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Key Points:

- Australia has advanced experience with allocative and technical efficiency levers to reduce total water consumption
- A framework calling for balance between these levers in practice is tested, and stylized examples are used to reinforce case study analysis
- Results emphasize the importance using both levers to balance contraction efforts with implications for water management in global contexts

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The Fifth Stage in Water Management: Policy Lessons for Water Governance

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Abstract Effective management of water resources is a critical policy issue globally. Using a framework developed by Turton, and a common set of characteristics describing key stages of water demand, we examine the effectiveness of isolated technical (e.g., irrigation upgrades) and allocative (e.g., buyback) efficiency for reducing water demand to sustainable levels. We base our analysis on Australia's water reform context which offers an advanced example of applying these levers to achieve allocative and technical efficiency. The study is motivated by appreciation of the benefits from increased policy flexibility and adaptability in response to the following: potential transformations toward inflexible production systems; uncertainty associated with impacts of climate change on future water reliability; and the need for increased possible future equity between uses/users (productive/consumptive, environmental, cultural). Our results highlight that a balance between technical and allocative efficiency mechanisms is necessary, as neither is sufficient in isolation, when seeking to reduce total water use. This approach also enables a clearer representation of uncertainty in future policy choices in many global settings with respect to water demand reduction.

1. Introduction

Water demand curves are used to describe transitions in water supply and demand over time. Typical water demand begins with initial periods of very low water use when society is learning about how to utilize water supply (NWC, 2011). This period has been referred to as the exploratory stage. This is typically followed by an expansion phase where rapid infrastructure growth increases total conjunctive water supply and policy incentives to utilize resources. However, as the limits to total water supply are reached, water demand may mature and further growth may cease as water use flattens. Supply limits, population change, climatic events, shifts in public sentiment, and/or access to new information may require a reduction in total water extraction toward sustainable levels, which constitutes a transition or contraction stage. Ideally, as societies develop past peak supply, total water demand will reduce to a sustainable level or a new (lower) mature stage of use that matches demand with system replenishment potential. However, this sustainable balanced level is seldom achieved, and water scarcity remains a global concern (World Economic Forum, 2019) evidenced by major cities facing increasing severe water shortages (e.g., Cape Town, Sao Paulo, Mexico City, Phoenix, Harare, and Chennai).

A number of authors have explored water demand stages, suggesting policy/program solutions to match. For example, Scheierling and Tréguer (2018) discussed transitions from expansion to maturity in water demand. They recommend engineering (e.g., supply storage) interventions, where managers make better use of existing resources rather than necessarily developing new supply sources (Winpenny, 1997). This emphasizes initial public investments followed by private intervention measures coupled to demand-side policy (e.g., pricing) and sophisticated choice assessments. Randall (1981) explored water demand up to mature stages, where demand-side policies (property rights, pricing, and water marketing arrangements) were expected to address externalities and the need for water reallocation. The practicality of market reallocation of water is also discussed by the National Water Commission (2011) for the Australian context—which is arguably at an advanced stage and undergoing contraction in agricultural water uses to favor reallocation to the environment. Few authors discuss the latter stages of water demand. Notable exceptions include Turton (1999) on the issue of matching social adaptive capacity to sustainable extraction outcomes, Musgrave (2008) on the increasing recognition of environmental water requirements in Australia's Murray-Darling Basin (MDB) and the need for sectoral water use shifts, and Mai et al. (2019) with respect to the potential for water market systems to facilitate sustainable water use over time. However, none of these authors offer empirical analysis

of the success or likelihood of policy/program transitions toward sustainable extraction for contexts experiencing forced water demand contraction. The solutions they provide are solved with certainty, and either accidentally or deliberately ignore complex questions such as the prevention of irreversible outcomes arising from catastrophic tipping points (Loch, Adamson, et al., 2020) that may arise when dealing with uncertain water supply and an insatiable demand for water. If policy continues to lack adaptive capacity, uncertainty may force policy makers toward a continual and costly cycle of reform to deal with these complexities and achieve allocation transformation.

Large-scale transformation often does not sit well with existing policy design/assessment processes. Change is costly to transact and therefore in conflict with the political economy of promise; that is, delivering effective policy solutions at low transaction costs and without the inequity generated by winners and losers. Current/future water supply/demand is also highly uncertain in many contexts due to climate change impacts (Milly et al., 2008). Alongside climate change, additional complexities emerge where traditional objectives of economic growth are traded off against “emerging” objectives including environmental flows, recognition of cultural rights, and/or the search for effective reallocation mechanisms. Some property right reallocation “solutions” include the introduction of new rights, often in conflict with existing right owners (Quiggin, 1986), or calls for compensation from those right owners who are part of the problem, and not the solution. Further, current/future natural resource systems will likely operate very differently from when many current policy, governance, and legal frameworks were designed (Polasky et al., 2019). Uncertainty with respect to water demand paths beyond a contraction stage set us on what we term a *fifth-stage* water demand curve with ambiguous characteristics. Eventual *fifth-stage* pathways will be revealed over time in response to decisions made today and will ideally improve national welfare via the recognition of increasing risk and uncertainty, an effective reallocation of resources in response, and a capacity to reflect dynamic social expectations. An important question therefore is what policies/program levers may enable effective transitions to sustainable water demand over time? Further, what evidence can be offered in support of that view?

This paper utilizes a framework provided by Turton (1999) which suggests two main policy/program levers for transitioning water systems toward optimal use: (i) investing in water efficiency upgrades (*technical efficiency*) and/or (ii) the purchase of existing water rights (*allocative efficiency*). We further explore the role that market signals, subsidized infrastructure incentives, and an uncertain future climate play in achieving water demand contraction via the use of technical/allocative efficiency levers. We use Australia's MDB as a case study—where water demand is currently in a contraction phase, with the view to achieving sustainable extraction levels by 2024 (MDBA, 2012). We draw on several sources to create a set of criteria to describe water demand stages to enable comparison of Turton's levers in the MDB context, and to examine the part each plays in transitioning water demand toward sustainable levels. This offers an interesting perspective on current arrangements in Australia that highlight barriers to achieving sustainable objectives in the MDB, which may also be relevant for other jurisdictions facing similar future choices.

2. The Theoretical Framework

A set of water demand stages incorporating shifts over time to sustainable extraction via adaptive capacity is espoused by Turton (1999), based on adaptive capacity work undertaken by Ohlsson (1999). In most settings, initial surplus water slowly declines as demand pressures (e.g., population increase) drive exponential growth. Total supply may be increased through storage (e.g., dams) and/or technical (e.g., efficiency) solutions. However, total demand will eventually outstrip any additional supply created by storage or efficiency gains, forcing managers to recognize maturity in supply/demand arrangements. If additional storage or technical supply-side solutions cannot be identified to meet demand, managers will also be forced to recognize requirements for a reduction in total water demand by some/all sectors to achieve sustainable extraction levels. Reductions in total water use may then necessitate demand-side solutions (e.g., pricing, increased charges, sectoral reallocation) ahead of transitioning water users to a new future based on adaptation to absolute scarcity.

In line with these water demand stages society may also experience transitions in required adaptive capacity from initial supply-side solutions, through demand-side solutions, toward adaptive management allocations of social resources (Quiggin, 1986). Water management phases will thus shift from receiving more water,

