture in the River Murray to increase from less than 50 % in the 1980s and 1990s to 76 % over the period 2000–2008 (see Table 1).

The consequence of the Millennium Drought and counter-cyclical water management has been that many of the wetlands fed by the Murray River have only received

Table 1 Average annual net inflows in the Murray River and total water diversions by decade

	1930–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2008
Net inflows (10^6 m^3)	8,893	5,529	14,160	7,928	12,822	9,181	9,932	4,449
Water use (10^6 m^3)	1,178	1,676	2,185	3,119	3,465	4,025	4,351	3,368
Percentage diverted (%)	13	30	15	39	27	44	44	76

Data is sourced from the Murray-Darling Basin Authority (2009): net inflows are from the first column (Murray System Inflows—no Darling or Snowy River inflows) in the Murray River inflows table; water use is the sum of Murray River (NSW) total diversion, total south Australia diversion in MDB and River Murray (Victoria) gross diversion in the Murray River water use table

water at intervals of every 30 years or so while they may have expected flooding to occur every 1–5 years under natural conditions (CSIRO 2008; Overton et al. 2009). During the Millennium Drought key species, such as River Red Gums (*Eucalyptus camaldulensis* Dehnh), that encompass an area of about four-fifths of the Murray River floodplain (Mac Nally et al. 2011), died all across the southern part of the MDB (NRC 2009, Chap. 8, pp. 102–199; Pittock et al. 2010). Even before the Millennium Drought, wetlands were identified as greatly degraded (Norris et al. 2001; Jones et al. 2002).

RIVER FLOWS AND WATER EXTRACTIONS

The effects of reductions in natural flows in the MDB during the Millennium Drought are shown in Fig. 5 for the Murray River, as measured near its confluence with the Darling River. The median ratio of observed flow to modeled natural flow is 32 % over the period 1998–2008. Several expert assessments have recommended the reallocation of water from agriculture to the environment to sustain key environmental services, especially the health of the major wetlands (NRC 2009; Pittock et al. 2010; MDBA 2010a), with a minimum increase in flows equivalent to about 40 % of average annual surface water consumption. The MDB Authority that is responsible for basin-wide water planning originally proposed a minimum of 60 % of natural flows within rivers to protect key environmental assets and ecosystem functions (MDBA 2010b, p. 110), but subsequently agreed to reallocate less water for environmental purposes in the 2012 basin plan equivalent to about one quarter of long-term extractions.

The 2012 basin plan allows for increased groundwater diversions equivalent to about 10 % of average surface water extractions for irrigation (SSCRRAT 2013). Increased groundwater allocations from connected aquifers will likely reduce river inflows, especially base flows. If

