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Australia 4072

Web: www.uq.edu.au

Authors: Adam Loch, David Adamson, Thilak Mallawaarachchi

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Hydrology and economics in water management policy under increasing uncertainty

A. Loch[a], D. Adamson[b] and T. Mallawaarachchi[b]

[a.] CRMA, School of Commerce, University of South Australia, GPO Box 2471 Adelaide, SA 5000 Australia. Corresponding author; Phone: +61 8 8302 7296, Fax: +61 8 8302 7001, Email*:* *adam.loch@unisa.edu.au*

[b.] RSMG, School of Economics, University of Queensland, Brisbane, QLD 4072, Australia. Email: d.adamson@uq.edu.au

[b.] RSMG, School of Economics, University of Queensland, Brisbane, QLD 4072, Australia. Email: t.mallawaarachchi@uq.edu.au

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ABSTRACT

Well-designed public policy stimulates social progress. However, when governments translate political vision into programmes to deliver desirable social change, the complexity of issues can overwhelm the policy-making process, creating disappointment for all parties and suboptimal outcomes. In this paper we examine why well-known approaches to evidence-based policy-making often fail to provide policy-makers with credible, consistent and clear outcomes in line with broad social interest. We use the Murray-Darling Basin to highlight key stages to formulating effective natural resource policy, and identify key sources of difficulties that need to be managed to maximize scientific contributions. We argue that the need for public policy primarily arises from a lack of perfect knowledge, which causes individuals and agencies to behave in ways that counter social interest. We hypothesize that effective public policy formulation involves: determining what evidence is available, relevant and useful; as well as identifying critical gaps to making public policy necessary and meaningful. We then examine how effective public policy decisions can still be made and how information asymmetry can be managed via strong evidence, expert analysis to verify that evidence, and an understanding of knowledge gaps such that critical interventions can be agreed upon and objectives achieved in view of how they will be managed and resourced. We draw attention to the opportunities available and challenges that exist for hydrologists, economists and other social scientists to work together in assisting the policy process, and in particular to minimize the burden of information constraints in making effective water resource policy.

Keywords: public policy, economics, uncertainty Murray-Darling Basin

JEL Codes: Q25, H89

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1 Introduction

The need for policy arises due to uncertainty in the processes governing society, while the purpose of public policy is to improve social welfare. Governments generally achieve improved social welfare by selecting certain courses of action over others from a consideration of the relevant benefits and costs associated with alternatives. Since the 1990s, there has been increasing recognition that the problem of social choice may be better served through improved scientific input to policy development (OECD, 2002). Acceptance of this logic has resulted in mainstreamed policy-making, where prior internalized government choices have transformed to pluralistic processes involving wider external engagement (e.g. consultation). The pursuit of a scientific approach to policy development dates back to the enlightenment era, but its modern expression, the rational model of decision-making, owes to the seminal work of Herbert Simon (1947), that probed the logic and psychology of human choice. Simon further developed this to form the modern theory of organization (Simon, 1976). The approaches took root in environmental policy-making, and collaborative governance now dominates a broad range of policy areas where uncertainty features prominently as the primary policy concern (Escobar, 2013). This transformation is well demonstrated by the public discourse associated with development of the Murray-Darling Basin (MDB) Plan (MDBA, 2012).

However, in the absence of an established policy science, policy-making remains a craft that brings together existing knowledge (evidence) from various fields to blend diverse interests and opinion with political ideals. In the arena of Australian water policy for example, expert hydrologists, economists and other specialists have provided advice and technical inputs to improve policy design and function. Social input to the policy reform process has typically been achieved through consultation among relevant stakeholders (Crase et al., 2013). Arguably, much of the resultant policy reform has been beneficial and representative of world’s best practice (National Water Commission, 2012; Quiggin et al., 2012). The policies so crafted work broadly within existing legal frameworks underpinned by the Australian Constitution to define individual and group choice sets, thereby influencing how firms and individuals make decisions that collectively impact on society.[1]

The aim of this paper is to identify critical issues surrounding practical water resource public policy, particularly in relation to hydrological realities and economic aspirations. Using the MDB for representative examples, we draw attention to the opportunities available and challenges that exist for hydrologists, economists and other social scientists to work together in assisting the policy process, and in particular to manage the burden of information constraints in the formulation of effective water resource policy. We also examine the benefits of modeling as a means to inform choices for water managers within hydrological or ecological constraints, including risk, ambiguity and uncertainty.