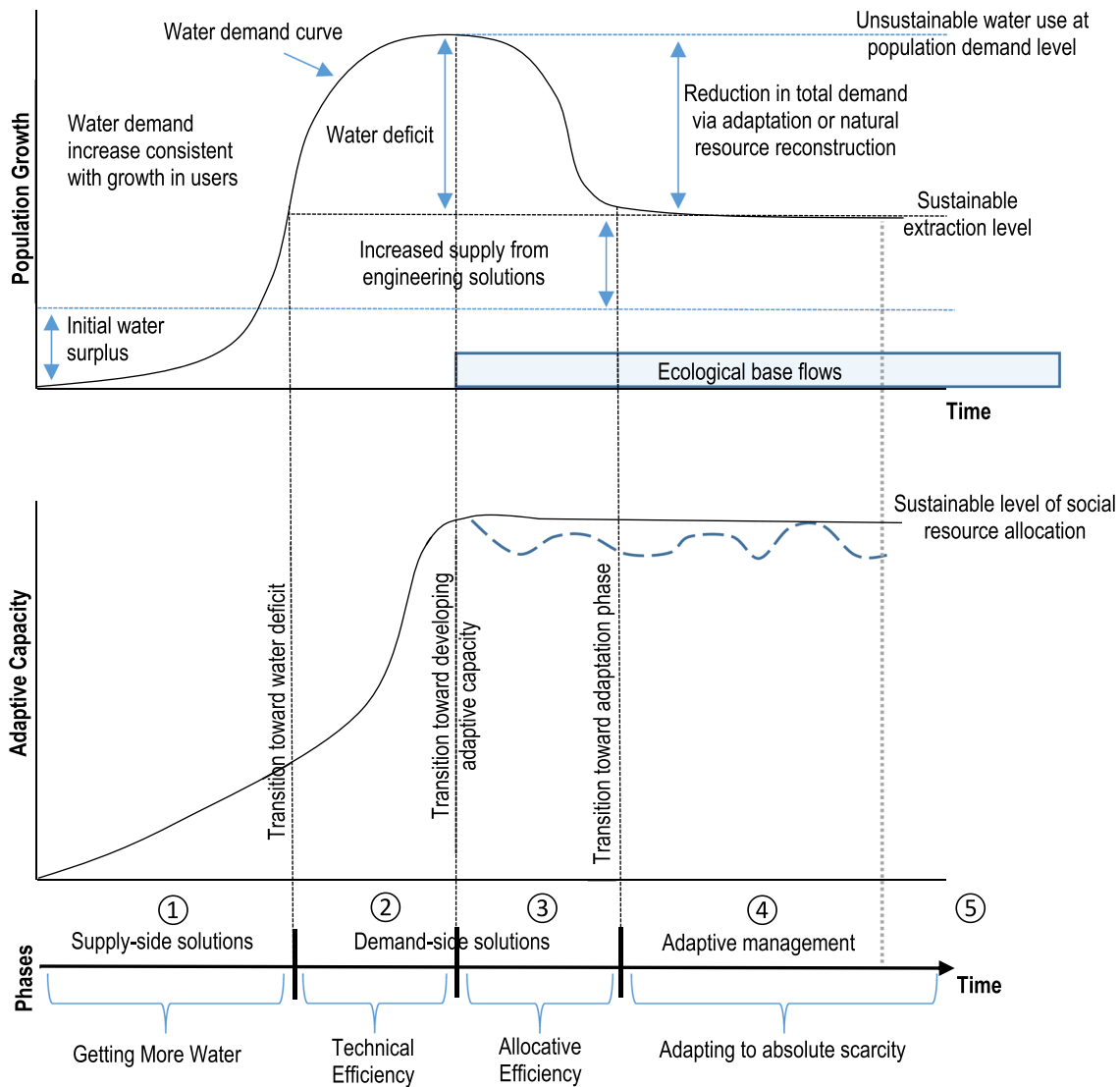


Figure 1. Links between increasing scarcity and adaptive capacity to achieve sustainable water use over time (adapted from Turton, 1999).

through technical (e.g., water savings at user level) and allocative (water shifts between sectors) efficiency solutions, to arrangements enabling adaptation to absolute scarcity (Figure 1). Critically, Turton (1999) contends that the use of technical and allocative efficiency policy/programs to reduce total water demand toward long-term sustainable extraction levels are necessary, and insufficient on their own, for natural resource reconstruction; that is, self-replenishment of natural water endowments in the system. Thus Turton's view would suggest that, where we follow single applications of technical or allocative efficiency solutions to achieve long-term sustainable extraction, transitions to later adaptation phases could follow different end-paths—that is, increasing, flat, or decreasing. Total demand may vary around that sustainable level, but ideally will never exceed it; as indicated by the dashed line in the lower half of Figure 1.

These alternative end paths (e.g., accelerated resource destruction versus long-term sustainability) are consistent with suggestions from Rostow (1959) that, beyond maturity, economies could turn in one of three major directions dependent upon the consequences of the previous phase. For example, overreliance on sectoral reallocation programs like water right buybacks from consumptive users could deplete political legitimacy in the eyes of water users and result in policy reversals—forcing total water demand above sustainable extraction. Alternatively, overreliance on technical efficiency (e.g., on-farm water savings) may result in lower than expected reallocation and reduce political legitimacy in the eyes of nonwater users. It could

also result in a need for further reductions in total water demand, beyond (expected) sustainable extraction levels, to replenish system endowment capacity and meet minimum base flow requirements for river health (which typically appear after the maturity stage, as depicted in the top-half of Figure 1). Balanced approaches would therefore be more likely to produce Turton's flat sustainable adaptation outcome.

2.1. Key Water Demand Stage Characteristics

Water reforms undertaken in Australia's MDB provide an opportunity to broadly assess the necessity/sufficiency characteristics of Turton's framework. It also provides opportunity to evaluate recommended combined technical/allocative efficiency policy/program approaches, and whether applications of single levers in isolation increases the probability of unsustainable water extraction/natural resource reconstruction outcomes. Ultimately, any *fifth-stage* demand curve should have a maximum threshold limit, suggesting equitable and sustainable use outcomes consistent with Turton's assessment. Comparing the levers suggested by Turton to drive equitable/sustainable outcomes first requires common reform stage criteria. To establish a set of common criteria on which to base comparisons, we follow Randall (1981), later adapted by Cummins and Watson (2012), and finally utilized by Adamson (2015) to assess how Australian water policy reforms in the MDB (i) impact on water demand curve transitions in response to growing water scarcity and (ii) deal with the complex nature of trade-offs between all water users. Table 1 details seven criteria with properties common to each of the water demand stages discussed above, drawing parallels between criteria provided for the expansion stage in Scheierling and Tréguer (2018) and the maturity stage in Randall (1981). For the contraction stage we draw on the social-ecological system characteristics described by Ostrom (2009) to embody sectoral transitions and/or contractions in favor of other users (e.g., the environment). This approach is also aimed at identifying an ultimate objective of equitable and sustainable water sharing arrangements consistent with Turton's objective. It should be noted that there is no assumption of a sequential nature to these criteria, although in some contexts that may be required (Young, 2014). However, a general demand transition from expansion stages, through maturity, toward contraction is assumed.

We begin with long-run supply of impounded water that reflects existing dam/weir storage and any potential for new storages to increase total supply (Criteria 1). The physical condition of those storage/delivery systems will change over time, but also reduce opportunities for further new public storage construction as "low-hanging fruit" projects are exhausted (Criteria 2). Supply system characteristics can be set against the total demand for delivered water (Criteria 3) which effectively matches the water demand curve described previously. As limits to increased supply are reached, but demand continues to grow, the security/reliability for existing users may be tested, highlighting a need for future demand-side reallocation mechanisms and/or institutional change (Criteria 4). Demand-side mechanisms may include pricing and/or water market programs; although in extreme supply periods (e.g., drought) prices and market-based transfers may reflect nonlinear (non-convex) outcomes favoring some users over others and failing institutional equity tests (Baumol & Bradford, 1972) (Criteria 5). A growing recognition of non-convex solutions may require social costs to subsidize increased water use—at least in the short term (Criteria 6). Finally, water managers may become more exposed to and familiar with both the positive and negative externalities from water use (Criteria 7) and be better equipped to evaluate policy/program transitions to equitable and sustainable extraction level objectives (Ultimate Objective). Table 1 applies these criteria across the four stages of water reform in Australia to provide a common set of sustainable adaptation criteria, while Table 2 provides some examples of those sustainable adaptation evaluation criteria with respect to the four stages of water demand transitions in Australia's MDB.

Policies or programs aimed at managing uncertainty will undoubtedly be expensive in terms of short-run institutional transaction costs (Loch & Gregg, 2018), take longer to implement/realize, and thus may be at odds with political legitimacy. We will return to this in the section 9. In the next section, we detail our case study of water demand transitions in the MDB as an initial basis for our analysis of Turton's framework.

