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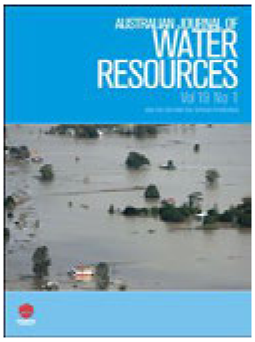

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ARTICLE

The three-infrastructures framework and water risks in the Murray-Darling Basin, Australia

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ABSTRACT
Using a three-infrastructures (grey, soft, and green) framework, we examined key risks to water availability and quality in the Murray-Darling Basin, Australia. These risks include increased irrigation efficiency, without a quantitative knowledge of the impact on water flow pathways, particularly return flows, growth in farm dams and floodplain harvesting, and unsustainable management of salinity. Critical to mitigating these risks are the metering, monitoring, and auditing of water flows, effective linkages between evidence and analysis, and accountability of decision-makers operating in the public interest. We contend that these approaches need to be supported by innovative risk assessments, which are fit-for-purpose under the MDB Plan, wherein the 'who, what, when and where' are assessed in relation to cumulative, systemic, and cascading risks from human actions.

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Water audits; water governance; climate change; grey infrastructure; soft infrastructure; green infrastructure; risk analysis

. . . management of the Murray-Darling has been compromised by 'very, very bad administration over the years by governments of both persuasions'.
Former Australian Prime Minister John Howard, 8 February 2021

1. Introduction

Much of the arid and semi-arid regions of the world, including the Murray-Darling Basin (MDB) of south-eastern Australia, are in a water crisis; extractions exceed the volumes that would prevent further deterioration of riparian environments (Haddeland et al. 2014). These excess water extractions provide private benefits but also impose external costs on others and inter-temporally from reduced streamflows, recharge, and deterioration of freshwater habitats.

A typical response to the ongoing water crises has been to build and to enlarge physical water infrastructure to store water inter-temporally, and to divert water from within the landscape. Much of the investments have been for 'grey' infrastructure, with some notable exceptions (Grafton and Wheeler 2018), to capture, to store, and to deliver water over time and across the landscape. Such infrastructure primarily supports direct use values of water, such as growing irrigated crops. Yet irrigation water extractions are a major contributor to the decline of Australia's inland waters (Green and Moggridge 2021).

Here, with a focus on the MDB, we evaluated water infrastructure risks that we define as the events or circumstances that may cause harm when they occur, such as excess water extractions or changes to return flows. We developed and employed a 'Three-Infrastructures Framework' (TIF) in relation to water infrastructure that includes one, 'grey' infrastructure, such as dams, groundwater wells, irrigation channels, levees and water delivery systems; two, 'soft' infrastructure (Grafton 2017), such as laws and regulations, water education, water markets and water planning that represents water governance; and three, 'green' infrastructure, such as the floodplains, stream and river channels, aquifers, wetlands and estuaries, that can potentially deliver multiple ecosystem services (Davies et al. 2012).

Using the TIF, we evaluated the Murray-Darling Basin Plan (MDBP) that was passed in the Australian Federal Parliament in November 2012, as mandated by the Federal *Water Act (2007)* (Commonwealth of Australia 2007). As written in the Water Act (2007), in relation to the MDBP, we evaluated:

(1) Risks to '. . . the condition, or continued availability, of the Basin water resources' from
(2) '(a) the taking and use of water (including through interception activities)' on
(3) '(a) environmental outcomes; (b) water quality and salinity; (c) long-term average sustainable diversion limits and temporary diversion limits; and (d) trading in water access rights'.

(Water Act (2007), Section 22 'Mandatory content of Basin Plan', Items 3 and 4)

Our evaluation examined the risks, the actual and possible consequences posed by irrigation water extractions, including farm dams, floodplain

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harvesting, and water delivery (both on- and off-farm) in the MDB. These risks were examined in relation to streamflows, return flows, and salinity.

Section 2 describes the TIF. Section 3 focuses on the MDB and is in three parts: part one explains the possible impacts of irrigation in relation to return flows of water to surface and groundwater, part two highlights the relationship between irrigation and salinity, and part three reviews the extent and growth in farm dams and floodplain harvesting. Section 4 highlights key knowledge gaps and possible ways to mitigate the risks to MDB water resources from irrigation. In Section 5 we offer our conclusions.

2. Three-infrastructures framework (TIF) and irrigation in the Murray-Darling Basin

Here, we describe the three infrastructures and connect them to water risks in relation to irrigated agriculture in the MDB. The components of the TIF include:

(1) *Grey (Hard) Infrastructure*: dams, channels, weirs, fishways, roads, railways, levee banks, culverts and bridges, and on-farm irrigation infrastructure; all of which serve to store, redirect, and change the nature and function of water flows and their ecological functions.
(2) *Soft Infrastructure*: governance (including auditing and compliance); regulation (including water management plans and their implementation); water markets and water trading both encompassing and exercising powerful influence of what happens with water in the MDB and how it is valued; education and awareness; and management (including the integrated use of both grey and green infrastructure).
(3) *Green (Natural) Infrastructure*: floodplains, wetlands, river channels, lakes and estuaries, soil, and water storage along with groundwater aquifers including the pathways of recharge and discharge that is critical to hydrological and ecological functions (Williams 2017).

How these infrastructures are integrated, governed, regulated, and managed affects the type and scale of risk on the availability and condition of water resources in the MDB.

2.1. Infrastructure systems in the MDB

Grey infrastructure in the MDB encompasses farm dams and intercepting infrastructures that enable floodplain harvesting (such as levees), as well as technologies that reduce water losses within irrigation systems (such as lining channels, better farm layouts, sprinkler, and drip irrigation). Soft infrastructure includes water resource plans, legislation, water entitlements and water allocations (Grafton, Horne, and Wheeler 2016a), audits, compliance, education and training, scientific research, and the many elements of water management, policy, and regulation. Green infrastructure includes the many elements of the MDB landscape that encompasses over 1 million km^2, from Queensland to South Australia. These assets include the billabongs, streams and rivers, estuaries, hills and mountains, and the hundreds of both small and large wetlands that provide a home to flora and fauna and that convey and store water through the landscape.

Well-functioning green infrastructure provides both private benefits (such as water supply from rivers for agricultural and domestic use) and social benefits (such as improved water quality for urban water services and maintaining cultural, recreational, and amenity values). While green and grey water infrastructure can complement each other in the delivery of water services (such as to reduce flooding events), the cost of engineered structures to completely replace nature-based assets is prohibitively expensive (Vörösmarty et al. 2021). That is, healthy wetlands and rivers in the MDB (Davies et al. 2010) provide much more to human societies than a network of concrete channels ever could. Further, ecosystem services from green infrastructure and nature-based solutions to water management are often not valued in water planning and policy in Australia (Hatton MacDonald et al. 2011), but their role in sustaining economic activities and human wellbeing is increasingly being recognised by government agencies (Wyrwoll and Grafton 2021; UNEP 2022; USACE 2022), multilateral organisations (WWAP/UN-Water 2018; Matthews and Dela Cruz 2022), and businesses (The Coca Cola Company 2021; Capitals Coalition 2022) around the world.

2.2. Risk management in the MDB plan

The MDBP (Australian Government 2012) defines three specific risks to the condition of Basin water resources:

(1) Insufficient water available for the environment and also to maintain social, cultural, Indigenous, and other public benefit values;
(2) Water of insufficient quality to be suitable for consumptive and other economic uses; and
(3) Poor health of water-dependent ecosystems.

The MDBP stipulates that water resource plans (WRPs) should respond to the following: (1) risks to the capacity to meet environmental watering requirements; (2) risks associated with groundwater; (3) risks arising from potential interception activities; and (4) risks arising from elevated levels of salinity or other types of water quality degradation (Australian Government 2012, p. 116).

A key feature of the MDBP is the allocation of risks associated with changes in future water availability between water users and governments. Namely, paragraphs 46–51 of the 2004 *National Water Initiative* specify: water entitlement holders should bear the risk of less reliable allocations from seasonal or long-term changes in climate and periodic green events, such as bushfires (Akter and Grafton 2021), but governments bear the risk from changes in government policy.

Cumulative and interconnected risks have been identified as *complex risks* (Simpson et al. 2021) that include *cascading risks* that spread across interdependent systems via feedbacks, possibly at a global scale (Helbing 2013); *interconnected risks* that involve interactions among human-environment-technological systems (Pescaroli and Alexander 2018); and *systemic risks* that may lead to complete system failures (Renn et al. 2019). In the context of water management, complex risks are evident in the 'Water-Food-Energy Nexus' (Grafton, Horne, and Wheeler 2016b), and climate change (Pittock, Hussey, and Dovers 2015). A notable danger is to treat risks as separate and disconnected such as when the impact of upstream extractions on town drinking water supplies during a drought are either ignored or ineffectively mitigated (Australian Academy of Science 2019).

Figure 1 highlights the possible interactions between water infrastructure systems in the MDB and the alternative pathways through which risk is caused, allocated, and managed. Grey infrastructure responds to the policies, regulations, and other incentives defined by soft infrastructure. Grey infrastructure, in turn, affects the health and functioning of green infrastructure via changes to streamflows, return flows, and other hydrological processes. Soft infrastructure can be both a risk source (e.g. subsidies for irrigation construction or lack of floodplain harvesting regulation) or a risk control (e.g. monitoring and enforcement to prevent illegal grey infrastructure construction or environmental policies to support the functions of green infrastructure). Similarly, grey infrastructure can cause risks by reducing the quantity of water available to green infrastructure or may support the control of risks, such as salinity and flooding. Green infrastructure provides services to grey, including water supply, and can support the capacity of grey infrastructure to provide benefits under risks (e.g. droughts and floods).

Different types of infrastructure provide different benefits to various water users and their communities. For example, grey infrastructure in the MDB provides mainly private benefits to a sub-set of water users, while green infrastructure, typically, provides a mix of public and social benefits to many water users. Importantly, the complex interactions among water users, communities, and decision-makers influences both the size and distribution of the possible benefits. Further, interactions and feedbacks between infrastructure systems and water users change over time depending on what values are prioritised and who has power and influence over the 'who, what, when and where' of the allocation of water (Grafton et al. 2021). External drivers, such as climate change and market forces, also affect the capacity of grey and green

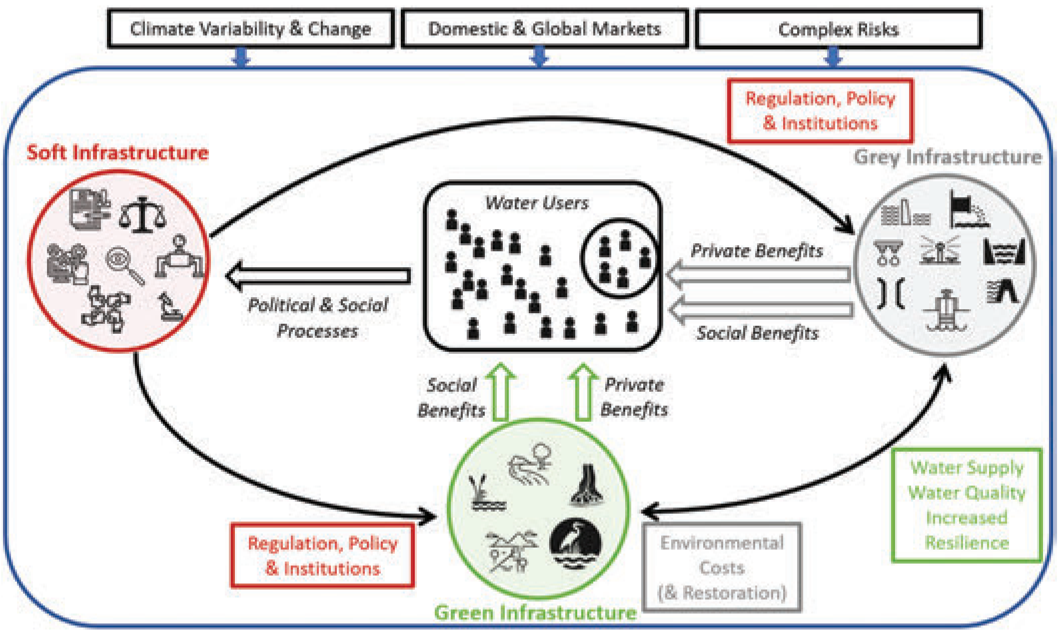

Figure 1. Emergence and management of complex risks and the three infrastructures of the Murray-Darling Basin. (Icons downloaded from the Noun Project (https://thenounproject.com/) under a Noun Pro member licence.) Source: Wyrwoll and Grafton (2022).

infrastructure to deliver benefits and may promote changes to both soft (e.g. water resource plans) and grey infrastructure systems (e.g. dams) in response.