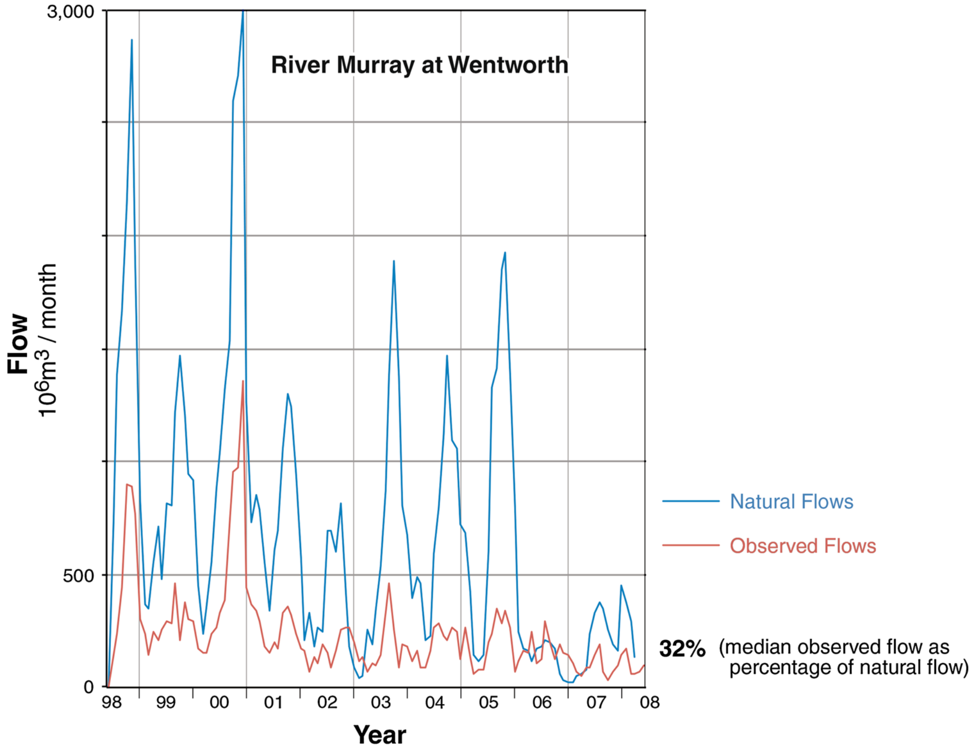

Fig. 5 Natural and observed annual flows of Murray River at Wentworth

this were to be the case, higher groundwater diversions may mean the proscribed constraints on surface water extractions, defined as sustainable diversion limits in the basin plan 2012, have been set at too high a level to achieve the intended environmental benefits (Gibbs et al. 2012). Another challenge is that the 2012 basin plan leaves unchanged the seasonal water sharing rules that favor water extractions over environmental flows and that proved ecologically damaging during the Millennium Drought.

POSSIBLE EFFECTS OF CLIMATE CHANGE

Climate projections in terms of precipitation and runoff are highly uncertain (Sun et al. 2011). Nevertheless, a comparison of the historical climate to median 2030 climate change projections from The Commonwealth Scientific and Industrial Research Organization (CSIRO), is provided in Fig. 6. Without assigning any probability to the CSIRO modeling, projected model outcomes range from an extreme dry scenario of a 37 % reduction in water availability and 69 % fall in outflows, through to an extreme wet scenario of a 7 % increase in water availability and 20 % increase in outflows.

The median 2030 scenario suggests that basin inflows could suffer a small decline (12 %) relative to the historical climate (1895–2006), but outflows would decline by a much greater proportion (24 %). This projection is consistent with the finding that under a 2030 median climate change scenario the decline in end-of-valley flows will be more than twice as large as the proportional reduction in expected runoff under current water planning rules, and would be six times larger than the expected reduction in extractions (Young and Chiew 2011, p. 457). The median scenario has been used in government policy making, but was not explicitly accounted for in the 2012 basin plan which makes no allowance for climate change in terms of current sustainable diversion limits (Pittock 2013).

The observed economic and environmental consequences of the Millennium Drought provide an observational counterpoint to the projections from climate change models. Critically, the fall in surface water availability during the Millennium Drought (short-term variability) in the southern MDB was much larger than the worst case climate scenarios (average long-term change) for 2030. In particular, reductions in autumn rainfall were as great as 30 % (Proctor et al. 2009, p. 9) while annual runoff relative to 1990 fell by nearly 40 % (CSIRO 2008, p. 26).