3. Australian Water Demand Transitions

Australian water reform in the MDB provides world-leading examples of policy design and implementation aimed at addressing dynamic demand changes within highly uncertain and constrained water supply

Table 1
Parallels Between Maturing Water Demand and Social-Ecological Subsystem (SES) Criteria/Objectives

Expansion	Maturity	Contraction	Sustainable adaptation evaluation criteria
Scheierling and Tréguer (2018) Supply of agricultural water	Randall (1981) Long run supply	Ostrom (2009) Resource units	Relate to Turton (1999) (1) Long-run supply from impounded water
Comprehensive assessment of hydrologic and institutional contexts	Physical condition of impoundment and delivery systems	Resource systems	(2) Physical condition of impound/delivery system
Demand for agricultural water	Demand for delivered water	Users	(3) Demand for delivered water
Interdependence among users and need to address trade-offs	Competition for water among uses, and maintenance	Related ecosystems	(4) Improved security/reliability for all water users
Interventions – especially demand-side	Social cost of subsidizing increased use	Social, economic and political settings	(5) Non-convex demand solutions in water markets (6) Social costs of subsidizing increased water use
Significant externalities – focus on environmental flows and the value of water	Externality problems	Interactions and outcomes to other SES's, among other things	(7) Externality recognition and management
Ultimate objective:			Equitable and sustainable water-sharing arrangements

conditions. Price signals, polluting behavior deterrents, shared environmental rights, welfare savings, and market-based reallocation mechanisms are all features of the Australian policy arrangements (Krutilla & Alexeev, 2014). The design and implementation of market-based reallocation mechanisms required significant investments to reduce demand in the MDB via a Cap on further water extraction, and unbundling (separation) of land and water rights to enable reallocation between users. More recently, policy reforms have focused on buying back water rights from willing irrigators (agricultural sector) to

Table 2
Assessing the Four Stages of Water Development in Australia's Murray-Darling Basin

Sustainable adaptation evaluation criteria	Exploration	Expansion	Maturity	Contraction/ environmental
Long-run supply from impounded water	Elastic	Elastic to Inelastic	Inelastic	Inelastic
Physical condition of impound/delivery system	Little to no infrastructure. All infrastructure systems are new	Public-funded infrastructure is in new to good condition	Aging public infrastructure in need of expensive repair, upgrade, or replacement	No new large-scale public infrastructure
Demand for delivered water	Minimal, often no or minimum charges to access water	Low but growing demand. Elastic (but not perfectly) at low prices; inelastic at high prices	High and increasing demand. Elastic at low prices; inelastic at high prices. Market failures	High but stable demand. Elastic at low prices; inelastic (but not perfectly) at high prices. Market reallocation
Improved security/reliability for all water users	Not applicable (only during extreme drought or low-supply events)	Minimal but increasing. Drought exposure prompts new rounds of investment in long-run supply	Intense apart from periods of increased supply (e.g. flooding)	Reallocation improves security/reliability for all users
Non-convex demand solutions in water markets	Nil	Nil	Yes (increasing frequency of occurrence)	Yes (stable frequency of occurrence)
Social costs of subsidizing increased water use	Zero to very low	Low	High and rising	Should be nil
Externality recognition and management	Nil	Minimal	Extensive externalities (mainly negative)	Reduction (increase) in negative (positive) externalities
Equitable and sustainable water-share arrangements	No	No	No	Yes

Source: Adapted from Adamson (2015).

recover water to support ecological functions (environmental sector) under the 2007 *Water Act* that empowers a basin-wide management Plan (hereafter Basin Plan) incorporating sustainable diversion limits (SDLs) and agreed social, economic, and environmental water use objectives (Wheeler et al., 2014). To get to this point, water policy in Australia experienced four major stages of demand transition as described below.

3.1. Supply-Side Solutions

3.1.1. Exploratory Stage

The period of water reforms from European settlement to approximately 1915 is referred to as the *Exploratory Stage* (Musgrave, 2008). During this period, the allocation of water resources was via riparian rights. The 1886 *Victorian Irrigation Act* first altered riparian rights so that ownership and control of water resources were vested with the states (in the MDB these include Queensland, New South Wales (NSW), Victoria, and South Australia), allowing state-centralized management and greater utility of larger areas. New water entitlement rights that varied with the climatic conditions were created to provide a proportion, rather than a fixed, volume of water to users which was novel in comparison to the rest of the world (Connell, 2007). At the time of Federation in 1901, the new *Constitution* upheld state rights to own and use water for conservation and irrigation (Waye & Son, 2010), requiring cooperative arrangements to design and implement water policy that persist to this day.

3.1.2. Expansion (Growth) Stage

The second period of reforms (1915 to the 1970s) is referred to as the *Expansion Stage* (Musgrave, 2008). During this period, water resource and irrigation development comprised a nation-building exercise to drought-proof the country (Davidson, 1969). After Federation, the states controlled and operated water resources. However, federal government funding helped to develop irrigation schemes and soldier-settlement farms for successive returning servicemen after World War One, World War Two, and the Korean and Malayan Operations (NWC, 2011). This period saw a shift of water resources from navigation uses to irrigated production, a tenfold increase in major dam storage capacity, and protectionist agricultural policy including imported product tariffs, production controls and quotas, price reserve schemes, and statutory marketing to bolster irrigation water uses and food security (Industry Commission, 1991). Each state responded differently to these signals. For example, NSW agriculture was dominated by annual crops such as rice and cotton under incentives to use all water each year (Musgrave, 2008). Victorian farmers invested in dairy and horticulture with higher fixed-water demand characteristics requiring reliable supply sources and conservative water management (Bjornlund & McKay, 2001). Finally, South Australian water users focused on irrigated horticulture and navigational uses of water that, closer to the end of the river system, required even more conservative management attitudes (Cruse, 2008).

3.2. Demand-Side Solutions—Including Technical and Allocative Efficiency

3.2.1. Maturity Stage

Water policy in the 1960s and 1970s reflected a growing awareness of limits to water resources. South Australian moratoriums on new water entitlements in 1969 were followed by a general 10% reduction in volumetric allocations by 1979 (Bjornlund & O'Callaghan, 2003). NSW imposed catchment-specific embargoes on new entitlements in 1977, and a full state embargo in 1981. Victorian rights to pump from unregulated streams during summer months ceased after the 1967/1968 drought, effectively capping extraction at existing levels. However, total extraction already exceeded sustainable levels causing environmental degradation in the form of widespread algal bloom events, rising soil and water salinity, and flora/fauna species losses (Connell, 2007). Informal seasonal trade capacity allowed the states to redistribute water under discretionary powers aligned with granting/withdrawing licenses (Clark & Moore, 1985) and policy preferences in favor of consumptive (e.g., irrigation) water use. However, as agriculture protectionist policies began to wane and new low-cost water storage infrastructure sites were largely exhausted, the need to incorporate environmental water externalities (e.g., salinity) in water management agreements became increasingly apparent (MDBC, 2007). Economists suggested water reallocation should be achieved via markets with inputs/outputs valued at their economic cost (AWRC, 1986). These factors meant that water policy had shifted to a *Mature Stage* (1980s to 2007) characterized by appreciation of the limits on river systems, federal powers increasingly being applied to resource management, and arguments for market-based reallocation (Randall, 1981).

Market-based reallocation required several reforms. First, riparian rights were gradually replaced with legislative arrangements and de jure property rights recognized by formal legal instruments that, if challenged jurisdictionally or administratively, would most likely be upheld (Schlager & Ostrom, 1992). Second, land and water rights were unbundled to enable transfers in response to risk, seasonal conditions, and/or strategic planning. Unbundling was essential for market-based reallocation to work effectively and efficiently (Wilson & Francis, 2010). Low levels of trade occurred from the early 1980s (South Australia), with NSW and Victoria experiencing transfers by the early 1990s. Third, a 1995 audit of river flows concluded that median annual flow-to-sea levels were 27% of natural, creating drought-like flow patterns in 60% of years as compared with 5% under natural conditions (MDBMC, 1996). On July 1 1997 regulators imposed a Cap on further extraction in the MDB. Fourth, the states were encouraged to introduce water management and planning arrangements to address overallocation and achieve sustainable (contracted) levels of extraction. However, by 2004 many states had failed to deliver on these commitments, and water planning proved inadequate for the reallocation task (NWC, 2007). Finally, early assessments of water reallocation requirements to achieve sustainable outcomes concluded that a ~1,900 GL (or about 1.5 million acre-feet) reduction in current demand could achieve a moderate probability of future environmental health (Jones et al., 2003).

3.3. Adaptive Management

3.3.1. Environmental (Contraction) Stage

Recognition of the need to reallocate water from consumptive (e.g., irrigation) to environmental uses triggered an *Environmental Stage* (2007 to present)—also described as a contraction phase (Watson & Cummins, 2010). A series of intergovernmental agreements set requirements for water recovery via market mechanisms and/or efficiency investments (COAG, 2004a) and made the states responsible for achieving sustainable extraction levels (COAG, 2004b)—largely mirroring Turton's (1999) technical/allocative efficiency levers. In addition, the Basin Plan was enacted with periodic reviews (MDBA, 2012). Part of the Basin Plan addresses the need for a better understanding of all conjunctive water resources—including groundwater regulation to increase sustainable future management—to recognize nonlinear relationships (Chiew et al., 1992) and an attempt to manage both known future risks, as well as uncertainties (Carey & Zilberman, 2002).