An important distinction between grey and green infrastructure in the MDB, and more broadly, is whether and how their respective benefits are valued in policy and society. Many of the benefits of grey infrastructure for agriculture, such as irrigation water and crop production, can easily be measured through market transactions. Access to on- and off-farm irrigation infrastructure increases the value of agricultural land, thereby capitalising these assets into the value of a tradeable factor of production (Thiene and Tsur 2013; Dent 2014). Although the MDB's green infrastructure is fundamental to all water users and uses, the goods and services it provides beyond water supply are not typically traded. For example, aquatic ecosystems cannot be bought and sold at a catchment scale. While the economic values of the MDB's green infrastructure can and have been estimated (e.g. Hatton MacDonald et al. 2011; Akter, Grafton, and Merritt 2014), these values are rarely, if ever, incorporated into decision-making. Rather than a source of economic and social benefits, the MDB's green infrastructure and its health are considered constraints and costs in a trade-off with the main priority: maintaining or expanding the mainly private benefits provided by grey infrastructure. The Sustainable Diversion Limit Adjustment Mechanism (see MDBA 2022a), a policy program to improve the 'efficiency' of environmental water delivery and thereby reduce the volume of water recovered from irrigators, illustrates how a 'market transactions' perspective is implemented and which has important consequences for how risks are perceived and managed.

3. Irrigation and infrastructure risks in the Murray-Darling Basin

Figure 2 provides a map of the major wetlands, dams, irrigation districts and towns in the MDB. Irrigated agriculture comprises only about 3% of the agricultural land in the Basin but accounts for some 95% of the water consumed (MDBA 2017a, p. 19), while contributing more than AU$8.6 billion to the Australian economy (ABS 2019a; Horne 2021). Most of the water extracted is in the southern part of the Basin and in three large catchments: the Murrumbidgee, Murray

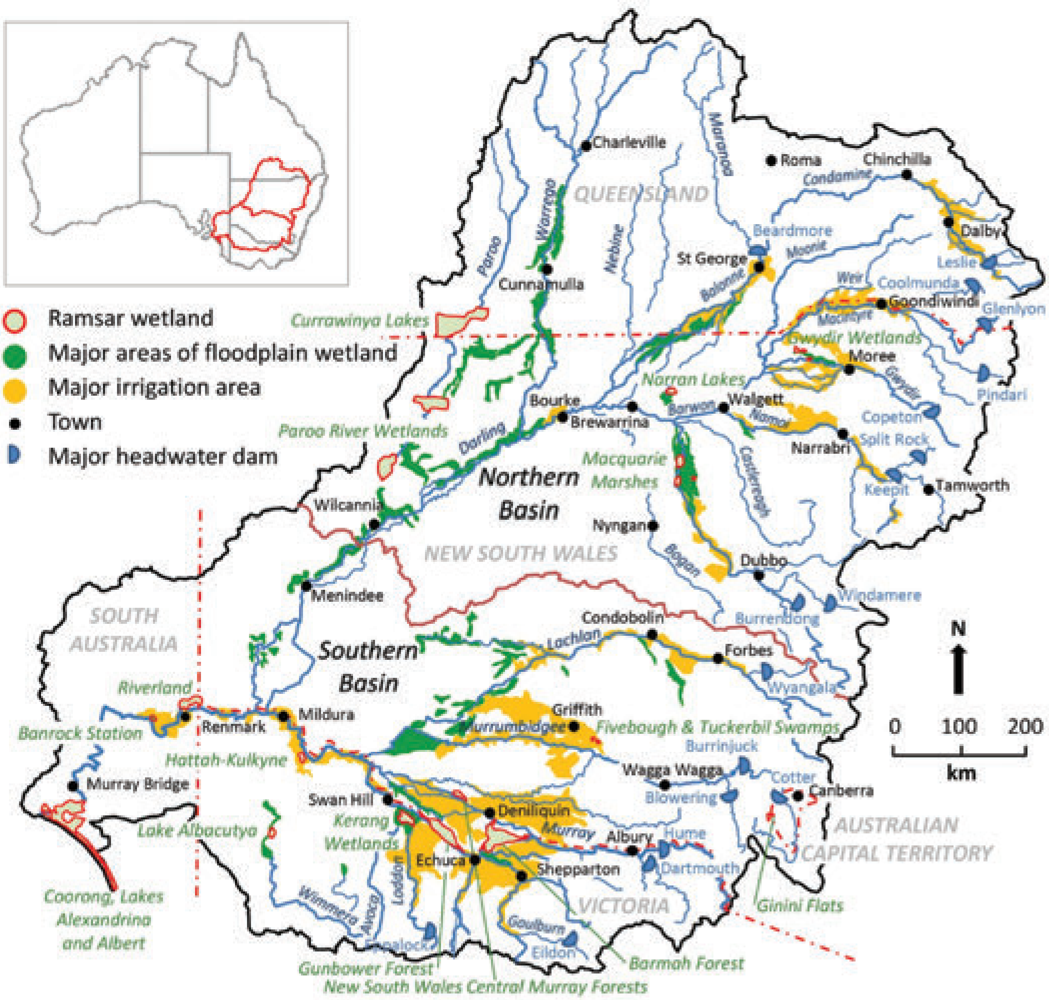

Figure 2. Map of the Murray-Darling Basin, showing irrigation areas, wetlands, and major regional centres.

and Goulburn Broken. In these catchments, much of the irrigation is supported by large public-owned water storages, such as the Dartmouth and Hume Dams, and through thousands of kilometres of canals that convey water to large irrigation districts with many irrigators.

The northern and southern MDB differ hydrologically as do the type of irrigation practices (Wheeler and Garrick 2020). The main irrigated crops in the southern MDB are pasture, hay or silage, cereals, fruit and nuts, rice, and grapes, while in the northern Basin pasture and cotton dominate (ABS 2019b). In the northern MDB, irrigation is, typically, practised through direct pumping from rivers by each irrigator to large farm dams, or by the capture, storage, and use of flood waters with levees and dams.

Groundwater use for irrigation depends on surface water availability. In 2019–20, it was about 24% of the total irrigation water extracted (BOM 2020) but was 12% in 2014 and 7% in 2012. In some northern MDB catchments, and in drought years, the proportion of water extracted for irrigation provided by groundwater may exceed 30% (MDBA 2016).

3.1. Irrigation infrastructure affects water cycle and risks to streams and groundwater availability

Irrigation influences the hydrological cycle in multiple ways, including through substitution between surface and groundwater; the conveyance of the water to fields; the return of water via seepage, leakage, and recharge to streams and groundwater; and through its evapotranspiration of irrigated crops. These are shown in Figure 3 and defined below.

The approximate magnitude of these flows in the Murray-Darling Basin were computed as follows: (1) The water extractions under current development and historical climate for irrigation is from CSIRO (2008) with surface extraction of 10,075 GL/year on page 30 and groundwater extraction of 1,832 GL/year found on page 47.

(2) The water losses from water extraction are given in Table 4, page 10 of Williams (2003) and Rendell et al. (2020), Figure 5, page 35. Percentage of water extraction delivered to regional irrigation area, farm boundary, farm field, and soil profile was approximately 75%, 60%, 50% and 36%, respectively. The crop transpiration was set to range from 18% to 26% of water extraction (Williams 2003, p. 10).

(3) The evaporation on-farm and off-farm were estimated from CSIRO and NSW Government (2005) as from 29% to 54% of total losses.

(4) A supplementary data worksheet is available which sets out details of each estimation of water flow shown in Figure 3.

These flows include:

(1) ***Non-beneficial consumption***: water evaporation and water transpired for purposes other than the intended use, such as transpiration from foliage (e.g. weeds and riparian vegetation) along with direct evaporation from water storages, canals, and soil surfaces.
(2) ***Beneficial consumption***: beneficial transpiration by irrigated crops. For the MDB, the beneficial consumption in transpiration ranges from around 2,143 to 3,095 GL/year. The historical long-term water extractions for the

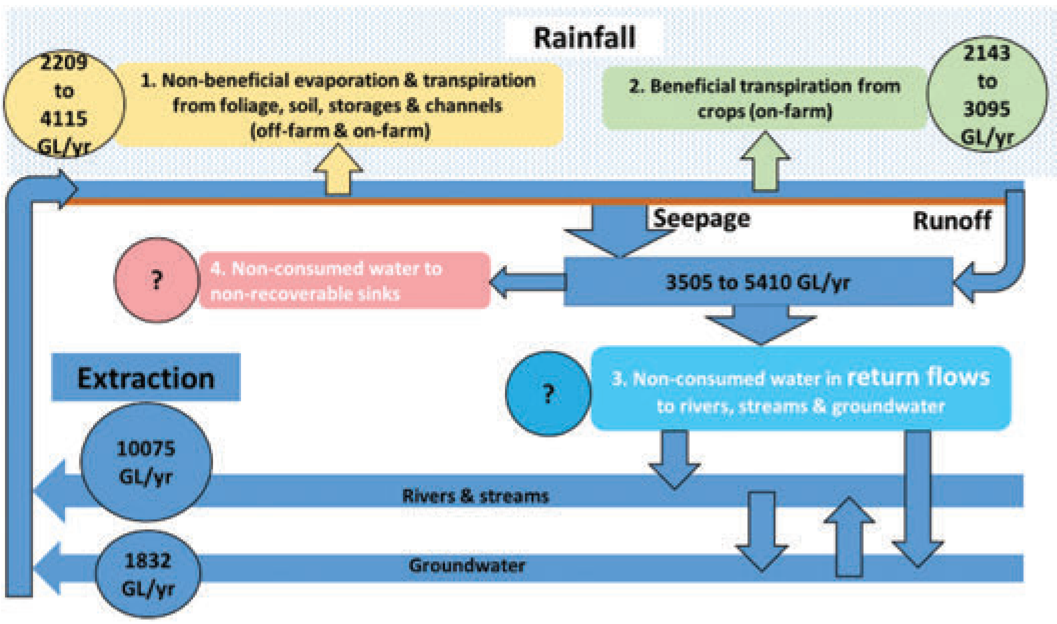

Figure 3. Illustration of the pathways of water flows and the water consumed in an irrigation district using the terminology of the International Commission on Irrigation and Drainage (Perry 2011). The approximate magnitude of these flows in the Murray-Darling Basin are derived from data in Williams (2003), CSIRO (2008), Rendell et al. (2020) and CSIRO and NSW Government (2005).

MDB are some 10,075 GL/year of surface water and approximately 1,832 GL/year of groundwater (CSIRO 2008) with non-beneficial consumption in evaporative and transpiration flows estimated to range from 2,009 to 4,115 GL/year.

(3) ***Non-consumed and recoverable water***: water that can be captured and later reused and, thus, at a Basin scale these are not water 'losses'. This would include non-consumed water in return flows of runoff to surface water systems, water in the soil profile and deep drainage beneath the root zone to groundwater systems, which usually then discharge to streams and wetlands. Surface runoff is usually captured in surface drains and reused or flows back to the river, together with escapes losses (water ordered but not used) as return flows. Return water flow to streams and rivers may also occur through groundwater aquifers depending on the water levels and degree of connectivity between groundwater and the stream. If some of this return flow enters a groundwater aquifer which has little or no flow to the river, the return flows from deep drainage must accumulate in the groundwater aquifers. Estimates of total return flows for the MDB are unavailable, but an estimate of the total seepage and runoff which generate both the return flows and the non-recoverable flows range from 3,505 to 5,410 GL/year.

(4) ***Non-consumed and not recoverable water*** is water that is 'lost' and no longer available at the Basin scale. It includes water flows to saline groundwater sinks and deep aquifers that are not economically exploitable. We are not aware of any estimates of these losses at the scale of the MDB.

As shown in Figure 3, the beneficial consumption of water as crop transpiration is only one of the multiple water flows. Irrigation efficiency is defined as the ratio of beneficial water consumption to the water extracted for irrigation or the volume of water applied to irrigated fields. Efficiency will always be less than 100% because of non-beneficial water flows via evaporation to the atmosphere (losses), and non-beneficial and recoverable water in return flows to rivers and streams via surface drainage and seepage to groundwater systems. When defining irrigation efficiency, the spatial scale is important because what may be considered a 'loss' at a farm level (e.g. return flow to a stream or river or to groundwater aquifers) may represent a gain to downstream water users depending on the quality of the 'lost' water returning to the stream or groundwater systems (Grafton et al. 2018).

3.1.1. Water losses

Losses in irrigation systems vary across the MDB within the framework of the broadscale magnitude of flows, as depicted in Figure 3. As far as we are aware, the MDB lacks a quantitative water balance where all flow components are quantified (see Figure 3). Nevertheless, Khan et al. (2005) and Khan et al. (2006) have calculated quantitative water balances for the Murrumbidgee Irrigation Area (MIA) at a sub-Basin scale. They reported losses (in the MIA) totalling 230 GL/year, comprising off-farm losses of 130 GL/year and 100 GL/year as on-farm losses. For the Coleambally Irrigation Area (CIA), they reported 30 GL/year as off-farm losses and 60 GL/year as on-farm losses. These losses have been reduced substantially due to on-farm and off-farm improvements. Paydar, Gaydon, and Chen (2009) used simulation modelling for different soils, crops and watertable depth to upscale on-farm losses in the CIA and reported 17.9 GL as deep drainage losses and 7.2 GL for runoff losses under irrigation.

At the scale of the MDB, an imprecise estimate of the losses in the whole irrigation delivery system (Kirby et al. 2010) showed a possible saving of 300 to 450 GL by improving the irrigation water delivery system through reducing seepage and leakage from channels in years of average diversions, but less in drier years. Measures that include engineering and technological solutions (grey infrastructure) as well as improvements in plant breeding, irrigation scheduling and strategies to use less water on-farm (such as soil tillage and farm layouts for less losses, deficit irrigation, and partial root zone drying) can improve the measurement and control of water in irrigation.