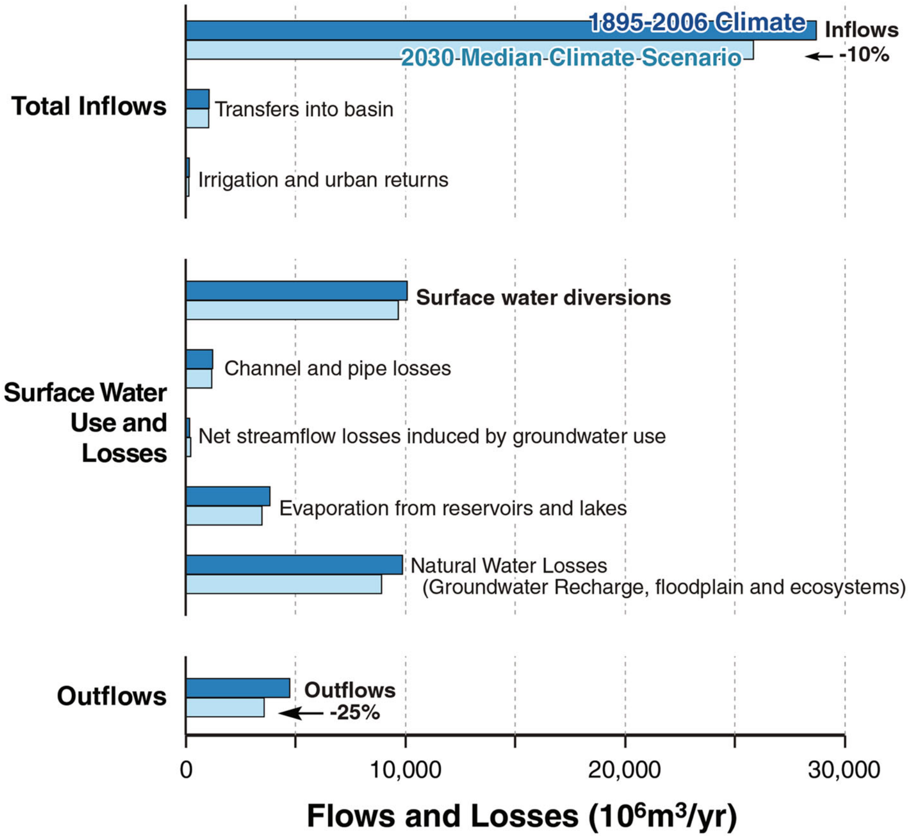

Fig. 6 Annual average inflows, uses, and losses and outflows, historical and 2030 median climate projection

Basin-scale factor effects associated with net water fluxes due to irrigation extractions are not only an issue for the MDB. In particular, enhanced evapotranspiration (ET) as a result of irrigation use can affect regional climates such as in the Mahanadi River Basin, India (Asokan et al. 2010) and may result in regional cooling, such as in the Area Sea Drainage Basin (ASDB) (Destouni et al. 2010). Further, irrigation may reduce the resilience of ecosystems due to the projected effects of climate change. For instance, in the ASDB, and under current irrigation practices, the projected river runoff decline over the period 2010–2039 could completely deplete the major rivers in this basin. By contrast, in the absence of irrigation, the temperature increase associated with climate change would need to be even 50 % higher in the Syr Darya River of the ASDB before it generated the same decline in river runoff (Jarskjö et al. 2012).

TRADE-OFFS FROM WATER REALLOCATION

Using agricultural surface water diversions in 2000–2001—a “normal” period of inflows—Table 2 presents the effect on annual net profits and gross returns in irrigated agriculture in the MDB from a least-cost way of acquiring water for the environment. The results were obtained from a hydro-economic model of irrigated agriculture (Grafton and Jiang 2011) and show that, with an optimal allocation of water across all irrigation uses, a reduction in surface water extractions equivalent to about one-third of total extractions in the basin—the annual net profits and gross value of irrigated agricultural production would fall by about 17 and 16 %, respectively, relative to the base case of no reductions.

Modeling projections of the effects of reduced extractions on irrigated agriculture are broadly consistent with survey data from the Australian Bureau of Statistics compiled during the Millennium Drought. These data show that, despite a decline in irrigated water use of about 70 % between 2000–2001 and 2007–2008, the nominal gross value of irrigated agricultural production fell, in nominal terms, by less than 1 % (Kirby et al. in press). A critical factor in this adjustment was the substitution to higher value crops and horticulture (Kirby et al. in press) facilitated by water markets (Grafton and Horne 2014). This finding suggests that, at least in the short run, irrigated agriculture can cope remarkably well with very large reductions in inflows.

A comprehensive analysis by Kirby et al. (in press) identifies four key factors that mitigated the effects of drought in the MDB:

(1) input substitution, particularly in the dairy industry, whereby purchased feed was substituted for water to irrigate dairy pastures;
(2) land-use changes from annual pastures to multiple cropping mixes;
(3) land-use change from more water-intensive crops such as paddy rice to less water-intensive crops such as grapes; and
(4) investments that have reduced water application rates, improved soil water management, and contributed to yield increases.

Destouni et al. (2013) observe that water consumption as a result of crop transpiration is not only related to irrigator decisions, the use of irrigation water or other inputs. In particular, during droughts an increased use of stored soil water can help compensate for reduced irrigation water. The challenge in the MDB, and elsewhere, will be continue to improve the use of stored soil water in the presence of an extended drought (Leblanc et al. 2009), or a drying trend due to climate change.