Three significant water recovery programs have been implemented. First, *The Living Murray* (TLM) initiative invested ~AU\$1 billion to recover 500 GL between 2005 and 2009 using a mixture of technical (irrigation upgrade) and allocative (buyback) efficiency levers. Second, under a new recovery target of up to 3,200 GL the federal *Restoring the Balance* (RtB) program invested AU\$3.1 billion to purchase up to 1,500 GL of water entitlements from willing sellers between 2008 and 2015. This was coupled with the *Sustainable Rural Water-Use and Infrastructure Program* (SRWUIP) which will ultimately invest AU\$8.4 billion to achieve up to 1,700 GL of water savings. These water recovery targets can be reduced if water managers can achieve environmental (sustainable) objectives with (i) less water (i.e., *supply measures*), (ii) greater delivery system efficiency savings (i.e., *efficiency measures*), and/or (iii) more effective environmental water delivery in future (i.e., *constraint measures*); as long as they avoid negative socioeconomic impacts (MDBMC, 2014). Progress as at 30 June 2019 suggests 2,100 GL have been recovered toward the SDL target, including the adjustment mechanisms listed above (DAWR, 2019).

4. Framework and Critical Assessment Results

In this section we evaluate the major policy/program levers implemented in the MDB as discussed to achieve the *Environmental Stage* (i.e., contraction of consumptive resource use) which should lead autonomously to adjustment capacity, with little recourse to further policy or intervention. Further, we evaluate what current policy lever implementation suggests for necessary future reforms in the MDB, and how this might inform other water management contexts. Current MDB reallocation policies (Table 2) allow us to assess how well different policy elements align with water reform stage characteristics and their objectives according to Turton (1999). Following that, we can assess where current MDB reforms may not be responding effectively to evolving, more demanding, and multifaceted sustainability objectives. Subsequently, we posit what trajectory any fifth-stage water demand may assume. First, recall the ideal characteristics of the *Environmental (Contraction) Stage* shown in Table 2, adopted under the Basin Plan to achieve water demand reductions and

a transition to sustainable extraction levels. In addition, our common water demand characteristics can be applied across the three recovery programs described above (i.e., increased groundwater access under new regulation, *SRWUIP* technical efficiency, and *RtB* allocative efficiency) to analyze their effectiveness with respect to sustainability objectives.

4.1. Groundwater Regulation

Groundwater resources in the MDB are viewed by water managers as underutilized, with capacity for expanded extraction. Increasing access to groundwater under the Basin Plan (MDBA, 2012) is resulting in elastic supplies of water resources in the short run, via relatively new infrastructure maintained by private users. We expect demand to be high and stable, inelastic at higher prices, and increased total water demand should see resources reallocated to consumptive users such as irrigators over time, as surface water supply decreases. Some non-convex market reallocation may occur during extreme supply events where uncertainty results in short-run adaptation (e.g., inflated water market prices). But overall the impact to positive/negative externalities should be low together with the social cost of subsidizing groundwater investment. Thus, the sustainability of MDB groundwater systems, and the effectiveness of this policy in contributing to a contraction of water demand, will depend on the final water user where any future increased negative environmental externalities will signal failure. As such, the groundwater component of the Basin Plan contains elements of both the *Expansion* and *Environmental Stages* as defined in the preceding section (Table 3).

4.2. Allocative Efficiency via Buyback

By contrast the government *RtB* program, underpinned by a tender-driver buyback of water entitlements from willing sellers (irrigators) to reallocate water to environmental objectives, is not expected to reduce the inelastic supply of water (following redistribution). Infrastructure will be maintained by irrigators (on-farm and off-farm), and increasingly by public programs via environmental manager contributions to costs (off-farm and new structures at environmental sites). Demand will remain high and stable, but consumptive water availability may decrease in some years; potentially increasing competition among irrigation users. This will drive non-convex market solutions in such years where sectoral access to allocative efficiency mechanisms may be limited. However, there are no social costs of subsidized water uses, and reduced (increased) negative (positive) externalities. The result is arguably equitable and appears to drive sustainable water-sharing arrangements that most closely resemble an *Environmental (Contraction) Stage* of demand (Table 3).

4.3. Technical Efficiency via *SRWUIP*

Last, we examine the *SRWUIP* recovery component via investments in on- and off-farm water use technical efficiency (Table 3). Long-run supply will remain inelastic as no new large-scale storages are built. However, a significant proportion of relatively small-scale water infrastructure will be new, subsidized, and more expensive to operate (Adamson & Loch, 2018). Demand will likely increase, particularly during drought events, and total water use may increase under changes to land use or irrigation practices (Ward & Pulido-Velazquez, 2008). If commodity transitions also occur, then competition for water resources will increase with non-convex market solutions becoming more evident (Adamson et al., 2017). Importantly, if production systems (economic, natural, cultural, and social) transition toward requiring fixed water inputs in all years, then the delivery system will become less flexible and exposed (Loch, Adamson, et al., 2020).

It is possible that the social costs of achieving these outcomes will be relatively high, increasing over time as investment options diminish; especially while water savings continue to be split equally (i.e., 50/50) between irrigators and the environmental water holder (Loch et al., 2014). Uncertainty surrounding savings from technical efficiency will undermine any assessment of equitable and sustainable water sharing, indicating that the components of the Basin Plan resemble both *Expansion* and *Maturity Stages* of demand. This assessment suggests that, where the components are jointly applied (i.e., technical and allocative efficiency programs are balanced) contracted water demand is achievable consistent with Turton's framework, while groundwater access provides a basis for adaptive future management. However, the Basin Plan has varied Turton's balanced approach over time, as detailed below.

Table 3
Comparing Key Characteristics of the Basin Plan to Turton's (1999) Sustainable Adaptation Water Demand Outcomes

Sustainable adaptation evaluation criteria	Ideal characteristics of the <i>Environmental Stage</i>	Basin plan policy characteristics		
		Groundwater	RtB	SRWUIP
Long-run supply from impounded water	Inelastic	Elastic in the short run	Inelastic	Inelastic
Physical condition of impound/delivery system	No new large-scale public infrastructure	Private infrastructure new and maintained by users	On-farm infrastructure maintained by private users, off-farm unknown	Public infrastructure (on- and off-farm) new and subsidized
Demand for delivered water	High but stable demand. Elastic at low prices; inelastic (but not perfectly) at high prices. Market reallocation	High but stable demand. Elastic at low prices; inelastic at high prices. Some market failure. Water use increases	High but stable demand. Elastic at low prices; inelastic at high prices. Market reallocation decreases water use	High, potentially increasing demand in droughts. Elastic at low prices; inelastic at high prices. Water use may increase
Improved security/reliability for all water users	Reallocation improves security/reliability for all users	Reallocation of groundwater to irrigators	Reallocation increases security/reliability for all users	Reallocation results in regional winners/losers for water security/reliability
Non-convex demand solutions in water markets	Yes (stable frequency of occurrence)	Yes but with low probability	Yes with stable frequency	Yes with increasing frequency
Social costs of subsidizing increased water use	Should be nil	Nil to very low	Nil	High and rising as low-hanging fruit expended
Externality recognition and management	Reduction (increase) in negative (positive) externalities	No impact	Reduction in externalities and social costs	Some reduction in externalities but social costs remain high
Equitable and sustainable water-share arrangements	Yes	Depends on the final user	Yes	No
Stage the policy component resembles		Elements of <i>Expansion and Environmental Stages</i>	Elements of <i>Environmental Stage</i>	Elements of <i>Expansion and Maturity Stages</i>

Source: Adapted from Adamson (2015).

4.4. Technical/Allocative Efficiency Applications in the MDB

The MDB case study exhibits general policy applications of technical and allocative efficiency programs to reduce water demand in an *Environmental Stage*. However, the two levers have not been routinely utilized at the same time. For example, in TLM program allocative efficiency formed part of the policy but this was overshadowed by technical efficiency projects to recover water. Ultimately, the program had to be lengthened—and the funding doubled to AU\$1 billion—to achieve 225 GL of water savings through technical efficiency projects (DotE, 2014); though TLM water does not contribute to demand contraction objectives in the Basin Plan (Adamson & Loch, 2014). By contrast, environmental water recovery under the AU\$13.1 billion *RtB* and *SRWUIP* programs began toward the end of the Millennium Drought (2000–2010) with a focus on allocative efficiency buyback from willing sellers (2008–2011). After a return to normal supply conditions, pressure was bought to bear on the federal government to downscale buyback in favor of technical efficiency (Australian Parliament, 2011). In effect the government had lost its political legitimacy with irrigators. Despite suggested means by which buyback could be made more attractive to end-users, and address some of the design issues (Bark et al., 2014), by 2015 buyback had been capped at 1,500 GL of total recovery (DotE, 2015), and technical efficiency became the main policy lever in play.

A focus on *SRWUIP* technical efficiency has in turn raised concerns about the cost per recovery unit (Loch et al., 2014), return flow impacts on environmental flows (Grafton & Williams, 2019), and the accuracy of water savings (Adamson & Loch, 2014)—causing government to lose legitimacy with much of the scientific and wider community. While some reports state that it is not the volume but the application of recovered water that is important (Wang et al., 2018), many scientists remain concerned about the emphasis on technical efficiency projects to generate demand contraction alone. Alongside this, economists have raised concerns that the most cost-effective pathway to water recovery (buyback from willing sellers) has been underutilized and as a consequence, and the recovered water has come at a much greater cost to taxpayers than necessary (Loch et al., 2014).