3.1.2. Irrigation efficiency

Grey infrastructure that increases irrigation efficiency includes lining of irrigation channels or replacing open channels with pipes that may reduce both evaporation and return flows and the conversion from surface irrigation to pressurised systems (e.g. drip and sprinkler) that reduce return flows. In the MDB, for example, the irrigation efficiency of growing cotton has increased with the use of irrigation scheduling tools and furrow-irrigation system optimisation reducing deep drainage losses (Roth et al. 2013). Notably, this has not been associated with either a reduction in water extractions or water consumption for growing cotton within the MDB.

Irrigation alters the water balance and the water flows by changing how water is consumed (beneficially or not). This, in turn, has consequences for both surface and groundwater flows. In the southern MDB, for example, irrigation has changed the seasonal variation and pattern of flow, reducing the spring peak flows, and increasing flows in summer when water is needed for irrigation (Khan, Ahmad, and Malano 2008). As a result, there has been an increase in evapotranspiration (crop water use) and higher watertables, which in arid and semi-arid regions like the MDB, can result in land salinisation and water quality degradation.

Irrigation efficiency influences both the quantity (flow patterns and volumes) and quality of the return flow of water to streams and rivers. For the MDB, this is estimated to vary from as little as 1% to 20% of the diverted water in the southern part of the Basin (van Dijk et al. 2006). EarthTech (2003) reported an indicative return flow value of 760 GL from the CIA, Shepparton, and MIA in the southern MDB, and projected that return flows could be halved from 2003 to 2023 because of increases in irrigation efficiency, decline in water availability, increase in waterlogging, and from salinity control and reuse of drainage water.

More than AU$5 billion has been spent to date in the MDB (Grafton and Wheeler 2018) to increase irrigation efficiency through a series of subsidies for on- and off-farm efficiency improvements. Increases in irrigation efficiency provide private benefits to subsidy recipients but also generate external costs on others and environmental losses from reduced streamflows. For example, Hughes, Donoghoe, and Whittle (2020) studied the effect of the federal government funded *On-Farm Irrigation Efficiency Program* on participating farms. A total of 1,580 projects were studied with a total funding of AU$499 million and an estimated 150 GL of water recovered to increase streamflows. In this study, on-farm programs were found to generate benefits for participating farms (higher productivity and higher profits). Such programs also resulted in a rebound effect such that farm water demand *increased* following a grey infrastructure upgrade. Hughes, Donoghoe, and Whittle (2020) found not only an increase in farm water demand and area irrigated but also an increase in net allocation and entitlement trade post-upgrade.

Similar findings of a rebound effect in irrigated agriculture, in relation to water extractions following grey infrastructure upgrades, were obtained from surveys of irrigation farmers in the MDB (Wheeler et al. 2020). This is also true at a global level, where in a review of 230 cases, Pérez-Blanco et al. (2021) found that in 70% of the cases increases in local irrigation efficiency reduced water availability elsewhere. They also found that actual savings were only achieved in 11% of cases, either because controls on access to water were introduced or because return flows were not recoverable. Both sets of findings highlight the importance of regular monitoring of changes in return flows and robust estimates of the effects of water infrastructure on the availability of downstream surface water and future groundwater.

We highlight that there are two related but separate processes at work in terms of the hydrological impacts of increased irrigation efficiency. First, is the *physical* effect in which as irrigation efficiency increases, beneficial water consumption rises. Second, is the *economic* effect, a type of 'rebound effect', that occurs because, in the Murray-Darling Basin, the constraint cap is on water extractions, not water consumption. That is, the demand for an input into a production process (such as water to irrigate crops) increases as the input becomes more productive, all else equal. In the case of water and irrigation efficiency, this occurs because the production per unit of water *delivered* to the farm increases in parallel with irrigation efficiency. Improved irrigation infrastructure, which often involves piping water rather than using open channels, has also ecological consequences associated with the loss of open water for some water-dependent species (Baral et al. 2014).

All these sets of findings highlight the importance of regular monitoring of changes in return flows and robust estimates of the effects of water infrastructure on the availability of downstream surface water and future groundwater for a diversity of ecological function in the landscape.

3.1.3. Return flows

At the Basin scale, the reduction of return flows associated with government subsidies for increased irrigation efficiency have been estimated at between 490 and 630 GL/year (Williams and Grafton 2019) and between 130 and 565 GL/year (Walker et al. 2021, Table IV). To have such a large unknown value (see Figure 3) in the MDB poses a critical management risk and especially in relation to public subsidies intended to increase irrigation efficiency (Grafton 2019).

Fundamental to effective water management is to have accurate measures of water flows and an understanding of what these flows do (Batchelor et al. 2017). For example, if seepage water from irrigation enters a groundwater aquifer, it must remain stored in the aquifer if it does not subsequently flow to streams and rivers or used in evapotranspiration (see Walker et al. 2020, Table I). Without an appropriate set of independently audited water accounts (Molden 1997; Molden and Sakthivadivel 1999; Clemmens and Molden 2007; Karimi, Bastiaanssen, and Molden 2013) to identify where the water is and who gets the water and when, following changes in grey and soft infrastructure, decision-makers are 'flying blind' (Grafton and Williams 2019a) and cannot know whether the intended outcomes (e.g. increased streamflows from subsidies for irrigation efficiency) are realised or not.

3.1.4. Water accounts

The National Water Account for the MDB only reports a point irrigation return figure of a small amount (238 GL, compared to 4,223.7 GL of diversions for irrigation in 2019–20). Notably, this return figure is only for the CIA to the Murrumbidgee River and the Broken Creek and Torrumbarry Irrigation Areas to River Murray (Figure S4 in the National Water Account, 2019–20). Return flows from the water used for the environment is reported to be 688.9 GL.

van Dijk et al. (2008) reported 'unaccounted losses' of up to 15,000 GL in a given year and that could not be attributed to the components of water accounts. These are very large volumes of water that occur at high flows in the system (Paydar and van Dijk 2011). Other factors, such as droughts, can have a material effect on return flows associated with lower water extractions, decreased connectivity between surface and groundwater systems, and increased incentives to improve on-farm irrigation efficiency.

3.1.5. Climate change

Grafton et al. (2022) show that for the northern MDB over the period 1981–2020 there has been an increase in average surface temperature of 0.26°C per decade and a decline in precipitation of 11 mm per decade. Projected changes in climate and water availability (CSIRO 2008; Leblanc et al. 2012; Whetton 2017; Alexandra 2021; Prosser, Chiew, and Stafford Smith 2021) suggest that there will be further hydro-ecological responses in the MDB on both streamflows, water availability, and return flows.

Climate model projections for the future (mid-range climate change to 2030), in particular, show a decrease in rainfall, particularly in the southern half of the Basin, as global average temperatures rise (CSIRO 2008). Under this projection, there would be a median decline of river flows by 11% for the entire MDB and a subsequent average decline of surface water use by 4% with much variation in regions (up to 50% reduction in Victorian regions). Under the dry extreme climate, surface diversions would fall by over 70% in the Murray system and 80–90% in Victorian regions (CSIRO 2008; Whetton 2017), while groundwater use is projected to increase from 16% of the total water use (in 2008) to over 25% by 2030. More recent studies (Alexandra 2022 - this edition) confirm the high likelihood of future drier conditions, more frequent droughts, and below-average rainfall resulting in lower streamflow and water availability for all water users in the MDB.

3.1.6. Cropping patterns

Changes in the area of irrigated perennial crops, particularly tree crops, can generate important impacts on both streamflows and water availability. For example, the area of perennial tree crops has grown substantially over the past two decades in the downstream parts of the Murray River. Irrigated horticulture, including almond plantings, is a significant land use in the Lower Murray-Darling (LMD), with a continually expanding footprint and a constantly changing profile. From 2003 to 2018, the irrigable area increased by 52,315 hectares. From 2015 to 2017, there was an increase in permanent plantings of 11,060 hectares, an increase in seasonal cropping of 12,585 hectares and a decrease in areas not irrigated by 9,405 hectares (MDBA 2019).

Loch, Adamson, and Auricht (2019) estimate that, as a consequence of recent almond plantings, the additional *minimum* requirement to ensure the survival of the trees has grown from 85 to 120 GL in 2007 to between 176 and 244 GL by 2020. Notably, the almond plantings have contributed to a large transfer of water downstream with most of this water conveyed during the summer months.

3.1.7. Water trading

Higher summer streamflows due to water trading impose delivery challenges where, due to the green infrastructure (such as at the Barmah Choke), streamflow is constrained (Davies 2019). Water trading across regions and states is an important response to risk, especially during droughts (Grafton, Horne, and Wheeler 2016a). In 2019–20, water market turnover in the Murray-Darling Basin was AU$6.6 billion with 6,952 GL of surface water and 474 GL of groundwater being traded (BOM 2020) and with a total value of all water entitlements of some AU$26.3 billion (ACCC 2021).

Much of the claimed market failures around water markets in the MDB are attributed to water governance problems rather than problems with the markets themselves (Wheeler 2022). The overall direction of inter-state net trades of physical volumes of water within the MDB are shown in Figure 4. Almost 90% of the physical water volumes traded was downstream from Victoria and New South Wales (NSW) to South Australia.

3.2. Irrigation infrastructure risks for salinity

Irrigation affects water quality through salt and nutrient flows by altering return flows to surface drainage and streams or the groundwater. For example, surveys have indicated that most of the nitrate and much of the phosphate exported from the Goulburn Broken and Lower Murray regions are from return flows from irrigated dairy and horticultural areas (Khan, Ahmad, and Malano 2008; Khan et al. 2008).

When drainage beneath the root zone is sufficiently large to keep the root zone salt levels low, salt is transferred to groundwater aquifers where it may accumulate, or it may move and discharge to drainage systems or streams and rivers. These streams and rivers either deliver the salt to the ocean or the salt will need to be stored indefinitely in the landscape. The work of Biggs, Silburn, and Power (2013) showed, for the Queensland catchments of the MDB, that the

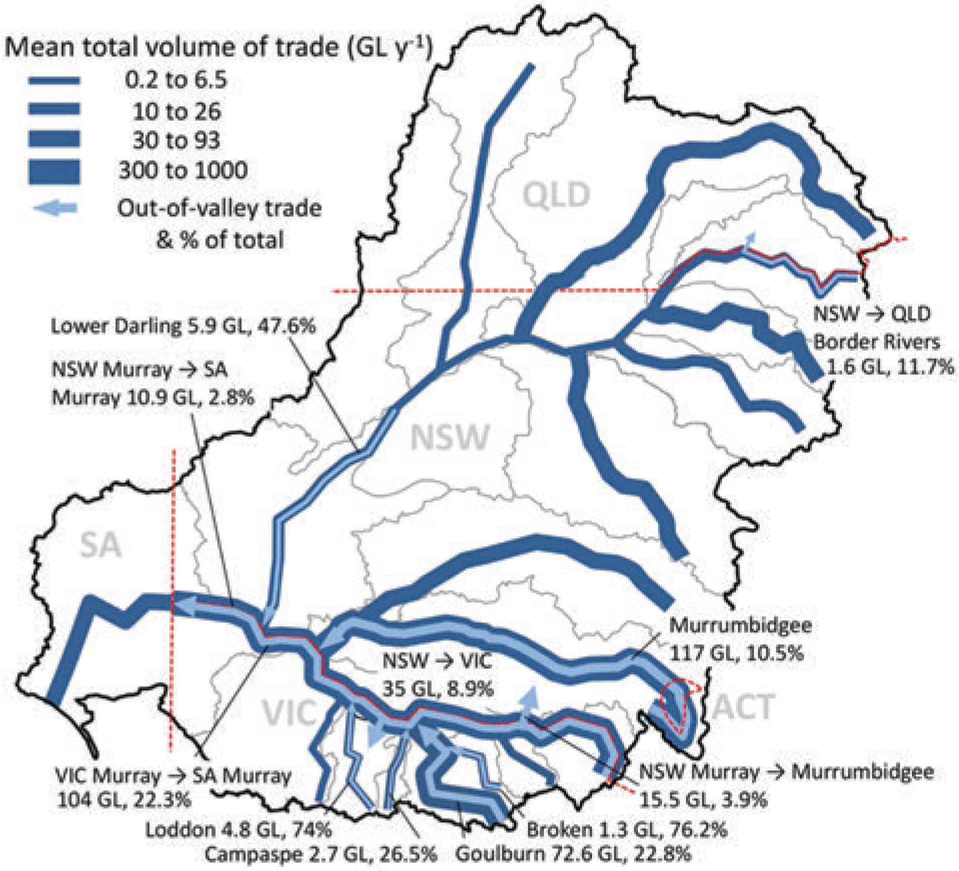

Figure 4. Mean annual net total volume of inter-valley and inter-state allocation trades in the Murray-Darling Basin, 2018–19 to 2020–21. The volume (GL) of out-of-valley trade and the percentage this represents of the total valley trade is stated for each major valley. (Based on data downloaded from the Bureau of Meteorology (BOM 2022) Water Information, Water Markets Dashboard, Murray-Darling Basin.) http://www.bom.gov.au/water/dashboards/#/water-markets/national/state/at.

average annual streamflow salt export is generally much less than salt input. This is the case even when atmospheric inputs alone are considered and is strongly influenced by episodic, large events. It appears that, in general, the natural status of these Queensland catchments is one of salt accumulation and significant hydrologic change (Biggs, Silburn, and Power 2013).