Possible long-term farm effects of climate change are illustrated by simulations we undertook using a model of land and water allocation under conditions of uncertainty described by Adamson et al. (2009). In this model, irrigators choose production plans to maximize expected returns over three possible states of nature—Normal, Wet (120 % of normal inflows, occurring with a probability of 0.3), and Drought (60 % of normal inflows, occurring with a probability of 0.2). Two scenarios are compared to a baseline representing optimal allocations under the current climate.

In scenario one, climate change reduces inflows in all states of nature by 30 %, but water allocations and entitlements remain unchanged. The result is that flows of water to the Lower Lakes and Coorong, at the Murray River Mouth, are reduced by 63 % under current water plans. Conversely, water use in irrigated agriculture declines by only 16 %. Adjustment to reduced inflows

Table 2 Reduction in annual net profits and annual gross value of irrigated production (GVIAP) in irrigated agriculture (% from base case) in the MDB from a least-cost acquisition of surface water entitlements owned by irrigators based on long-term agricultural surface water diversions (10^6 m^3 $year^{-1}$ on average)

	3000 GL reduction	3500 GL reduction	4000 GL reduction	4400 GL reduction	7600 GL reduction
% Reduction in net profits	10	14	17	21	46
% Reduction in GVIAP	10	13	16	18	41

arises primarily through a contraction in rice and cotton production and irrigated dairying. This scenario is representative of what occurred during the Millennium Drought.

In scenario two, allocations to water entitlements are adjusted downward in the same proportion as declines in water availability. This proportional reduction in water extractions, however, does not involve any direct reallocation of water from irrigation to the environment. The reduction in flows of water at the Murray Mouth is 47 %—an amount less than the no policy change given in scenario one (63 %), but much more than the proportional reduction in inflows to the system (30 %). The value added in irrigated agriculture falls by just 3 % in scenario two relative to scenario one. This indicates that equal-proportional water sharing between extractive and non-consumptive uses has a minimal impact on irrigated agriculture.

The economic benefits of increased environmental flows are more difficult to calculate. Grafton et al. (2011a) use a stochastic dynamic programming model calibrated to the Murray River and show that a reallocation of surface water from irrigated agriculture to environmental flows over the period 2002–2009 could have increased overall net benefits from consumptive and non-consumptive uses from between A$ 600 million and A$ 3.2 billion. Their findings indicate that, contrary to current practice, small or medium floods should be created every 1 or 3 years.

Non-market valuation techniques can be used to quantify the value of marginal improvements in environmental assets that could be associated with increased environmental flows. For example, a recent non-market valuation study in the MDB found that the estimated willingness to pay for environmental benefits associated with increased flows at the Macquarie Marshes is comparable to both the market price of water entitlements and the average gross value of irrigated agricultural production (Akter et al. 2014).

CONCLUSIONS

The 2002–2010 Millennium Drought in Australia's MDB provides a "window to the future" in terms of the choices that many countries face when allocating water between consumptive and non-consumptive uses as inflows decline. Our study finds that despite the adoption of a basin plan in 2012 that provides for a reallocation of water to the environment, water consumption will, in the presence of droughts, likely continue to degrade river and floodplain landscapes and generate large losses in terms of amenity, cultural and existence values.

We find for the MDB that: (1) under normal inflows, reallocating a larger share of the water diverted for extractive uses to environment flows would reduce net profits proportionally much less than the decline in extractions; (2) during the Millennium Drought, very large declines in irrigated agricultural surface water extractions left the reported nominal gross value of irrigated agriculture virtually unchanged; and (3) if climate change were to reduce inflows by a similar amount to what occurred during the Millennium Drought, water planning that ensures the environment and irrigated surface water extractions decline by the same proportion has only a small effect on the value added in irrigated agriculture.

General insights from our study for other river basins include: (1) Irrigation water extraction drives basin-wide impacts in terms of regional river runoff; (2) the reallocation of water from extraction to environmental flows is critical to effectively respond to the effects of droughts and drying trends on riparian ecosystems; (3) in the presence of well-functioning water markets, the reallocation of water from extractive to non-consumptive uses can substantially reduce the adjustment costs on irrigated agriculture; and (4) equal-proportional reductions in extractions and environmental flows, an adaptation response to reduced inflows during droughts, can be achieved with only a small decline in the value added of irrigated agriculture.

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