Consequently, the policy discussion surrounding water recovery in the MDB has turned toxic, with farmers arguably oversupported by current policy, and scientists and economists arguing for a return to allocative efficiency programs such as buyback (e.g., Adamson & Loch, 2018). In the MDB case study there was a brief period when both levers were in operation (~2009–2012), which by contrast with current debate appeared quite calm. This offers some support for Turton's framework; that is, when both levers are operating all parties are (un)happy to some degree, but placated with some technical/allocative efficiency contributions to recovery objectives.

Consistent with Quiggin's (2014) reflections on climate change policy and the use of different programs (e.g., carbon pricing versus renewable energy targets) in a context of financial and political trade-offs, our analysis suggests that Turton's framework has some value in describing appropriate pathways to effective water demand reduction. In support of this claim, and the implications of current policy decisions for alternative pathways to a fifth stage, we offer three additional examples using stylized data to emphasize likely water supply/demand outcomes from the use of technical and allocative efficiency levers. The requirement for balance is found in their opposite effects.

5. Stylized Examples

Any imbalance between the studied policy levers may create incentives that misallocate resources. We illustrate this by providing a set of oversimplified equations. Assuming demand = supply, or $D = S$, we can represent the supply equation as:

$$S = (u_{sw} + l_{sw}) + (u_{gw} + l_{gw}) \quad (1)$$

Supply is a combination of water use (u) and system losses (l) to move water from location to location through conjunctive sources (e.g., surface (sw) or groundwater (gw)). For simplicity we focus on surface water—although groundwater could also be examined via equation 1. A surface water entitlement E , such as that of an irrigator, is represented as $(E) = (u_{sw} + l_{sw})$, and for this argument we assume that $E = S$. In our example there are two forms of arbitrary supply: a *Mature Stage* (S_1), and a *Contraction Stage* (S_2). This assumes $S_1 > S_2$ and that a change to demand is required. As before, to shift from S_1 to S_2 we could invest in system improvements (technical efficiency) and/or purchases of E (allocative efficiency) to change u_{sw} and/or l_{sw} . Below, we drop the (sw) notation and address each investment option separately.

5.1. Technical Efficiency—Network Savings Example

Where $S_1 = (u_1 + l_1) = E$, as $l_1 \rightarrow S_1$ entitlement reliability will decrease and more water will be needed to deliver residual u_1 . Losses, l_1 comprise conveyance values (seepage or evaporation), minimum ecological base flows as shown in Figure 1, and/or groundwater recharge. To reduce l_1 a focus on savings in the delivery network through technical efficiency gains is required. Technical efficiency gains may result in win-win situations; that is, technical efficiency investments may change l_1 so that $S_1 > S_2$ and $u_1 > u_2$. We illustrate this as follows. Assume total system E is owned by irrigators (individual farmers E_f) and the network manager (E_N), such that $\sum E = (E_f + E_N)$. If $S_1 = 1200$ ML (or about 970 acre-feet) of which $E_f = (u_1 + l_1) = 950$ ML + 50 ML = 1,000 ML, and $E_N = (l_1) = 200$ ML, then farmers receive a 95% reliable entitlement (i.e., 950/1,000), and 200 ML is required to deliver irrigation water. In many MDB irrigation systems, users are shareholders in the network and may benefit equally from efficiency gains (i.e., 50/50 equal share of any water savings). Thus, if we require $S_2 = 1,150$ ML (i.e., a 50 ML contraction in system losses) total loss reductions will need to be 100 ML—where 50 ML of savings is assumed to return (r) to irrigators. In that case, $S_2 = 1150$ ML, of which $E_f = (u_1 + l_1 + r) = 950$ ML + 50 ML + 50 ML = 1,050 ML and $E_N = (l_2) = 100$ ML. Note that if entitlement reliability remains at 95% irrigators now have 997.5 ML of water at their disposal, which could drive total irrigated area increases (Adamson & Loch, 2014) and a wealth transfer in favor of consumptive users.

5.2. Technical Efficiency—Farm Savings Example

Alternatively, where $S_1 = (u_1 + l_1) = E$, as $u_1 \rightarrow S_1$ this suggests savings should be sought on-farm from lower-scale investments. Logically, funds could be directed toward productive efficiency (e.g., increased yield/ML) and/or application efficiency (e.g., reduced field/channel loss) projects. These options could be described as $u_1 = (c + m + a + v)$, where c is the water volume used by crops, m is how water is delivered

within the farm, a is the application technology, and v is a varietal choice of commodity that may use less water inputs (Adamson & Loch, 2019). Repeating the previous example, assume $S_1=1200$ ML, of which $E_f=(u_1+l_1)=950$ ML+50 ML = 1,000 ML, and $u_1=(7+0.5+1.5+0.5)$ ML/ha, giving us 100 ha of production. To achieve $S_2=1,150$ ML, we must save 0.5 ML/ha (i.e., $100 \times 0.5 = 50$ ML) via changes to the following: commodity/varietal choice (e.g., wheat over lucerne planting), irrigation practices (e.g., deficit irrigation), management practices (e.g., irrigation timing), farm design (e.g., channel lining), and/or application technology (e.g., central pivot over flood). To benefit, irrigators must therefore consider combined investments into c , m , a , and v to achieve 100 ML of savings—of which they will receive 50 ML back. However, decisions not only change what is produced (increased or decreased production area), but also potentially the delivery system, field losses, water use by variety, and/or the amount of water available to downstream users where that supply was dependent on (for example) return flows—especially where such interactions are not properly accounted for or recognized in the system (Adamson & Loch, 2014)—although we note that, if system models suggest return flows are zero, then arguably there are no savings to be made in the first place. In sum, these choices provide insight into the decision-maker's risk attitudes, which may be averse. As with many technical efficiency programs, public subsidy incentives may help to change this risk attitude, triggering transformation at the farm level, wider sectoral adjustment, and possible downward pressure on predicted future returns. Note though that, in this case, expected entitlement reliability will not necessarily increase as the irrigator would be required to locate savings and surrender them.

5.3. Allocative Efficiency—Entitlement Buyback Example

As a last example, if water recovery can only be sourced from entitlement purchases, reduction could come from underutilized entitlements or sellers willing to relinquish short-run productive opportunities/risk mitigation. Again, if $S_1=1,200$ ML of which $E_f=(u_1+l_1)=950$ ML+50 ML = 1,000 ML, and $u_1=9.5$ ML/ha, then the 50 ML savings required for $S_2=1,150$ ML must come from retiring 5.26 ha of production (50 ML/9.5 ML). By contrast, buyback offers a far “cleaner” set of circumstances under which savings are achieved, and also a more accurate signal of water value for both irrigators and recovery buyers. Further, buyback may provide capital for irrigators to reduce farm debt, buy water in the future, and/or to privately invest in efficiency gains—providing second round benefits in the market/industry sector. Note also in this case that the entitlement reliability will not change—and that same reliability will transfer completely to the buyer.

5.4. Market Price Impact From Allocative Versus Technical Efficiency

Consistent with our earlier assertion of uncertain *fifth-stage* outcomes, the examples presented above highlight that total water used on-farm can increase/decrease depending on the policy lever choice/setting, which may also be reflected in future water market prices and irrigator asset values. Where irrigation network upgrades are selected, total supply and/or entitlement reliability (as a function of use and losses) may increase—along with a potential increased demand for that entitlement (Figure 2a). The movement of both supply and demand may create mixed market signals, including mixed outcomes for price, dependent upon elasticities (Adamson et al., 2017). By contrast, where on-farm efficiency upgrade investments or entitlement buyback are selected, total supply will contract without change in demand (Figures 2b and 2c). Further, as prices increase, entitlement owners gain wealth from the appreciation in asset base—where buyback signals will be immediate, but on-farm efficiency signals will take time to emerge through the market (as indicated by the dotted line). Increased time to achieve price signaling change may also result in increased perceived (unfounded) fears about impacts from market speculation.

In summary, these examples offer additional support to the different end path outcomes suggested by Turton (1999), and a need for balanced approaches to achieve sustainable demand following contraction efforts—which will be costly to enact. Further, these examples speak to the importance of fully accounting for system losses and a required understanding of the differentials between S_1 and S_2 prior to making policy/program investment decisions. While this issue has been noted by others (e.g., Grafton & Williams, 2019) in some respects greater clarity is offered by the examples above. In the final section of this paper we elaborate on these findings and highlight some additional issues that may be relevant to Australian water managers approaching an (uncertain) *fifth stage* of water reforms, as well as other contexts considering their own transitions to reduced total water demand.