In many irrigation regions, the increased rates of leakage and groundwater recharge cause the watertables to rise. Rising watertables, in turn, bring salts into the plant root zone and the salt remains behind in the soil where water is taken up by plants in evapotranspiration or is lost to soil evaporation. Salts in the water are then deposited as the water evaporates, causing salts to accumulate at the soil surface. Salt dynamics, such as the soil type, quality of irrigation water, irrigation system, and plant type, all influence salinity build-up in the soil (Shahrokhnia and Wu 2021).

In irrigated soils, when drainage does not meet leaching requirements (i.e. the quantity of extra irrigation water that must be applied above the amount required by the crop to maintain an acceptable root zone salinity), the quality and quantity of the irrigation water will result in salt accumulation. Soil salinity may also result from poor drainage or a shallow watertable; physical and chemical soil conditions that reduce leaching of salts from the soil profile; poor irrigation quality; topography; and saltwater intrusion.

A major salinity risk for MDB water resources is that grey infrastructure projects to increase irrigation efficiency, such as drip irrigation, may contribute to the build-up of salt in soils. Notably, to maintain a sustainable salt balance in the root zone of crops, a leaching fraction is required (Rhoades 1974), where the depth of drainage water moving below the root zone needs to be approximately 10–30% of the depth of the applied water in irrigation to maintain a healthy salt balance in the root zone (Shahrokhnia and Wu 2021, Figure 7 therein). Leaching is essential in irrigated croplands where natural precipitation is insufficient to control salinity build-up. It is also critical that such leaching and movement of salt to rivers and streams be carefully managed, such that stream and river flow regimes dilute the salts and transport it to the oceans. The use of green infrastructure and soft infrastructure to manage streamflow to dilute salt inflows from both the landscape and grey irrigation infrastructure and to transport salts safely to the oceans has not been given the attention it requires under the current MDB Plan. Instead, the focus has

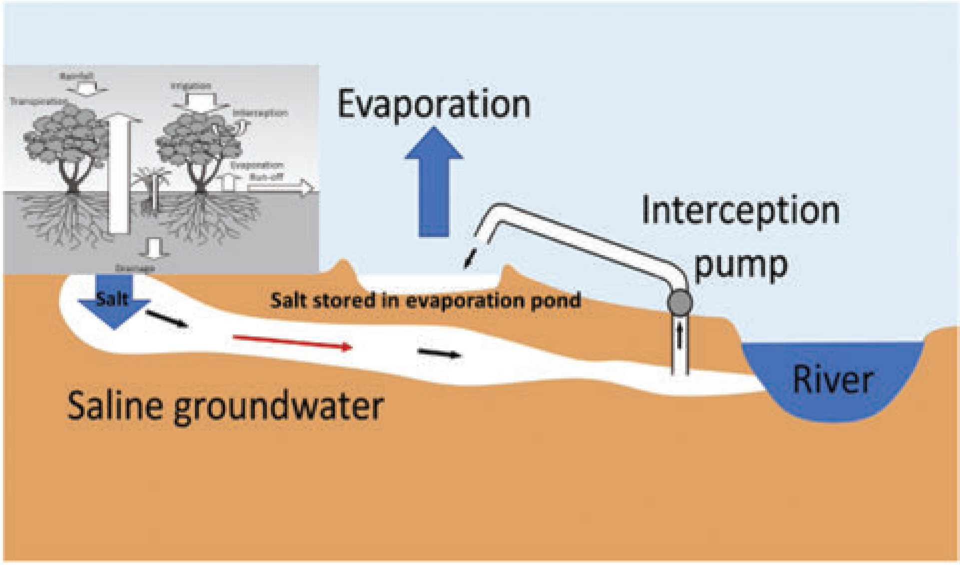

Figure 5. Schematic diagram of a salt interception scheme (redrawn from Williams, Walker, and Hatton 2002).

been on grey infrastructure salt interception schemes within irrigation districts (Hart et al. 2020).

In these salt interception schemes, depicted in Figure 5, saline groundwater is intercepted with energy-intensive grey infrastructure and diverted to regional disposal basins, where it is concentrated by evaporation and possibly stored indefinitely in the landscape. While some of the salt is used for commercial purposes, the biggest proportion remains in the landscape and will, in the absence of remedial actions and indefinite maintenance, pose a significant risk of eventually being mobilised and move into regional groundwater systems.

The water evaporated in salt interception schemes is essentially extracted from the green infrastructure and, thus, consumed. In a liquid form this water could have provided a range of other benefits if whole-of-river flow regimes, using soft and green infrastructure, had been used to dilute the salt and manage its safe transport to the oceans. Importantly, Khan et al. (2008) explored several interventions at a farm scale, such as evaporation ponds and serial biological concentration of salts to reduce salt soil build-up. Khan et al. (2008) showed that, with careful management of flows in tributary streams, salt can be effectively managed at a farm scale. While their methods were trialled and tested in the MDB, they have not yet been widely adopted.

3.3. *Farm dams and risks of floodplain harvesting to streamflows*

3.3.1. *Farm dams – status of risks in 2004 and 2021*

Growth in the number of farm dams was one of the six risks to shared water resources requiring attention, as highlighted by van Dijk et al. (2006). These authors make the important distinction between small dams storing a few megalitres of water for stock and domestic consumption and much larger dams used for irrigation of crops and pastures that intercept overland flow and capture floodwater; commonly referred to as floodplain harvesting.

For every 1 ML of farm dam capacity, there is an estimated decrease in streamflow of 1–1.3 ML (Neal et al. 2002). Nathan and Lowe (2012) estimated the impact per ML of storage in the range of 0.3–1.1 ML reduction in annual streamflow (mean of 0.84 ML in Victoria), with twice as much during summer. In a catchment such as the Gwydir, with a dam density on the floodplain of nearly 50 ML/km^2, this translates to a potential reduction of inflows in the order of 920 GL; noting that inflows under current water resource development and recent climate are 1,105 GL/year (CSIRO 2008, Appendix A therein).

The density of farm dams (ML per km^2) has increased substantially since 2004, especially in the northern Basin (Figure 6). Pre-2004, only three catchments in the southern Basin had high dam densities and only one in the northern Basin. By 2015–21, this number had increased to six catchments each in the southern and northern Basins (Figure 6). In the northern Basin, densities of farm dams (2015–21) varies from 11.6 ML/km^2 (Macquarie) to 39.8 ML/km^2 (NSW Border Rivers) to 48.7 ML/km^2 (Gwydir).

In 2004, there were an estimated 502,819 hillside farm dams in the Basin, with a total storage capacity of 2,213 GL; an increase of 37% between the Cap on diversions in 1995 and 2004 (Agrecon 2005). In a more detailed study in 2005 covering about half of the MDB, 519,931 artificial water bodies were identified in the eastern Basin catchments (covering 509,000 km^2), the vast majority of which were small farm dams (<0.1 ha); an increase of 31,206 since 1994

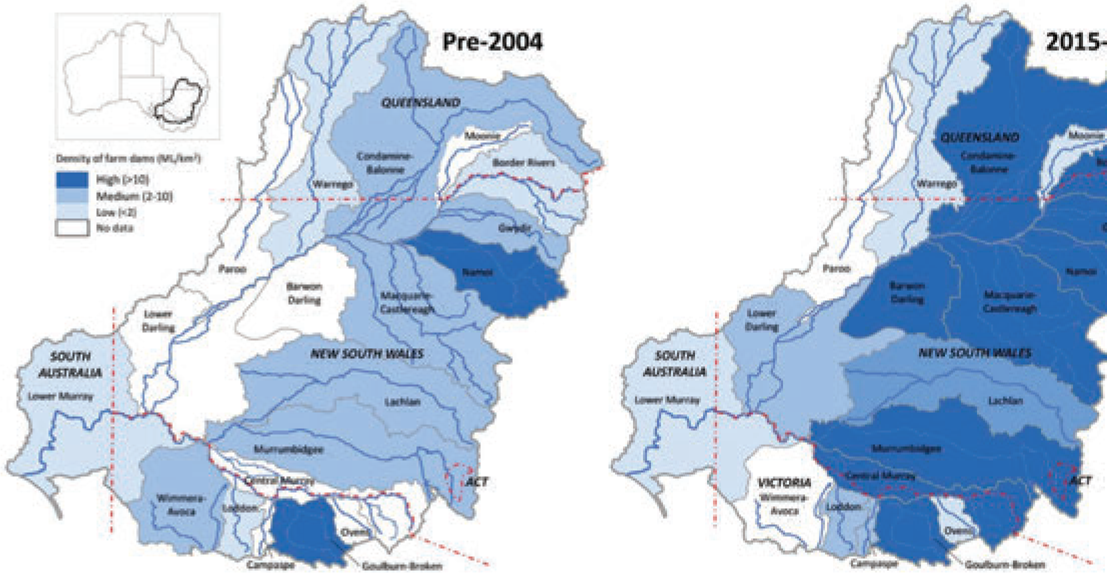

Figure 6. Estimated changes in density of farm dams (in megalitres of storage capacity per square kilometre) in the catchments of the Murray-Darling Basin prior to 2004, and between 2015 and 2021. Based on data collated from EarthTech (2003); Agrecon (2005); MDBC and Geosciences Australia (2008); SKM, CSIRO, and BRS (2010); Slattery & Johnson (2021) and Brown et al. (2022).

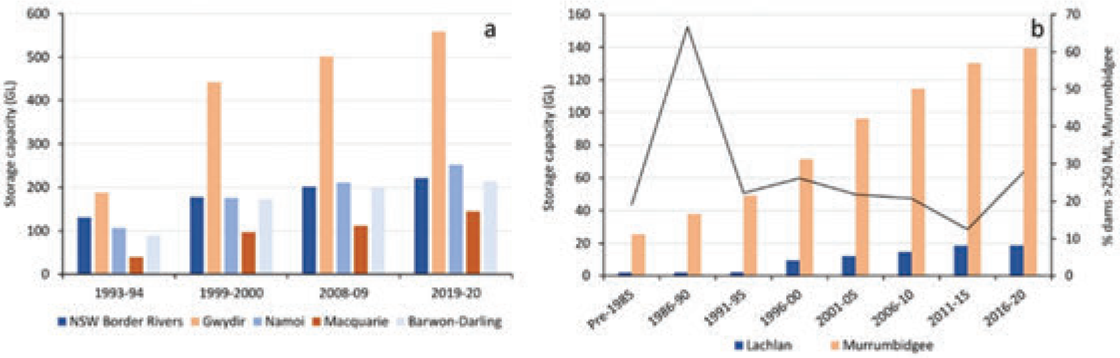

Figure 7. Growth in storage capacity of farm dams in the Murray-Darling Basin catchments where floodplain harvesting is practised: a) catchments in the NSW northern Basin; b) the Lachlan and Murrumbidgee catchments in the southern Basin. Black line = percentage of total dams in the Murrumbidgee larger than 250 ML capacity.

(MDBC and Geosciences Australia 2008). The highest rates of increase over the decade ending 2005 were all in northern Basin catchments: the Condamine-Balonne (18%), Namoi and Moonie (13%) and Gwydir (12%).

Rates of growth in the number and size of farm dams have varied markedly between and within catchments (MDBC and Geosciences Australia 2008). Periods of rapid growth in farm dams have occurred during droughts (van Dijk et al. 2006) and also immediately following the Cap on diversions in June 1995 (Brown et al. 2022) and, more recently, in the Lower Murrumbidgee and Lachlan catchments due to new plantings of nut crops (cf. Section 3.3.3. below). The highest farm dam densities within the Basin are located within peri-urban localities, indicating more rapid expansion in these areas than elsewhere (SKM, CSIRO, and BRS 2010). Malerba, Wright, and Macreadie (2021), in a national mapping exercise (2018–19), estimated NSW had the highest number of farm dams (655,000; 37% of the total), with a storage capacity of 4,270 GL, and the most rapid growth occurring between 1998 and 2000.

From 2015 to 2030, increases in farm dam volumes of 5–10% were projected for the MDB locations in NSW, with 10–16% in Victoria, and only 0.01–5% in Queensland (SKM, CSIRO, and BRS 2010, Figure 10 therein). We contend these figures underestimate the actual increases because they are based on the unjustified assumption that there would be no expansion of floodplain harvesting in the northern Basin catchments.

3.3.2. Floodplain harvesting

A risk caused by larger farm dams is floodplain harvesting – the diversion and storage of rainfall runoff and overland flows to large, custom-built dams and temporary storages – widely practised by irrigators, particularly (but not exclusively) in the northern Basin (Steinfeld and Kingsford 2011). By reducing volumes of river flows, floodplain harvesting has negative effects on downstream water users and the environment (Brown et al. 2022). The volume of these mostly unlicensed diversions is not measured or accounted for accurately under the Basin Plan, creating a major source of uncertainty and risk over water availability and use, as emphasised in the National Water Initiative (NWI) Interception Position Statement: ' . . . activities which use unaccounted water present a risk to the security of water access entitlements and the achievement of environmental objectives for water systems. These activities therefore urgently need to be accounted for in planning and regulation regimes'. (SKM, CSIRO, and BRS 2010, p. viii). Despite this uncertainty, the NSW Government is attempting to licence and regulate floodplain harvesting (DPIE 2021) and these attempts are currently the subject of an NSW Parliamentary Inquiry (NSW Parliament Legislative Council 2021).

The estimated floodplain harvesting storages in 2008 in the northern MDB were 2,575 GL, with 950 GL in NSW and 1,625 GL in Queensland (SKM, CSIRO, and BRS 2010). The authors of this report claimed: 'Floodplain harvesting is not likely to expand; there are moratoriums in place in the relevant river basins to restrict construction of new storages' (p. ii). Our analysis presented in (Figures 7 and 8) indicate otherwise. The information we present in Figures 7 and 8 is based on data compiled from mapping locations of on-farm storages by date of construction using the historical imagery function in *Google Earth Pro* and estimating contemporary surface area of storages greater than 0.56 ha in area. The estimated total storage volume was then derived by multiplying the surface area by an estimated average depth of 2.5 m.

Brown et al. (2022) assessed floodplain harvesting in the northern NSW catchments (Border Rivers, Gwydir, Namoi, Macquarie, and Barwon-Darling) and estimated that in 2019–20, there were 1,833 on-farm storages covering a total surface area of 42,650 ha. Storage capacity had risen from 557 GL in 1993–94; to 1,067 GL in 1999–2000; 1,225 GL in 2008–09; and to 1,393 GL in 2019–20, a 2.5-fold increase in 26 years (Figure 7a).

Brown et al. (2022) estimated the mean annual volume of floodplain harvesting extractions (2004–20) in the northern NSW Basin at 778 GL (range 632–926 GL) or about twice that estimated by the NSW Department of Planning, Infrastructure and Environment (DPIE) (Slattery & Johnson 2021, Table 2 therein). This volume, 778 GL, is about half that of all the environmental water released annually for the entire Basin between 2009–10 and 2018–19 (1,576 GL), and six times the volume of environmental water (125 GL) used in the northern NSW Basin (Chen et al. 2020).

In Queensland, the mean annual floodplain harvesting extraction from the Condamine-Balonne catchment reported in MDBA Cap compliance reports (2006–07 to 2018–19) was 333 GL. Given that 420 GL

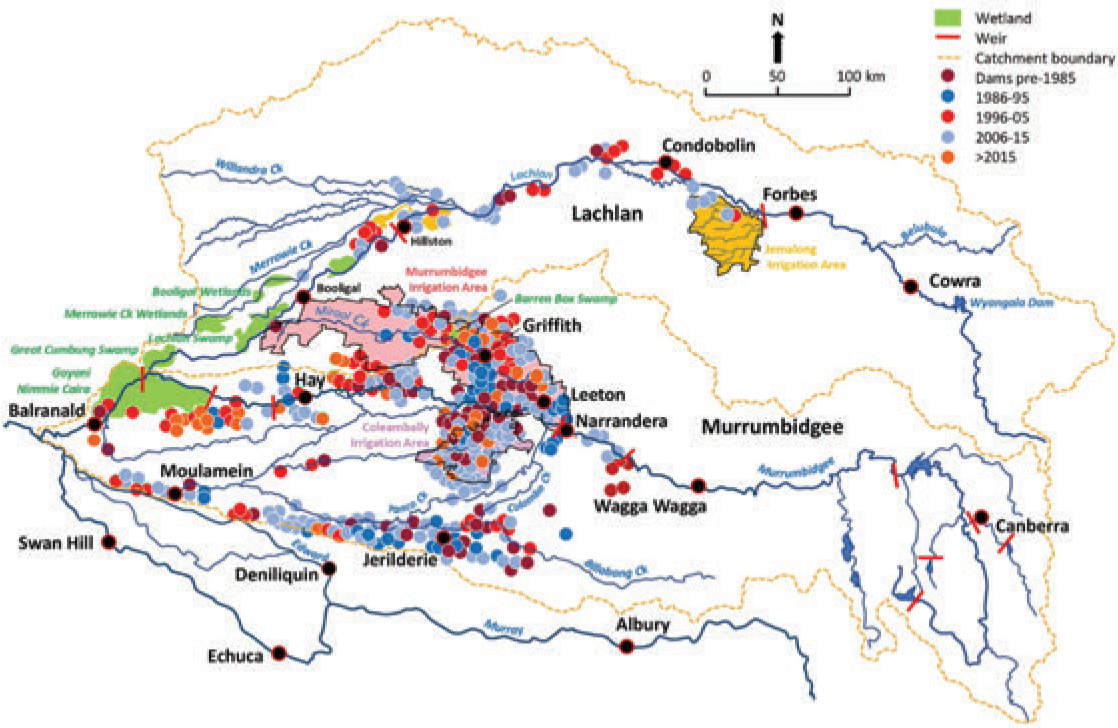

Figure 8. Increase in large farm dams (>0.6 ha, ca. 25 ML capacity) over time (pre-1985 to post-2015) in the Lachlan and Murrumbidgee catchments, southern Murray-Darling Basin. Note: clusters (mostly pre-2015) around the irrigation areas in the Murrumbidgee but also major recent (post-2015) off-irrigation developments on the Hay Plains, east and west of Hay.

was harvested on the Lower Balonne in a single flood (Feb – Mar 2020; DNRME 2020), the actual figure would appear to be much higher. For the entire northern Basin, water extractions due to floodplain harvesting could be 1,200 to 1,500 GL/year in periods of high inflows. Diversions of this scale impose large costs on downstream communities and flow-dependent ecosystems (Reid et al. 2013; Mallen-Cooper and Zampatti 2020; Brown et al. 2022).

Importantly, water extractions due to floodplain harvesting are in breach of Commonwealth and State legislation on water use and management. This is because in most catchments in the NSW northern Basin, floodplain harvesting considerably exceeds limits on diversions under the Basin Plan and are, thus, unlawful (Brown et al. 2022).

3.3.3. Future risks

There has been a marked increase in plantings of perennial tree crops, particularly almonds and walnuts, in the Murrumbidgee and Lachlan catchments in the southern Basin by large corporate agribusinesses (Davies 2019). Almond plantings increased from 3,500 ha in 2000 to 45,000 ha in 2018, increasing pressures on irrigation water demand (Gupta and Hughes 2018; MDBA 2022b). This expansion has been accompanied by a proliferation of farm dams, including on the Hay Plains and Lower Lachlan Floodplain, areas which have never been used for irrigated cropping (Figure 8). Should this trend continue, it could add to the existing water risks and, in particular, the risk that perennial plantings may die from insufficient water available at an affordable market price.

4. Next steps

Key risks to water availability exist in the MDB from grey irrigation infrastructure intended to increase irrigation efficiency and to divert and store on-farm surface water. These risks include reduced stream and return flows and increased soil and water salinity. Such risks are greatly magnified by the absence of systematic and robust measurements and water auditing (Grafton and Williams 2019a, 2019b), in relation to both the direct effects (reduced flows and salinity) and the indirect effects on ecosystem services (Cresswell, Janke, and Johnston 2021, p. 48), and include the multiple (including non-market) values of water.

To give context to the gaps in measurements and monitoring, in 2017, around one-third of the water extracted for consumptive use for irrigation was *not* accurately metered (MDBA 2017a, 2017b). Yet, despite an allocation of more than half a billion dollars of federal funds for water metering and monitoring in the MDB committed in 2007 by the Australian Prime Minister (Howard 2007), subsidies are still being provided for water metering to ensure compliance with state regulations in relation to water extractions (Matthews 2017). For example, in November 2021 the Federal Water Minister committed AU$25 million to '... improve water measurement and telemetry in the Northern Basin so water users can more easily comply with requirements' (Pitt 2021a).

Another critical data gap is reliable and accurate data in the northern MDB in relation to stream gauging stations. Stream gauge data, supplemented with remote sensing data, is critical to assess the risks of non-metered extractions, especially floodplain harvesting in NSW and Queensland (MDBA 2017a, 2017b). Such data are also needed for fit-for-purpose modelling of the MDB so as to accurately estimate the effects of increased irrigation efficiency on return flows.

Basin-scale water audits using remote sensing could help fill key data gaps in the MDB (Grafton and Williams 2019a, 2019b) and are already being applied in parts of Africa, such as the Awash Basin, Ethiopia (FAO and IHE Delft 2020). For example, the Awash Basin water audit answers three key questions: What are the current water resources? How much water is being consumed by different land use classes and, in particular, the largest water consumer, irrigation? And what are the safe caps of water withdrawals for the agricultural sector? (FAO and IHE Delft 2020, p. 4).

Notwithstanding the substantial progress and quality of remote sensing for water accounting in Africa, within the MDB there still remains large uncertainty and disputes over:

(1) the size of water diversions and consumption from floodplain harvesting, despite plans by the NSW Government to create tradable water licences for such diversions; and
(2) reductions in streamflows from grey irrigation infrastructure, despite the Federal Government spending many billions on grey infrastructure subsidies over more than a decade, with more subsidies planned (Pitt 2021b).

Without adequate data, accessible to all in real time, catchment and Basin water planning cannot be properly assessed nor can the multitude of subsidies and grants for grey irrigation infrastructure (Horne 2021), costing AU$ multi-billions, be properly evaluated. While monitoring, metering, and compliance are necessary, they are not sufficient. At a minimum, water audits need to:

(1) support compliance;
(2) inform economic assessments of past and planned investment programs in grey and green infrastructure;

(3) provide the evidence base to continuously improve soft infrastructure through a process of accountability of the decisions and actions undertaken by organisations (including their leadership) at a state and federal level;
(4) promote scenario modelling of alternative futures under 'business as usual' and alternatives; and
(5) risk management, and mitigation of cumulative, systemic, and cascading risks from human actions (such as increases in floodplain harvesting and farm storages), and subsidies to increase irrigation efficiency with risk multipliers (such as climate change).

Soft infrastructure, that includes water audits, encompasses multiple domains and should be consistent with the 15 key water governance principles welcomed by Ministers at the OECD Ministerial Council Meeting on 4 June 2015 (OECD 2015). In the MDB, soft infrastructure must also effectively mitigate risks if key objects of the Water Act 2007 (Commonwealth of Australia 2007) are to be delivered. Improvements in soft infrastructure are critically needed because Lewis, Farrier, and Kelsall (2021, p. 14), in the Second Independent Review of the Water for the Environment Special Account, estimated that in December 2021 the gap between the original (2,750 GL/year) and additional environmental water requirements (450 GL/year) legislated in the Basin Plan was 1,065 GL/year. Importantly, their gap estimate does not account for reductions in return flows from on- and off-farm grey water infrastructure developments in the Basin that may range from 130 to 630 GL/year (as discussed in Section 3.1.3. above).

We highlight that grey (hard) infrastructure delivers market value and especially increases the capital value of land (Thiene and Tsur 2013; Dent 2014). We contend that this is a key reason why on- and off-farm subsidies and grants for irrigated agriculture have been the primary means of delivering water 'savings' or to reduce water 'losses' when there is published evidence from the MDB that, in general, they deliver the opposite outcome (Grafton et al. 2018; Wheeler et al. 2020; Pérez-Blanco al. 2021). By contrast, because green infrastructure has little or no market value in a 'market society' where '… the value of something, of some act or of someone is equated with their monetary value, a monetary value that is determined by the market' (Carney 2022, p. 4) means they become a second-order priority. This has had important and negative consequences for the MDB, and globally, as highlighted by Sir Partha Dasgupta (2021, p. 2) in his *Economics of Biodiversity*: 'Nature's worth to society – the true value of the various goods and services it provides – is not reflected in market prices because much of it is open to all at no monetary charge. These pricing distortions have led us to invest relatively more in other assets, such as produced capital, and underinvest in our natural assets. Moreover, aspects of Nature are mobile; some are invisible, such as in the soils; and many are silent. These features mean that the effects of many of our actions on ourselves and others – including our descendants – are hard to trace and go unaccounted for, giving rise to widespread 'externalities' and making it hard for markets to function well'.

We contend that improved data collection and availability, which is now well supported with current technology (ATSE 2022), would enable assessment of the costs and benefits of past and planned grey infrastructure programs and comply with government guidelines around probity and due diligence (e.g. Department of Finance and Administration 2006; Infrastructure Australia 2021). For green infrastructure, improved data resources would enable economic valuation of non-market benefits and their explicit consideration in decision-making. This shift would help to end the lopsided status quo where benefits from grey infrastructure are ascribed dollar values, but the degradation or restoration of environmental assets are abstracted from economic analysis and, therefore, not valued (e.g. NSW DI 2017).

Globally, market and non-market valuation of green infrastructure services is set to become more prominent as governments and industries seek finance for 'nature-based solutions' to climate change mitigation and adaptation (e.g. UNEP/WEF/ELD 2021). The MDB's waterways, aquifers, and ecosystems are critically important natural capital stocks (Grafton et al. 2008, p. 323) for the major economies and population centres of eastern Australia; they require public investments with returns that can be measured in the calculus of a market society. Valuation of ecosystem services in the MDB can also support landholders to be renumerated for private green infrastructure investments under the Australian Government's reforms to carbon credit markets (see DCCEEW 2022a) and planned national biodiversity market (see DCCEEW 2022b).

Further steps required to bring the transformational change needed include (but are not limited to):

(1) effective transparency about the 'who, what, when and where' of water and the diversity of services and values it delivers for particular policy decisions;
(2) development of institutional arrangements that can genuinely listen, rather than simply consult, and include a diverse range of voices so that not only those who have greater access to decision-makers get heard (as documented in Colloff, Grafton, and Williams 2021, 2022); and
(3) real opportunities for broader values (sustainability, justice, etc.) to flourish with use and with support for deliberative democratic processes

> noting that democracy is '... about rights, the rights to selfhood, participation, and inclusion as the fundamental justification for the whole range of rights valued in societies that aspire to be called democracies' (Grayling 2020, p. 146).