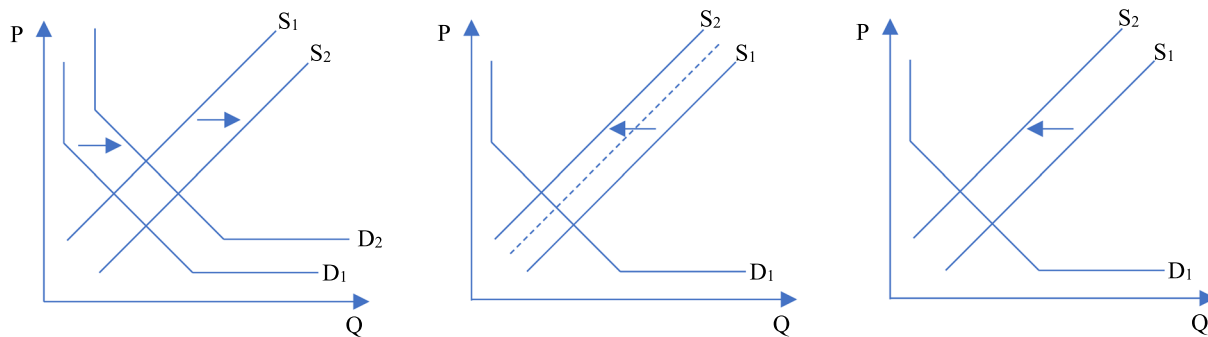


Figure 2. (a) Network efficiency. (b) On-farm efficiency. (c) Buyback.

6. Discussion

The development of water policies in Australia provides a useful example to illustrate issues including: the impact of past policy decisions, the role of generating and incorporating new information, and challenges for reflecting social expectations in policy processes and decisions. The paper also checks Turton's conclusions that both allocative and technical efficiency policy levers are necessary/insufficient on their own for natural resource reconstruction outcomes. While further assessment is needed to fully test these claims—for example using qualitative comparative assessment techniques—we would agree with Turton's assessment in the case of Australia's water reforms. An imbalance in these levers would suggest ultimate slippage in contraction gains, where one program may in fact cannibalize the successes of the other (Adamson & Loch, 2018). Ultimately, any *fifth-stage* of reforms must be capable of adapting to (i) on-going uncertainty associated with climate change impacts on future water reliability; (ii) any transaction costs associated with adaptation; (iii) social consultation to reflect dynamic change; and (iv) the relevance of minimum ecological base flows in river systems.

6.1. Uncertainty and Adaptability

Effective policy design and assessment must account for uncertainty and unawareness of how to adapt to future realized events, such as climate change impacts on water supply quantities and quality. We do not focus on water quality issues in this paper, as here our attention is upon reducing the total quantity of water consumption. That said, negative water quality issues may appear in the Maturity Stage, when externalities (e.g., blue-green algal outbreaks) could severely impact the full range of users. Advancing to the Contraction Stage should increase the probability of water available for dilution improvements, increasing total water quality as per common property theory (Ciriacy-Wantrup & Bishop, 1975). However, for both water quantity and quality issues uncertainty is increasing through more refined understandings of nature-human interactions (Norgaard, 2010), and because scarcity, innovation and rising population disturb the balance of environmental protection and economic development (Tainter, 2011). Typical stages of change (e.g., product life cycles) might experience renewal or shifts back to expansion on the basis of technological innovation. Current political fascination with technical efficiency innovations to grow total water supply in many areas around the world follows such thinking. However, in water, opportunities for (cost-effective) growth or large-scale supply expansion akin to product life cycle transformations are limited—if possible at all. Complex water problems will require nuanced policy responses featuring capacity to (ideally) respond proactively in the face of dynamic adjustment requirements and shifting social objectives, as we have tried to accommodate through our use of Ostrom's (2009) design principles in Table 1. We have therefore argued in this paper that flexible policy and program solutions should involve both allocative and technical efficiency programs to achieve sectoral demand change.

As such, evidence-based policy must prevail; emotion should have no place in policy design/implementation. One approach for dealing with increased future uncertainty may be to combine familiar policy assessments (e.g., cost-benefit analysis) with innovative models such as state-contingent analysis that use scenarios to capture adaptation to future variability and uncertainty of systems, including low-probability extreme events at the tails of distributions (Quiggin, 2018). This is the subject of current research into the riskiness of stochastic water supply, and the viability of encouraged investments in

water-use efficiency to reduce that riskiness. The findings of this research are discussed elsewhere (Adamson & Loch, 2019). However, we would expect that the findings reported herein will be important for informing future policy selection and program design in developing nation contexts, consistent with the advice provided by Gruère et al. (2018).

6.2. The Transaction Costs of Adaptation

The process of transitioning existing policy/programs to more adaptive arrangements—or creating new policies with inherent adaptive characteristics—will be complex and challenging. As our understanding of issues increases through scientific research in response to changes in social priorities and/or management requirements, this complexity also grows. Perhaps this is one reason why science and policy are drawing further apart, as the differential between useful and available information supporting quick and easy solutions in a political context—and scientific goals of rigorous, informed, and consistent information—becomes stark. Yet the complex nature of these problems and our growing appreciation of future uncertainty for many natural resources suggests a need for governance capable of change and adaptive learning in response.

Adaptive policy combining social expectations and rigorous science is possible. Salinity management in the MDB provides an example, where public institution investments over 30 years have resulted in the following: positive (and increasing) reductions to riverine salinity levels based on ex-post performance assessments, flexible management arrangements despite a reliance on engineering interventions to achieve those reductions, and improved scientific knowledge of management options (Loch & Gregg, 2018). This case suggests that natural resource policy can transverse a tendency toward meeting objectives combining governance requirements of today, incorporating new information, and meeting social expectations of tomorrow. But it also stresses the critical importance of investing correctly over a sustained period (beyond political cycles) to achieve success.

6.3. Social Consultation to Reflect Dynamic Change

In latter stages of demand management we may also be confronted with new uses that will need to be added. As the need for an expanded set of market property rights is recognized—that might include cultural flows (Jackson et al., 2019) or altered demand from ecosystems following severe fires and landscape change—effective policy will require mechanisms capable of incorporating changes into new/existing arrangements and implementing appropriate assessment metrics to assist in evaluating progress toward new collective objectives. Thus, another issue contributing to the emergence of a *fifth stage* of water reforms in Australia is the dynamic nature of social expectations and increasing community involvement in decisions about the management of natural resources. At a broad scale this shift to greater community involvement has been linked to a growing awareness of the complexity and interconnectedness of many environmental and social policy problems (Hartz-Karp et al., 2010). Locally, this could be linked to the growing distrust of institutions in Australia (AICD and KPMG, 2018), the dynamic nature of social expectations, and the emerging issue of irrigators' social license (e.g., Martin & Shepherd, 2011). The increasing involvement of community expectations and potency of social license issues has implications for policy. Any policy change may result in a transfer of welfare from one group to another (Shleifer, 2005); for example, from irrigators to the broader community, or from upstream to downstream water users. As we have discussed, the task for policy makers is to manage the trade-offs between different groups in society, their respective expectations for change, and facilitate social change toward collective desired long-term equity and sustainability outcomes, again highlighting the relevance of the connections shown in Table 1.

To achieve this balance, policy makers will need to employ information from social and natural sciences at all stages of policy design and implementation. As discussed, risk and uncertainty would feature prominently in the debate. Finding the common interaction point between science and policy will be critical in future natural resource policy design/effective implementation.

6.4. The Importance of Base Flows

Finally, we return to the importance of ecological base flows in water governance arrangements, as a specific feature of any *fifth stage* of demand reform. Base flows can be thought of as a critical “line in the sand” for many water governance contexts, where any reduction of resources below that line (somewhere between the blue line and the sustainable extraction level in Figure 1) represent increased risk of irreversible long-term natural, social, cultural, and financial capital loss. Where those same base flows provide the

basis for consumptive benefits to other users (e.g., flows on which to piggyback conveyance water, recreational flows, esthetic gains) they should be fully protected and awarded priority status within the system of rights that arise from policy development or change. Further, where base flows are prioritized and achieved we may have to lower the sustainable resource reallocation threshold. As discussed, where possible, changes should be openly communicated to users ahead of design and implementation and consulted upon widely before adoption.