We contend these transformational changes should be complemented and facilitated by regional governance improvements, such as with catchment management bodies, with special attention given to the policy levers that would involve local stakeholders more in the conservation and rejuvenation of green infrastructure. For example, in both NSW (Mitchell 2013) and Victoria (Whittaker, Major, and Geraghty 2004), progress was made through a resilience framework in strategic regional catchment action plans (NRC 2012) for improving the health, productivity and resilience of landscapes. These processes showed that it is possible to identify what the community and government value about these landscapes and to explain what needs to be done to ensure long-term sustainable management of a region's natural resources (Whittaker, Major, and Geraghty 2004). These regional bodies had priorities for increasing the devolution of decision-making, funding and control towards catchment management (NRC 2012; Mitchell 2013).

The Murray-Darling Basin Authority's risk assessment guidelines (MDBA 2017b) and the MDB Plan require revisions to ensure that complex interactions between grey, soft, and green infrastructure are addressed in water resource plans. The current approach draws heavily on the AS/NZS ISO 31,000:2009 Standard and is not applied in a consistent fashion across jurisdictions. In practice, linear risk statements are produced linking (1) the defined likelihood of a single risk source/threat (or set thereof) causing (2) a specific and categorised consequence (or set thereof) to produce (3) a level of risk, (4) uncertainty or confidence ratings for the risk assessment, and (5) strategies for risks assessed as medium or high level. In each water resource plan, this approach typically produces dozens, and sometimes hundreds, of individual risk statements in lengthy risk registers (e.g. DEWNR 2018; DELWP 2019; DNRME 2019; DPIE 2019).

Current risk assessment practice in the MDB is problematic. This is because compartmentalised and static assessments of what are complex risks disregards: cumulative impacts of, and interactions between, risk sources or threats; feedback effects from consequences and risk treatments to risk sources or threats; accumulation of upstream risks in downstream water resource plan areas; and other dynamic interactions within the complex adaptive system that is the Murray-Darling Basin. Further, while systems-based risk assessment frameworks already exist (e.g. Clark-Ginsberg, Abolhassani, and Rahmati 2018; IRGC 2018; Wyrwoll et al. 2018; Simpson et al. 2021), there is currently no 'out-of-the-box' system-based risk analysis framework for water basin planning. Thus, the MDBA and Basin state agencies have an opportunity, but have so far failed to develop, a world-leading approach to managing complex water risks. Importantly, 'best practice' risk practices, that are not currently widely used in the MDB, would support decision-making and promote outcomes consistent with the objectives of the MDB Plan.

5. Conclusions

To effectively respond to the ongoing water crises in arid and semi-arid environments, there must be an appropriate combination of grey, soft, and green infrastructures. Much of the focus in Australia, and elsewhere, has been to invest in grey infrastructure, such as building water storages and increasing irrigation efficiency as key risk management tools. While grey infrastructure is necessary, it has frequently been at the expense or the neglect of maintaining green infrastructure, such as streams and wetlands, and with insufficient support or consideration for soft infrastructure that encompasses water planning, regulation, and governance.

Our analysis indicates that if the value and importance of the strong interactions between soft, green and grey infrastructure in the analysis of complex risk to water had been incorporated in the design and implementation of the Basin Plan along the lines of the Three-Infrastructures Framework it may have avoided (1) a misalignment of infrastructure priorities and funding; (2) a failure to deliver key objects of the Water Act (2007); and (3) a gap between the required environmental water recovery in the Basin Plan and what has been delivered in excess of 1,000 GL/year. In our view, the adoption of a Three-Infrastructures Framework in the future reform and revision of the Basin Plan represents a significant opportunity for Australia to avoid past failures. A continuation of the current responses to water risks in the Murray-Darling Basin are akin to an unbalanced 'three-legged stool' such that the three infrastructures have not been managed to adequately mitigate the multiple risks to water availability, quality, accessibility, and security.

As pathways forward to better risk management and outcomes in the Murray-Darling Basin, we documented grossly inadequate water metering and measurements, and the lack of a Basin-scale independent audit of water resources and flows. These data gaps have meant that, despite multiple billions of dollars in public expenditures, key risks to streamflows and salinity remain unresolved a decade after the enactment of the Murray-Darling Basin Plan that was intended to deliver sustainable water extractions. In our view, these unmitigated risks require a radical transformation to business-as-usual decision-making.

We highlight four actions to respond to current and future water risks in the Murray-Darling Basin. First, improve the data collection, accessibility, and analysis of water and salt flows, along with appropriate monitoring of the Basin's ecosystems. Second, undertake independent water audits of the state of the Basin, supported by remote sensing technologies, to manage critical risks, such as salinisation of soils, water, and deterioration of riparian environments. Third, implement robust risk analyses to avoid and/or to facilitate mitigation of cumulative, systemic, and cascading risks from human activities (such as increases in floodplain harvesting and farm storages) and subsidies for irrigation efficiency with risk multipliers (such as climate change). Fourth, to facilitate these actions, senior federal and state decision-makers must be held accountable for their decisions and whether they contribute, or not, to the delivery of the key objects of the Water Act 2007.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

ABS. 2019a. *Gross Value of Irrigated Agricultural Production 2017-18*. Canberra: Australian Bureau of Statistics. Accessed 11 March 2022. https://www.abs.gov.au/statistics/industry/agriculture/gross-value-irrigated-agricultural-production/latest-release#data-%20download

ABS. 2019b. *Water Use on Australian Farms, 2017-18*. Report 4618.0. Canberra: Australian Bureau of Statistics.

ACCC. 2021. *Murray-Darling Basin Water Markets Enquiry: Final Report*. Canberra: Australian Competition and Consumer Commission (ACCC).

Agrecon. 2005. *Hillside Farm Dams Investigation, MDBC Project 04/4677DO*. Final Report. Canberra: Murray–Darling Basin Commission.

Akter, S., and R. Q. Grafton. 2021. "Do Fires Discriminate? Socio-Economic Disadvantage, Wildfire Hazard Exposure and the Australian 2019–20 'Black Summer' Fires." *Climatic Change* 165 (3–4): 53. doi:https://doi.org/10.1007/s10584-021-03064-6.

Akter, S., R. Q. Grafton, and W. S. Merritt. 2014. "Integrated Hydro-Ecological and Economic Modelling of Environmental Flows: Macquarie Marshes, Australia." *Agricultural Water Management* 145. doi:10.1016/j.agwat.2013.12.005.

Alexandra, J. 2021. "Navigating the Anthropocene's Rivers of Risk—Climatic Change and Science-Policy Dilemmas in Australia's Murray-Darling Basin." *Climatic Change* 165 (1–2): 1. doi:https://doi.org/10.1007/s10584-021-03036-w.

Alexandra, J. 2022. "Climate Risk Assessment in the MDB – a Review, Special Issue in Australasian Journal of Water Resources.

ATSE. 2022. *Technologies for Water Management*. Canberra: Australian Academy of Technological Sciences & Engineering. ATSE-Technologies-for-water-management-220912.pdf.

Australian Academy of Science. 2019. *Investigation of the Causes of Mass Fish Kills in the Menindee Region NSW Over the Summer of 2018-2019*. Canberra: Australian Academy of Science.

Australian Government. 2012. *Basin Plan 2012, Compilation No. 6, Authorised Version F2018L00982*. Registered 11 July 2018.

Baral, H., R. J. Keenan, S. K. Sharma, N. E. Stork, and S. Kasel. 2014. "Spatial Assessment and Mapping of Biodiversity and Conservation Priorities in a Heavily Modified and Fragmented Production Landscape in North-Central Victoria, Australia." *Ecological* Indicators 36: 552–562. doi:10.1016/j.ecolind.2013.09.022.

Batchelor, C., J. Hoogeveen, J-M. Faurès, and L. Peiser. 2017. *Water Accounting and Auditing – a Sourcebook*. Rome: Food and Agriculture Organisation.

Biggs, A. J. W., D. M. Silburn, and R. E. Power. 2013. "Catchment Salt Balances in the Queensland Murray-Darling Basin, Australia." *Journal of Hydrology* 500: 104–113. doi:10.1016/j.jhydrol.2013.07.027.

BOM. 2020. *National Water Account 2020: Murray–Darling Basin: Supporting Information*. Bureau of Meteorology. Accessed 11 March 2022. http://www.bom.gov.au/water/nwa/2020/mdb/supportinginformation/statementdetails.shtml#water_use

BOM. 2022. *Water Information, Water Markets Dashboard, Murray-Darling Basin*. Bureau of Meteorology. Accessed 11 March 2022. http://www.bom.gov.au/water/dashboards/#/water-markets/national/state/at

Brown, P., M. J. Colloff, M. Slattery, W. Johnson, and F. Guarino. 2022. "An Unsustainable Level of Take: On-Farm Storages and Floodplain Water Harvesting in the Northern Murray–Darling Basin, Australia." *Australasian Journal of Water Resources* 26 (1): 43–58. doi:http://dx.doi.org/10.1080/13241583.2022.2042061.

Capitals Coalition. 2022. *Natural Capital Protocol*. Accessed 11 March 2022. https://capitalscoalition.org/capitals-approach/natural-capital-protocol/?fwp_filter_tabs=training_material

Carney, M. 2022. *Values: An Economist's Guide to Everything That Matters*. London: William Collins.

Chen, Y., M. J. Colloff, A. Lukasiewicz, and J. Pittock. 2020. "A Trickle, Not a Flood: Environmental Watering in the Murray-Darling Basin, Australia." *Marine & Freshwater Research* 72 (5): 601–619. doi:10.1071/MF20172.

Clark-Ginsberg, A., L. Abolhassani, and E. A. Rahmati. 2018. "Comparing Networked and Linear Risk Assessments: From Theory to Evidence." *International Journal of Disaster Risk Reduction* 30: 216–224. doi:10.1016/j.ijdrr.2018.04.031.

Clemmens, A. J., and D. J. Molden. 2007. "Water Uses and Productivity of Irrigation Systems." *Irrigation Science* 25 (3): 247–261. doi:10.1007/s00271-007-0067-y.

The Coca Cola Company. 2021. *How to Create Natural Capital Through Nature-Based Solutions: Piloting the Methodology on 7 Water Replenishment Projects Across Europe*.

Colloff, M., R. Q. Grafton, and J. Williams. 2021. "Scientific Integrity, Public Policy and Water Governance in the Murray-Darling Basin, Australia." *Australasian Journal of Water Resources* 25 (2): 121–140. doi:10.1080/13241583.2021.1917097.

Colloff, M., R. Q. Grafton, and J. Williams. 2022. "A Rejoinder to the Comment by Stewardson Et Al. (2021) to the Published Article by Colloff Et Al. (2021) That Were Published in the Australasian Journal of Water Resources". 10.25911/WCHS-NW56.

Commonwealth of Australia. 2007. *Water Act 2007*. Compilation No. 27, 29 January 2020. Accessed 11 March 2022. https://www.legislation.gov.au/Series/C2007A00137/

Cresswell, I., T. Janke, and E. L. Johnston. 2021. *Australia State of the Environment Overview*. Accessed 4 August 2022. https://soe.dcceew.gov.au/sites/default/files/2022-07/soe2021-overview.pdf

CSIRO. 2008. *Water Availability in the Murray-Darling Basin. A Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*. Canberra: CSIRO Water for a Healthy Country National Research Flagship.

CSIRO and NSW Government. 2005. *Off- and On-Farm Savings of Irrigation Water: Murrumbidgee Valley Water Efficiency Feasibility Project*. Water for a Healthy Country. Canberra: CSIRO. Accessed 22 March 2022. OnAndOffFarmSavings.pdf (csiro.au)

Dasgupta, Sir P. 2021. *The Economics of Biodiversity: The Dasgupta Review. Headline Messages*. Accessed 25 October 2022. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/957629/Dasgupta_Review_-_Headline_Messages.pdf

Davies, A. 2019. "Tough Nut to Crack: The Almond Boom and Its Drain on the Murray-Darling." *The Guardian*, 26 May. Accessed 11 March 2022. https://www.theguardian.com/australia-news/2019/may/26/tough-nut-to-crack-the-almond-boom-and-its-drain-on-the-murray-darling

Davies, P. E., J. H. Harris, T. J. Hillman, and K. F. Walker. 2010. "The Sustainable Rivers Audit: Assessing River Ecosystem Health in the Murray-Darling Basin, Australia." *Marine & Freshwater Research* 61 (7): 764–777. doi:10.1071/MF09043.

Davies, P. E., M. J. Stewardson, T. J. Hillman, J. R. Roberts, and M. C. Thoms. 2012. *Sustainable Rivers Audit 2: The Ecological Health of Rivers in the Murray–Darling Basin at the End of the Millennium Drought (2008–2010)*. MDBA Publication No. 75/12. Canberra: Murray–Darling Basin Authority.

DCCEEW. 2022a. *Independent Review of Australian Carbon Credit Units*. Australian Government Department of Climate Change, Energy, the Environment and Water. Accessed 25 October 2022. https://consult.industry.gov.au/independent-review-of-accu

DCCEEW. 2022b. *Biodiversity Market*. Australian Government Department of Climate Change, Energy, the Environment and Water. Accessed 25 October 2022. https://www.dcceew.gov.au/climate-change/policy/nature-based-solutions-for-climate/biodiversity-market

DELWP. 2019. "Appendix B: Approaches to Addressing Risk." In *Victoria's North and Murray Water Resource Plan*. Victorian Department of Environment, Land, Water and Planning. Accessed 22 March 2022. AppendixB-ACCREDITED.pdf url Ctrl+Click to follow link" element-type="link" ref-type="DOI" aid="i0sya7x218v4563" icoretag="uri" ia_version="0">https://www.water.vic.gov.au/__data/assets/pdf_file/0023/484232/Victoria-North-and-Murray-WRP-Comprehensive_Report-AppendixB-ACCREDITED.pdf

Dent, J. E. 2014. "A Salad Bowl, Salt and Not a Drop to Drink: Recipe for Disaster? Three Essays on the Economic Value of Agricultural Land in a Changing Environment." PhD Thesis, The Australian National University. doi: 10.25911/5d690a7b09353.

Department of Finance and Administration. 2006. *Handbook of Cost-Benefit Analysis. January 2006*. Financial Management Reference Material No. 6. Accessed 22 March 2022. https://www.pmc.gov.au/sites/default/files/files/handbook-of-cb-analysis-2006.pdf

DEWNR. 2018. *South Australian Murray Region Water Resource Plan Risk Assessment*. DEWNR Technical Report 2017/20, Government of South Australia. Adelaide: Department of Environment, Water and Natural Resources. Accessed 22 March 2022. https://www.waterconnect.sa.gov.au/Content/Publications/DEW/DEWNR-TR-2017-20.pdf

DNRME. 2019. *Border Rivers and Moonie: Risk Management Report*. Brisbane: QLD Department of Natural Resources, Mines and Energy. Accessed 22 March 2022. https://www.mdba.gov.au/sites/default/files/pubs/qld-risk-management-report-border-rivers-moonie-2019_0.PDF

DNRME. 2020. *Lower Balonne Water Management Area: February to March 2020 Flow Event Report*. Brisbane: QLD Department of Natural Resources, Mines and Energy.

DPIE. 2019. *Barwon Darling Watercourse Risk Assessment: Schedule D*. Sydney: NSW Department of Planning, Industry and Environment. Accessed 22 March 2022. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0008/273752/schedule-d-barwon-darling-risk-assessment.pdf

DPIE. 2021. *NSW Floodplain Harvesting Policy*. Sydney: NSW Department of Planning and Environment. Accessed 11 March 2022. https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/nsw-floodplain-harvesting-policy

EarthTech. 2003. *Preliminary Review of Selected Factors That May Change Future Flow Patterns in the River Murray System*. Final Report for the Murray-Darling Basin Commission.

FAO and IHE Delft. 2020. *Water Accounting in the Awash River Basin*. FAO WaPOR Water Accounting Reports. Rome. Accessed 11 March 2022. https://www.fao.org/3/ca8668en/ca8668en.pdf

Grafton, R. Q. 2017. "Responding to the 'Wicked Problem' of Water Insecurity." *Water Resources Management* 31 (10): 3023–3041. doi:10.1007/s11269-017-1606-9.

Grafton, R. Q. 2019. "Policy Review of Water Reform in the Murray–Darling Basin, Australia: The "Do's" and "Do'nots." *The Australian Journal of Agricultural and Resource Economics* 63 (1): 116–141. doi:10.1111/1467-8489.12288.

Grafton, R. Q., W. Adamowicz, D. Dupont, H. Nelson, R. J. Hill, and S. Renzetti. 2008. *The Economics of the Environment and Natural Resources*. John Wiley & Sons. https://www.wiley.com/en-us/The+Economics+of+the+Environment+and+Natural+Resources-p-9781405142342 .

Grafton, R. Q., L. Chu, R. T. Kingsford, G. Bina, and J. Williams. 2022. "Resilience to Hydrological Droughts in the Northern Murray-Darling Basin." *Philosophical Transactions of the Royal Society A* 380: 2238. doi:10.1098/rsta.2021.0296.

Grafton, R. Q., S. Fanaian, G. Sacco, and L. Liberman. 2021. "Bending Towards Water Justice: Pathways for Truth, Reconciliation, Inclusion and Transformative Actions." *International Journal of Water Resources Development* 38 (1): 1–10. doi:10.1080/07900627.2021.1914003.

Grafton, R. Q., J. Horne, and S. A. Wheeler. 2016a. "On the Marketisation of Water: Evidence from the Murray-Darling Basin, Australia." *Water Resources Management* 30 (3): 913–926. doi:https://doi.org/10.1007/s11269-015-1199-0.

Grafton, R. Q., M. McLindin, K. Hussey, P. Wyrwoll, D. Wichelns, C. Ringler, D. Garrick, et al. 2016b.

"Responding to Global Challenges in Food, Energy, Environment and Water: Risks and Options Assessment for Decision-Making." *Asia and the Pacific Policy Studies* 3 (2): 275–299. doi:10.1002/app5.128.

Grafton, R. Q., and S. A. Wheeler. 2018. "Economics of Water Recovery in the Murray-Darling Basin, Australia." *Annual Review of Resource Economics* 10 (1): 487–510. doi:https://doi.org/10.1146/annurev-resource-100517-023039.

Grafton, R. Q., and J. Williams. 2019a. "Paddling Blind: Why We Urgently Need a Water Audit." *The Conversation*, 26 August 2019. Accessed 11 March 2022. www.theconversation.com/paddling-blind-why-we-urgently-need-a-water-audit-122118

Grafton, R. Q., and J. Williams. 2019b. "Thirst for Certainty: The Urgent Need for a Water Audit of the Murray-Darling Basin." *Farm Policy Journal* 16 (2): 14–22.

Grafton, R. Q., J. Williams, C. J. Perry, F. Molle, C. Ringler, P. Steduto, B. Udall, et al. 2018. "The Paradox of Irrigation Efficiency." *Science* 361 (6404): 748–750. doi:10.1126/science.aat9314.

Grayling, A. C. 2020. *The Good State: On the Principles of Democracy*. London: Oneworld Publications.

Green, J., and B. Moggridge. 2021. *Australia State of the Environment 2021: Inland Water, Independent Report to the Australian Government Minister for the Environment*. Canberra: Commonwealth of Australia. Accessed 4 August 2022. https://soe.dcceew.gov.au/sites/default/files/2022-07/soe2021-inland-water.pdf

Gupta, M., and N. Hughes. 2018. *Future Scenarios for the Southern Murray–Darling Basin Water Market*. Canberra: Australian Bureau of Agricultural and Resource Economics and Sciences.

Haddeland, I., J. Heinke, H. Biemans, S. Eisner, M. Flörke, N. Hanasaki, M. Konzmann, et al. 2014. "Global Water Resources Affected by Human Interventions and Climate Change." *Proceedings of the National Academy of Sciences* 111 (9): 3251–3256. doi:10.1073/pnas.1222475110.

Hart, B., G. Walker, A. Katupitiya, and J. Doolan. 2020. "Salinity Management in the Murray–Darling Basin, Australia." *Water* 12 (6): 1829. doi:10.3390/w12061829.

Hatton MacDonald, D., M. D. Morrison, J. M. Rose, and K. J. Boyle. 2011. "Valuing a Multistate River: The Case of the River Murray." *The Australian Journal of Agricultural and Resource Economics* 55 (3): 374–392. doi:10.1111/j.1467-8489.2011.00551.x.

Helbing, D. 2013. "Globally Networked Risks and How to Respond." *Nature* 497 (7447): 51–59. doi:10.1038/nature12047.

Horne, J. 2021. "Water's Role in MDB Regional Development." *International Journal of Water Resources Development* 1–24. doi:https://doi.org/10.1080/07900627.2021.1991780.

Howard, J. 2007. *A National Plan for Water Security*. Canberra: Transcript of Address to the National Press Club, Great Hall, Parliament House.

Hughes, N., M. Donoghoe, and L. Whittle. 2020. "Farm Level Effects of On-Farm Irrigation Infrastructure Programs in the Southern Murray–Darling Basin." *The Australian Economic Review* 53 (4): 494–516. doi:10.1111/1467-8462.12396.

Infrastructure Australia. 2021. *Guide to Economic Appraisal*. Accessed 25 October 2022. https://www.infrastructureaustralia.gov.au/guide-economic-appraisal

IRGC. 2018. *Guidelines for the Governance of Systemic Risks*. Lausanne: International Risk Governance Center. doi:10.5075/epfl-irgc-257279. Available from www.irgc.org and irgc.epfl.ch

Karimi, P., W. G. M. Bastiaanssen, and D. Molden. 2013. "Water Accounting Plus (WA+) – a Water Accounting Procedure for Complex River Basins Based on Satellite Measurements." *Hydrology and Earth System Sciences* 17 (7): 2459–2472. doi:https://doi.org/10.5194/hess-17-2459-2013.

Khan, S., A. Ahmad, and H. M. Malano. 2008. "Managing Irrigation Demand to Improve Seasonality of River Flows." *Irrigation and Drainage* 58 (2): 157–170. doi:10.1002/ird.405.

Khan, S., S. Akbar, T. Rana, M. A. Abbas, D. Robinson, Z. Paydar, D. Dassanayke, et al. 2005. *Off- and On-Farm Savings of Irrigation Water: Murrumbidgee Valley Water Efficiency Feasibility Project*. Water for a Healthy Country Flagship Report. Canberra: CSIRO.

Khan, S., M. N. Asghar, S. Mushtaq, and A. Ahmad. 2008. "On-Farm Options for Managing Stream Salinity in Irrigation Areas: An Example from the Murray Darling Basin, Australia." *Hydrology Research* 39 (2): 157–170. doi:10.2166/nh.2008.036.

Khan, S., R. Tariq, C. Yuanlai, and J. Blackwell. 2006. "Can Irrigation Be Sustainable?" *Agricultural Water Management* 80 (1): 87–99. doi:10.1016/j.agwat.2005.07.006.

Kirby, M., M. Ahmad, A. Abbas, Z. Paydar, and T. Rana. 2010. "Water Savings from Delivery Efficiency Improvements." In Irrigation Australia, 8−10 June 2010, Sydney. Sydney: Irrigation Australia.

Leblanc, M., S. Tweed, A. van Dijk, and B. Timbal. 2012. "A Review of Historic and Future Hydrological Changes in the Murray-Darling Basin." *Global and Planetary Change* 80-81: 226–246. doi:10.1016/j.gloplacha.2011.10.012.

Lewis, S., S. Farrier, and M. Kelsall. 2021. *Second Review of the Water for the Environment Special Account. Report to Commonwealth Minister for Water Resources as Required Under Section 86AJ of the Water Act 2007*. Accessed 4 August 2022. https://www.dcceew.gov.au/sites/default/files/documents/second-review-water-for-the-environment-special-account.pdf

Loch, A., D. Adamson, and C. Auricht. 2019. "(G)etting to the Point: The Problem with Water Risk and Uncertainty." *Water Resources and Economics* 32: 100154. doi:10.1016/j.wre.2019.100154.

Malerba, M. E., N. Wright, and P. I. Macreadie. 2021. "A Continental-Scale Assessment of Density, Size, Distribution and Historical Trends of Farm Dams Using Deep Learning Convolutional Neural Networks." *Remote Sensing* 13 (2): 319. doi:10.3390/rs13020319.

Mallen-Cooper, M., and B. P. Zampatti. 2020. "Restoring the Ecological Integrity of a Dryland River: Why Low Flows in the Barwon–Darling River Must *Flow*." *Ecological Management & Restoration* 21 (3): 218–228. doi:10.1111/emr.12428.

Matthews, K. 2017. *Independent Investigation into NSW Water Management and Compliance*. Publication No. PUB17/859. Sydney: NSW Government Department of Industry. Accessed 11 March 2022. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0019/131905/Matthews-final-report-NSW-water-management-and-compliance.pdf

Matthews, J., and E. O. Dela Cruz. 2022. *Integrating Nature-Based Solutions for Climate Change Adaptation and Disaster Risk Management. A Practitioner's Guide*. Asian Development Bank. Accessed 25 October 2022. https://www.adb.org/sites/default/files/publication/801226/nature-based-solutions-cca-drm.pdf

MDBA. 2016. *Water Audit Monitoring Report 2011-12: Report of the Murray–Darling Basin Authority on the*

Cap on Diversions. MDBA Publication No. 20/16. Canberra: Murray–Darling Basin Authority.

MDBA. 2017a. *Basin Plan Evaluation 2017*. Canberra: Murray–Darling Basin Authority. MDBA Publication No. 52/17.

MDBA. 2017b. *Water Resource Plans: Part 9 Guidelines*. Canberra: Murray–Darling Basin Authority. MDBA Publication No. 33/17.

MDBA. 2019. *Irrigated Crop Area Data for the Lower Murray-Darling 2003 to 2018*. Canberra: Murray–Darling Basin Authority. Accessed 11 March 2022. https://www.mdba.gov.au/sites/default/files/pubs/irrigated-crop-area-data-for-the-lower-murray-darling-2003-to-2018.pdf

MDBA. 2022a. *Sustainable Diversion Limit Adjustment Mechanism*. Canberra: Murray–Darling Basin Authority. Accessed 25 October 2022. https://www.mdba.gov.au/basin-plan-roll-out/sustainable-diversion-limits/sdlam

MDBA. 2022b. *Irrigation Trends in the Basin*. Canberra: Murray–Darling Basin Authority. Accessed 11 March 2022. https://www.mdba.gov.au/about-basin/irrigation-trends-basin

MDBC and Geosciences Australia. 2008. *Mapping the Growth, Location, Surface Area and Age of Man-Made Water Bodies, Including Farm Dams, in the Murray-Darling Basin*. MDBC Publication No. 48/08. Canberra: Murray–Darling Basin Commission.