Australia is presently struggling with illegal extraction of base flows, and how best to more adequately detect infringements, prosecute offenders, and recoup losses to ecological functions (Loch, Carmody, et al., 2019). The situation in Australia suggests future research should be focused on better understanding the nature of resource demand, supply, quality, and vulnerability to a range of shocks beyond climate change to enable informed policy making and investment choices. In the absence of proper enforcement, existing users may exceed their rights, and third parties without rights may also attempt to profit. Therefore, failure to properly account for total water use may mean that current actual water use is already on an upward trend—consistent with our earlier example. The MDBA could learn from experiences in the Colorado River Basin where field surveys and mapping, remote sensing, and return flow calculations are used to account for water use and returns (see Bruce et al., 2019). However, an exploration of the economic incentives behind illegal resource extractions—and the relevance of effective enforcement—underpins the broader policy design and implementation discussion above.

A further issue that is becoming evident in Australia has been the transition toward inflexible production systems that always require a fixed unit of water to maintain their capital integrity. As debated by Adamson (2019), all production systems (social, natural, cultural, and economic) follow similar processes involving water inputs that can be represented by fixed and variable requirements. Fixed water production systems include perennial crops, permanent wetlands, and critical human water supplies, while variable water production systems may be represented by ephemeral wetlands, recreation uses, and annual crops. Any increased transition toward higher fixed water production system requirements may result in unintended consequences such as capital loss where the net water demand in every year exceeds the ability of supply sources and/or the market to reduce risk from climate variability. This is a topic of research that will require some considerable future work to better understand and incorporate into science policy discussions.

7. Conclusion

Despite the best intentions of all parties during the development of Australia's water reforms, political trade-offs and rent seeking have delivered instances of second best outcomes—that is, a focus on technical efficiency projects in the absence of allocative efficiency reductions. The Australian approach to water reform has thus been reactive rather than proactive in terms of its design and implementation—resulting in actual outcomes far-removed from the original hypothesized arrangements. In this paper we have used previous reform stages to examine progress toward *fifth-stage* water demand reduction objectives within an adaptive capacity framework, and attempted to analyze the potential trajectory for future Australian water demand using a framework by Turton. The *fifth-stage* path will only be revealed over time in response to decisions made today. This highlights the importance of our current choices, and the role that both science and politics have in making those decisions. Ideally, any *fifth-stage* reforms should improve national welfare via the recognition of increasing risk and uncertainty, the effective reallocation of resources in response, and a capacity to reflect dynamic social expectations. Defining the *fifth stage* of water reforms in the MDB provides some additional assessment goalposts for periodic Basin Plan reviews.

This framework has applications that extend beyond water to describe and assess any critical resource (e.g., the 2030 Sustainable Development Goals, in particular SDG11: *Sustainable Cities and Communities*, SDG12: *Responsible Consumption and Production*, and SDG13: *Climate Action*). In addition, the lessons learned from this analysis of water reforms in Australia provides valuable insights for modern jurisdictions at earlier stages of water management change and adaptation, where managers may invest in adaptive policy design/implementation options that minimize future lock-in costs, reflect the opportunity cost of public expenditure, and result in adaptive arrangements more capable of responding to dynamic change and political rent seeking. It also clearly highlights the need for Australian policy to reconsider the role that buyback must play in future water demand reductions. Finally, the study also demonstrates a need for economists

and water managers to extend their remit; that is, to work with government and social decision makers to identify suitable transition pathway expertise and learn from other jurisdictions that are further ahead (e.g., energy supply and renewables). The insights provided herein suggest policy makers should return to planning for the long-term and developing systems capable of dealing effectively with dynamic conditions (e.g., adverse climate impacts on water supply and quality, revision in scientific knowledge, land use change or totally new demands, and/or political and social preferences for better environments). Ultimately, it is our view that astute water managers could skip the fourth stage completely, by identifying and investing in robust public and private institutional designs capable of dealing with all future states.

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References

- Adamson, D. (2015). Restoring the balance: Water reform & the Murray-Darling Basin plan. PhD, University of Queensland.
- Adamson, D. (2019). Irrigating the environment. *The Centre for Global Food and Resources Working Paper*. South Australia, https://drdavidadamson.weebly.com/uploads/1/0/3/7/103791100/irrigating_the_environment_wpaper.pdf: The University of Adelaide.
- Adamson, D., & Loch, A. (2014). Possible negative feedbacks from 'gold-plating' irrigation infrastructure. *Agricultural Water Management*, *145*, 134–144.
- Adamson, D., & Loch, A. (2018). Achieving environmental flows where buyback is constrained. *Australian Journal of Agricultural and Resource Economics*, *6*, 83–102.
- Adamson, D. & Loch, A. (2019). Investments and uncertainty: Cost-benefit analysis and water-use efficiency. *The Centre for Global Food and Resources Working Paper*. South Australia, https://drdavidadamson.weebly.com/uploads/1/0/3/7/103791100/wue_working_paper.pdf: The University of Adelaide.
- Adamson, D., Loch, A., & Schwabe, K. (2017). Adaptation responses to increasing drought frequency. *Australian Journal of Agricultural and Resource Economics*, *61*, 385–403.
- Aicd & kpmg (2018). *Maintaining the social licence to operate: 2018 KPMG-ACID trust survey*. Sydney, Australia: Australian Institute of Company Directors and KPMG.
- Australian Parliament (2011). *Of drought and flooding rains: Inquiry into the impact of the guide to the Murray-Darling Basin plan*. Canberra: House of Representatives Standing Committee on Regional Australia.
- Awrc (1986). Proceedings of the joint AWRC-AAES seminar on transferable water rights. *Joint AWRC-AAES seminar on transferable water rights*. Rural Water Commission of Victoria Auditorium, Melbourne 11 December: Australian Water Resources Council.
- Bark, R., Kirby, M., Connor, J. D., & Crossman, N. D. (2014). Water allocation reform to meet environmental uses while sustaining irrigation: A case study of the Murray-Darling Basin, Australia. *Water Policy*, *16*, 739–754.
- Baumol, W., & Bradford, D. (1972). Detrimental externalities and non-convexity of the production set. *Economica*, *39*, 160–176.
- Bjornlund, H., & Mckay, J. M. (2001). Current issues and future directions for Australian water market policies. *Water Australia*, *28*, 74–78.
- Bjornlund, H. & O'Callaghan, B. (2003). Property implications of the separation of land and water rights. *Ninth Annual Pacific-Rim Real Estate Society Conference*. Brisbane, Queensland, 19–22 January.
- Bruce, B. W., Prairie, J. R., Maupin, M. A., Dodds, J. R., Eckhardt, D. W., Ivahnenko, T. I., et al. (2019). Comparison of U.S. Geological Survey and Bureau of Reclamation water-use reporting in the Colorado River Basin. Boulder City NV: U.S. Geological Survey Scientific Investigations Report 2018–5021.
- Carey, J. M., & Zilberman, D. (2002). A model of investment under uncertainty: Modern irrigation technology and emerging markets in water. *American Journal of Agricultural Economics*, *84*, 171–183.
- Chiew, F. H. S., McMahon, T. A., & O'Neill, I. C. (1992). Estimating groundwater recharge using an integrated surface and groundwater modelling approach. *Journal of Hydrology*, *131*, 151–186.
- Ciriacy-Wantrup, S. V., & Bishop, R. C. (1975). Common property as a concept in natural resources policy. *Natural Resources Journal*, *15*, 713–728.
- Clark, S. D., & Moore, H. (1985). Economic criteria for water resource planning and management: Some legal implications. In Department of Arts Heritage and the Environment (Ed.), *Conservation and the economy: Conference papers and proceedings* (pp. 469–497). Canberra, Australia: AGPS.
- COAG (2004a). *Intergovernmental agreement on a national water initiative*. Canberra: Council of Australian Governments.
- COAG (2004b). *Intergovernmental agreement on addressing water over-allocation and achieving environmental objectives in the Murray-Darling Basin*. Canberra: Council of Australian Governments.
- Connell, D. (2007). *Water politics in the Murray-Darling Basin*. Annandale, NSW: The Federation Press.
- Cruse, L. (2008). An introduction to Australian water policy. In L. Cruse (Ed.), *Water policy in Australia: The impact of change and uncertainty* (pp. 1–16). Washington, DC: Resources for the Future.
- Cummins, T., & Watson, A. (2012). A hundred year policy experiment: The Murray-Darling Basin in Australia. In J. Quiggin, T. Mallawaarachchi, & S. Chambers (Eds.), *Water policy reform: Lessons in sustainability from the Murray-Darling Basin* (pp. 9–36). Cheltenham, UK and Northampton, MA: Edward Elgar.
- Davidson, B. (1969). *Australia wet or dry?: The physical and economic limits to expansion of irrigation*. Carlton: Victoria, Melbourne University Press.
- DAWR (2019). *Progress towards meeting environmental needs under the Basin Plan [Online]*. Canberra, ACT: Department of Agriculture and Water Resources. Available: <http://www.agriculture.gov.au/water/mdb/progress-recovery/progress-of-water-recovery> [Accessed 24 October 2019]
- DotE (2014). *Wetlands Australia national wetlands update February 2013 [Online]*. Canberra: Department of the Environment and Energy. Available: <https://www.environment.gov.au/water/wetlands/publications/wetlands-australia/national-wetlands-update-february-2013-1> [Accessed 16 July 2019]
- DotE (2015). *Water amendment bill 2015 [Online]*. Canberra: Department of the Environment. Available: http://www.aph.gov.au/Parliamentary_Business/Bills_Legislation/bd/bd1516a/16bd020 [Accessed Sept 24 2015]
- Grafton, R. Q., & Williams, J. (2019). Thirst for certainty: The urgent need for a water audit of the Murray-Darling Basin. *Farm Policy Journal*, *16*, 14–22.

- Grùere, G., Ashley, C., & Cadilhon, J. (2018). Reforming water policies in agriculture: Lessons from past reforms. In *OECD Food, Agriculture and Fisheries Papers* (pp. 1–71). Paris: OECD.
- Hartz-Karp, J., Anderson, P., Gasti, J., & Felicetti, A. (2010). The Australian Citizens' Parliament: Forging shared identity through public deliberation. *Journal of Public Affairs*, *10*, 353–371.
- Industry Commission (1991). *Statutory marketing arrangements for primary products* (p. 10). Canberra: Industry Commission report No.
- Jackson, S., Hatton Macdonald, D., & Bark, R. H. (2019). Public attitudes to inequality in water distribution: Insights from preferences for water reallocation from irrigators to aboriginal Australians. *Water Resources Research*, *55*, 6033–6048. <https://doi.org/10.1029/2019WR025011>
- Jones, G., Arthington, A., Gawne, B., Hillman, T., Kingsford, R., Thoms, M., et al. (2003). *Ecological assessment of environmental flow reference points for the River Murray system: Interim report*. Canberra: Scientific Reference Panel for the Murray-Darling Basin Commission, Living Murray Initiative.
- Krutilla, K., & Alexeev, A. (2014). The political transaction costs and uncertainties of establishing environmental rights. *Ecological Economics*, *107*, 299–309.
- Loch, A., Adamson, D., & Auricht, C. (2020). (g)etting to the point: The problem with water risk and uncertainty. *Water Resources and Economics*, *100154*. <https://doi.org/10.1016/j.wre.2019.100154>
- Loch, A., Carmody, E., Adamson, D., & Seidl, C. (2019). Grand theft water: The calculus of cost, compliance and consequence. *The Centre for Global Food and Resources Working paper*. South Australia, https://drdadavidamson.weebly.com/uploads/1/0/3/7/103791100/water_theft_working_paper.pdf: The University of Adelaide.
- Loch, A., & Gregg, D. (2018). Salinity management in the Murray-Darling Basin: A transaction cost study. *Water Resources Research*, *54*, 8813–8827. <https://doi.org/10.1029/2018WR022912>
- Loch, A., Wheeler, S., Boxall, P., Hatton-Macdonald, D., Adamowicz, W. L., & Bjornlund, H. (2014). Irrigator preferences for water recovery budget expenditure in the Murray-Darling Basin, Australia. *Land Use Policy*, *36*, 396–404.
- Mai, T., Mushtaq, S., Loch, A., Reardon-Smith, K., & An-Vo, D.-A. (2019). A systems thinking approach to water trade: Finding leverage for sustainable development. *Land Use Policy*, *82*, 595–608.
- Martin, P., & Shephard, M. (2011). What is meant by the social licence? In J. Williams & P. Martin (Eds.), *Defending the social licence of farming* (pp. 3–12). Melbourne, Australia: CSIRO Publishing.
- MDBA (2012). *Water act 2007—Basin plan*. Canberra: Murray-Darling Basin Authority.
- MDBC (2007). *A brief history of the Murray-Darling Basin Agreement [Online]*. Canberra: Murray-Darling Basin Commission. Available: http://www2.mdbc.gov.au/about/history_mdbc.html [Accessed 26 September 2011]
- MDBMC (1996). *Setting the Cap: Report of the independent audit Group*. Canberra: Murray-Darling Basin Ministerial Council.
- MDBMC (2014). *The sustainable diversion limit adjustment mechanism*. Canberra: Murray-Darling Basin Ministerial Council.
- Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, *319*, 573–574.
- Musgrave, W. (2008). Historical development of water resources in Australia: Irrigation policy in the Murray-Darling Basin. In L. Crase (Ed.), *Water policy in Australia: The impact of change and uncertainty* (pp. 28–43). Washington, DC: Resources for the Future.
- Norgaard, R. B. (2010). Ecosystem services: From eye-opening metaphor to complexity blinder. *Ecological Economics*, *69*, 1219–1227.
- NWC (2007). *National water initiative: First biennial assessment of progress in implementation*. Canberra, Australia: National Water Commission.
- NWC (2011). *Water markets in Australia: A short history*. Canberra: National Water Commission.
- Ohlsson, L. (1999). Environment, scarcity and conflict: A study of Malthusian concerns, Goteborg University, Department of Peace and Development Research.
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*, 419–422.
- Polasky, S., Kling, C. L., Levin, S. A., Carpenter, S. R., Daily, G. C., Ehrlich, P. R., et al. (2019). Role of economics in analyzing the environment and sustainable development. *Proceedings of the National Academy of Sciences*, *116*, 5233–5238.
- Quiggin, J. (1986). Common property, private property and regulation the case of dryland salinity. *Australian Journal of Agricultural Economics*, *30*, 103–117.
- Quiggin, J. (2014). How I learned to stop worrying and love the RET. In J. Quiggin, D. Adamson, & D. Quiggin (Eds.), *Carbon pricing: Early experiences and future prospects* (pp. 89–100). Cheltenham: Edward Elgar.
- Quiggin, J. (2018). The importance of 'extremely unlikely' events: Tail risk and the costs of climate change. *Australian Journal of Agricultural and Resource Economics*, *62*, 4–20.
- Randall, A. (1981). Property entitlements and pricing policies for a maturing water economy. *Australian Journal of Agricultural and Resource Economics*, *25*, 195–220.
- Rostow, W. W. (1959). The stages of economic growth. *The Economic History Review*, *12*, 1–16.
- Scheierling, S. M., & Tréguer, D. O. (2018). *Beyond crop per drop: Assessing agricultural water productivity and efficiency in a maturing water economy*. Washington, DC: World Bank.
- Schlager, E., & Ostrom, E. (1992). Property-rights regimes and natural resources: A conceptual analysis. *Land Economics*, *68*, 249–262.
- Shleifer, A. (2005). Understanding regulation. *European Financial Management*, *11*, 439–451.
- Tainter, J. A. (2011). Energy, complexity, and sustainability: A historical perspective. *Environmental Innovation and Societal Transitions*, *1*, 89–95.
- Turton, A. (1999). *Water scarcity and social adaptive capacity: Towards an understanding of the social dynamics of water demand management in developing countries*, MEWREW Occasional Paper No. 9, (). London UK: University of London Water Issues Study Group, School of Oriental and African Studies (SOAS).
- Wang, Q. J., Walker, G., & Horne, A. (2018). *Potential impacts of groundwater sustainable diversion limits and irrigation efficiency projects on river flow volume under the Murray-Darling Basin plan: An independent review*. Melbourne VIC: University of Melbourne School of Engineering, Water, Agriculture and Environment Program.
- Ward, F. A., & Pulido-Velazquez, M. (2008). Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences*, *105*, 18,215–18,220.
- Watson, A., & Cummins, T. (2010). Historical influences on irrigation and water policy in the Murray-Darling Basin. In *Network: A publication of the ACCC for the Utility Regulators' Forum* (pp. 1–7). Canberra: Australian Competition and Consumer Commission.
- Waye, V., & Son, C. (2010). Regulating the Australian water market. *Journal of Environmental Law*, *22*, 431–459.
- Wheeler, S., Loch, A., Zuo, A., & Bjornlund, H. (2014). Reviewing the adoption and impact of water markets in the Murray-Darling Basin, Australia. *Journal of Hydrology*, *518*, 28–41.

- Wilson, A., & Francis, R. (2010). Liquid markets. *Utility Week*, 32, 21–22.
- Winpenny, J. (1997). Demand management for efficient and equitable use. In M. Kay, T. Franks, & L. Smith (Eds.), *Water: Economics, management and demand* (pp. 296–303). London, UK: E & FN Spon.
- World Economic Forum (2019). *Global risks 2019*. Geneva: World Economic Forum.
- Young, M. (2014). Trading into trouble? Lessons from Australia's mistakes in water policy reform sequencing. In *Water markets for the 21st century* (pp. 203–214). Dordrecht, Netherlands: Springer.