Mitchell, M. 2013. "From Organisational Learning to Social Learning: A Tale of Two Organisations in the Murray–Darling Basin." *Rural Society* 22 (3): 230–241. doi:10.5172/rsj.2013.22.3.230.

Molden, D. 1997. *Accounting for Water Use and Productivity*. SWIM Paper 1. Sri Lanka: International Irrigation Management Institute. Accessed 11 March 2022. https://www.iwmi.cgiar.org/Publications/SWIM_Papers/PDFs/SWIM01.PDF

Molden, D., and R. Sakthivadivel. 1999. "Water Accounting to Assess Use and Productivity of Water." *International Journal of Water Resources Development* 15: 55–71. doi:10.1080/07900629948934.

Nathan, R., and L. Lowe. 2012. "The Hydrologic Impacts of Farm Dams." *Australasian Journal of Water Resources* 16 (1): 75–83. doi:10.7158/13241583.2012.11465405.

Neal, B., R. J. Nathan, S. Schreider, and A. J. Jakeman. 2002. "Identifying the Separate Impact of Farm Dams and Land Use Changes on Catchment Yield." *Australasian Journal of Water Resources* 5 (2): 165–176. doi:10.1080/13241583.2002.11465202.

NRC. 2012. *Framework for Assessing and Recommending Upgraded Catchment Action Plans*. Sydney: Natural Resources Commission. Version 2 June 2012.

NSW DI. 2017. *Broken Hill Long-Term Water Supply Solution. Summary of the Final Business Case*. NSW Department of Industry. Accessed 25 October 2022. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0011/143030/Broken-Hill-long-term-water-supply-solution-summary-of-final-business-case.pdf

NSW Parliament Legislative Council. 2021. *Select Committee on Floodplain Harvesting*. Sydney: Parliament of New South Wales. Accessed 11 March 2022. www.parliament.nsw.gov.au/committees/listofcommittees/Pages/committee-details.aspx?pk=274

OECD. 2015. *OECD Principles on Water Governance*. Paris: Organisation for Economic Co-operation and Development. Accessed 11 March 2022. https://www.oecd.org/cfe/regionaldevelopment/OECD-Principles-on-Water-Governance-en.pdf

Paydar, Z., D. Gaydon, and Y. Chen. 2009. "A Methodology for Up-Scaling Irrigation Losses." *Irrigation Science* 27 (5): 347–356. doi:10.1007/s00271-009-0151-6.

Paydar, Z., and A. van Dijk. 2011. "A Conceptual Model to Estimate Ungauged Losses in River Water Accounting." In *MODSIM2011, 19th International Congress on Modelling and Simulation*, edited by F. Chan, D. Marinova, and R. S. Anderssen, 3952–3958. Perth, Australia: Modelling and Simulation Society of Australia and New Zealand. 12-16 December 2011.

Pérez-Blanco, C. D., A. Loch, F. Ward, C. Perry, and D. Adamson. 2021. "Agricultural Water Saving Through Technologies: A Zombie Idea." *Environmental Research Letters* 16 (11): 114032.

Perry, C. 2011. "Accounting for Water Use: Terminology and Implications for Saving Water and Increasing Production." *Agricultural Water Management* 98 (12): 1840–1846. doi:10.1016/j.agwat.2010.10.002.

Pescaroli, G., and D. Alexander. 2018. "Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework." *Risk Analysis* 38 (11): 2245–2257. doi:10.1111/risa.13128.

Pitt, K. 2021a. *Improving Northern Murray–Darling Basin Water Metering*. 9 November 2021.

Pitt, K. 2021b. *Applications Open for Off-Farm Efficiency Grants Program to Generate Water Savings*. 24 November 2021.

Pittock, J., K. Hussey, and S. Dovers. 2015. *Climate, Energy and Water*. Cambridge: Cambridge University Press. doi:10.1017/CBO9781139248792.

Prosser, I. P., F. H. S. Chiew, and M. Stafford Smith. 2021. "Adapting Water Management to Climate Change in the Murray–Darling Basin, Australia." *Water* 13 (18): 2504. doi:10.3390/w13182504.

Reid, J. R. W., M. J. Colloff, A. D. Arthur, and H. M. McGinness. 2013. "Influence of Catchment Condition and Water Resource Development on Waterbird Assemblages in the Murray-Darling Basin, Australia." *Biological Conservation* 165: 25–34. doi:10.1016/j.biocon.2013.05.009.

Rendell, R., M. Toulmin, C. Fitzpatrick, C. Lyle, T. Cummins, D. Harriss, M. Smith, et al. 2020. "Water Use Efficiency in Irrigated Agriculture: An Australian Perspective." Canberra: Australian Water Partnership. Accessed 11 March 2022. https://waterpartnership.org.au/wp-content/uploads/2020/05/Water-Use-Efficiency-in-Irrigated-Agriculture-web.pdf

Renn, O., K. Lucas, A. Haas, and C. Jaeger. 2019. "Things are Different Today: The Challenge of Global Systemic Risks." *Journal of Risk Research* 22 (4): 401–415. doi:10.1080/13669877.2017.1409252.

Rhoades, J. D. 1974. "Drainage for Salinity Control." In *Drainage for Agriculture*, edited by J. van Schilfgaarde, 433–461. Vol. 17. California, USA: American Society of Agronomy.

Roth, G., G. Harris, M. Gillies, J. Montgomery, and D. Wigginton. 2013. "Water-Use Efficiency and Productivity Trends in Australian Irrigated Cotton: A Review." *Crop & Pasture Science* 64 (12): 1033–1048. doi:10.1071/CP13315.

Shahrokhnia, H., and L. Wu. 2021. "SALEACH: A New Web-Based Soil Salinity Leaching Model for Improved Irrigation Management." *Agricultural Water Management* 252: 106905. doi:10.1016/j.agwat.2021.106905.

Simpson, N. P., K. J. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, et al. 2021. "A Framework for Complex Climate Change Risk Assessment." *One Earth* 4 (4): 489–501. doi:10.1016/j.oneear.2021.03.005.

SKM, CSIRO, and BRS. 2010. *Surface and/or Groundwater Interception Activities: Initial Estimates*. Waterlines Report No. 30, Canberra: National Water Commission. Sinclair Knight Merz, CSIRO and Bureau of Rural Sciences Sciences. Accessed 11 March 2022. March 2022. www.mdba.gov.au/sites/default/files/pubs/1006-BPKId-surface-groundwater-interception-activities_0.pdf

Slattery & Johnson. 2021. *Floodplain Water Harvesting in the Northern New South Wales Murray-Darling Basin*. Canberra: Slattery & Johnson Pty Ltd. Accessed 11 March 2022. https://irnnsw.files.wordpress.com/2021/02/21022-fph-final-report.pdf

Steinfeld, C. M. M., and R. T. Kingsford. 2011. "Disconnecting the Floodplain: Earthworks and Their Ecological Effect on a Dryland Floodplain in the Murray–Darling Basin, Australia." *River Research and Applications* 29 (2): 206–218. doi:10.1002/rra.1583.

Thiene, M., and Y. Tsur. 2013. "Agricultural Landscape Value and Irrigation Water Policy." *Journal of Agricultural Economics* 64 (3): 641–653. doi:10.1111/1477-9552.12016.

UNEP. 2022. *CTCN Knowledge Brief. Nature-based Solutions to Emerging Water Management Challenges in the Asia-Pacific Region*. Nairobi: United Nations Environment Programme. Accessed 25 October 2022. https://www.ctc-n.org/sites/www.ctc-n.org/files/resources/CTCN_Brief_AsiaPacific.pdf

UNEP/WEF/ELD. 2021. *State of Finance for Nature 2021*. Nairobi: United Nations Environment Programme, World Economic Forum, and The Economics of Land Degradation. Accessed 25 October 2022. https://www.unep.org/resources/state-finance-nature

USACE. 2022. *Engineering With Nature*. United States Army Corps of Engineers. Accessed 25 October 2022. https://ewn.erdc.dren.mil/

van Dijk, A., R. Evans, P. Hairsine, S. Khan, R. Nathan, Z. Paydar, N. Viney, and L. Zhang. 2006. *Risks to the Shared Water Resources of the Murray-Darling Basin*. Canberra: Murray-Darling Basin Commission.

van Dijk, A., M. Kirby, Z. Paydar, G. Podger, M. Mainuddin, S. Marvanek, and J. Peña Arancibia. 2008. *Uncertainty in River Modelling Across the Murray-Darling Basin*. A Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, CSIRO Australia.

Vörösmarty, C. J., B. Stewart-Koster, P. A. Green, E. L. Boone, M. Flörke, G. Fischer, D. A. Wiberg, et al. 2021. "A Green-Gray Path to Global Water Security and Sustainable Infrastructure." *Global Environmental Change* 70: 102344. doi:10.1016/j.gloenvcha.2021.102344.

Walker, G. R., A. C. Horne, Q. J. Wang, and R. Rendell. 2021. "Assessing the Impact of Irrigation Efficiency Projects on Return Flows in the South-Eastern Murray–Darling Basin, Australia." *Water* 13 (10): 1366. doi:10.3390/w13101366.

Walker, G., Q. J. Wang, A. C. Horne, R. Evans, and S. Richardson. 2020. "Estimating Groundwater-River Connectivity Factor for Quantifying Changes in Irrigation Return Flows in the Murray–Darling Basin." *Australasian Journal of Water Resources* 24 (2): 121–138. doi:10.1080/13241583.2020.1787702.

Wheeler, S. A. 2022. "Debunking Murray-Darling Basin Water Trade Myths." *The Australian Journal of Agricultural and Resource Economics* 00: 1–25. doi:10.1111/1467-8489.12490.

Wheeler, S. A., E. Carmody, R. Q. Grafton, R. T. Kingsford, and A. Zuo. 2020. "The Rebound Effect on Water Extraction from Subsidising Irrigation Infrastructure in Australia." *Resources Conservation and Recycling* 159: 104755. doi:10.1016/j.resconrec.2020.104755.

Wheeler, S. A., and D. E. Garrick. 2020. "A Tale of Two Water Markets in Australia: Lessons for Understanding Participation in Formal Water Markets." *Oxford Review of Economic Policy* 36 (1): 132–153. doi:10.1093/oxrep/grz032.

Whetton, P. 2017. "Appendix 4. Climate Change in the Murray-Darling Basin: An Update." In *Review of Water Reform in the Murray-Darling Basin*. Sydney: Wentworth Group of Concerned Scientists. Accessed 11 March 2022. https://wentworthgroup.org/wp-content/uploads/2017/12/Wentworth-Group-Review-of-water-reform-in-MDB-Nov-2017-Review-Report.pdf

Whittaker, S., A. Major, and P. Geraghty. 2004. "Victoria's Emerging Framework of Regional Governance for Sustainability: The Case of Catchment Management Authorities and Regional Catchment Strategies." *Local Environment* 9 (6): 575–593. doi:10.1080/1354983042000288076.

Williams, J. 2003. *Wealth from Water: A National Perspective*. A Presentation to the Wealth from Water Conference, 14 March 2003 held at Wagga Wagga, NSW. Canberra: CSIRO Land and Water.

Williams, J. 2017. "Water Reform in the Murray–Darling Basin: A Challenge in Complexity in Balancing Social, Economic and Environmental Perspectives." *Journal and Proceedings of the Royal Society of New South Wales*, Sydney, Australia, 150: 68–92.

Williams, J., and R. Q. Grafton. 2019. "Missing in Action: Possible Effects of Water Recovery on Stream and River Flows in the Murray–Darling Basin, Australia." *Australasian Journal of Water Resources* 23 (2): 78–87. doi:10.1080/13241583.2019.1579965.

Williams, J., G. R. Walker, and T. J. Hatton. 2002. "Dryland Salinisation: A Challenge for Land and Water Management in the Australian Landscape." In *Agriculture, Hydrology and Water Quality*, edited by P. E. Haygarth and F. E. Jarvis, 457–475. London: CAB International.

WWAP/UN-Water. 2018. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. United Nations World Water Assessment Programme. Paris: UNESCO. Accessed 11 March 2022. www.unwater.org/publications/world-water-development-report-2018

Wyrwoll, P. R., and R. Q. Grafton. 2021. "Reforming for Resilience: Delivering 'Multipurpose Hydropower' Under Water and Energy Risks." *International Journal of Water Resources Development*. doi:10.1080/07900627.2021.1944844.

Wyrwoll, P. R., and R. Q. Grafton. 2022. "Reimagining River Futures by Reshaping Water Infrastructure." Global Water Forum. Accessed 25 October 2022. https://globalwaterforum.org/2022/09/25/reimagining-river-futures-by-reshaping-water-infrastructure/

Wyrwoll, P. R., R. Q. Grafton, K. A. Daniell, H. L. Chu, C. Ringler, L. T. H. Lien, D. K. Khoi, et al. 2018. "Decision-Making for Systemic Water Risks: Insights from a Participatory Risk Assessment Process in Vietnam." *Earth's Future* 6 (3): 543–564. doi:10.1002/2017EF000777.