Our discussion demonstrates that, despite improved scientific input, policy formulation remains a suboptimal activity; the evidence-policy relationship is not as clear-cut as its advocates might expect (Banks, 2009). However, we contend that effective policy formulation can be achieved by systematically reducing information asymmetry via strong evidence, expert analysis to verify that evidence, and an understanding of knowledge gaps. We reflect on specific water policy formulation complexity where resources flow across political boundaries, are highly variable in nature, and where the aspirations of resource users and beneficiaries are diverse. Complexity usually arises from uncertainties about how numerous parts of an entity interact. In relation to society, future needs drawn from the environment through economic activities, as well as various climatic states that govern capacity to meet those needs, determine the way we manage the environment. [2] From a hydrologic and economic viewpoint, the nature of our choice sets and how we achieve chosen outcomes are too complex to track through mere simple-system cause-and-effect relationships. When formulating policy interventions in complex systems it is imperative to develop robust and agreed foundations on critical intervention paths toward chosen social welfare objectives, with clear comprehension of societal capacity to fund and manage such objectives.

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[1] We use the term choice sets to represent available options for firms and individuals to select when making decisions within the freedom offered by existing rules of society.

[2] Climate states such as median flows, droughts and high flows

2 The science–policy relationship

2.1 Policy problem

Policies set by governments; social norms, customs or personal values affect how people interact with one another and with their broader surroundings. Instruments that modify the freedom of choice and patterns of interaction amongst individuals and organized entities drive policy outcomes. They do so by allocating rights to resources (property rights); defining incentives for social participation (market mechanism); controlling the way resources are used (regulations) and how rewards of resource ownership and use are shared amongst members of society (subsidies and taxes). Conventional economic wisdom suggests that the allocation and rewards from resource use in society can be primarily coordinated through markets, and that claims for changed resource-use rules must be linked to market failure. Market failure typically arises from externalities. Important sources of externality impacts around the allocation of public goods include: uncertainty; new information or social preferences; and technology changes that highlight such externalities. It is difficult to argue, however—despite their strong influence in the make-up of modern society—that markets drive all decisions of society and that, therefore, all social ills are the result of market failure (Bromley, 2007). It follows that a role of public policy is to address these issues. In resource policy-making this wisdom is somewhat limited because the issues largely involve prior assigned or implied rights for private consumption that have resulted in a loss of social welfare in aggregate, versus claims for public goods and future states of the environment (e.g. climate change). Fundamentally, the core resource policy driver is a perceived difficulty with the current arrangements. The policy problem involves difficult trade-offs in the reassignment of existing rights (changing the present) and the formulation of appropriate incentives to achieve behavioural change that results in more efficient resource use. Policy-makers therefore need an analytical process to judge the merits of proposed changes against the status quo, which considers the gains and losses to affected parties. This prompts the introduction of our first MDB (Figure 1) example.

[Figure 1] Murray-Darling Basin (MDBA, 2012)

The recent thrust for MDB water policy and institutional change (aside from periodic drought events following federation) can be traced back as far as the late 1960s. Prior to this, MDB policy sought to enhance production benefits from water use (Cummins and Watson, 2012). However, increasing awareness of negative environmental impacts from over-allocating water under such policies caused governments to expand the mandate of MDB authorities to take a stronger role in environmental management (MDBC, 2007). This, among other issues, led some Basin states to place moratoria on the granting of further consumptive (production) extraction rights (Loch et al., 2013). In this example, a problem existed: widespread environmental concerns including increasing river salinity and algal blooms (MDBC, 2007). It was known that the problem was associated with low flow regimes of the river, and that increasing irrigation use was a factor that affected low river flows. By the 1990s, social awareness had increased toward sustainable water resource management in river basins globally (Sitarz, 1993). There was also a shift in policy preferences from direct regulation to market-based instruments (e.g. property rights and trade) to achieve environmental objectives (Jordan et al., 2005).

To curtail further water extraction, a cap on diversions was introduced in 1997. Increased water allocations to the environment were also proposed, even though it was apparent this would create a shortage in irrigation water and hence higher irrigator costs (Crase, 2008). By 2006 Basin environmental conditions had deteriorated rapidly, and media attention increased public awareness on over-allocation problems leading the federal government to act. Fuelled by environmentalist claims and severe drought effects, a *National Plan for Water Security* was formulated with trifling economic or scientific analysis. Essentially, perceived changes in social preferences communicated through mass media and collective action of interest groups brought about policy change aimed at maximizing net social welfare.[3] Initial reaction from the beneficiaries of the status quo was to oppose government redistribution of rights to water resources, and the government’s challenge was to communicate to the public that the change was in fact welfare increasing, taking all benefits and costs into account. This

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[3] Net social welfare occurs via maximizing private rents subject to environmental and social standards. Notably, this policy change both strengthened consumptive (irrigation) property rights and increased their relative value due to a reduction in future supply uncertainty from continued over-allocation. This created private welfare gains. Consumptive water users would also be expected to benefit from further private welfare gains from enhanced environmental public good values and sustainability.

challenge was complicated by difficulties in identifying and implementing appropriate instruments to achieve this policy change, such that the total implementation costs did not exceed the perceived benefits, and that the original policy intent remained intact. We'll return to this issue in section 4.

2.2 Economic grounds for policy change

What then was the economic logic behind this MDB policy change to effect water reallocation? Let's consider a graphical representation of this social choice problem (Figure 2). Suppose social wellbeing from water use can be summarized by the net output from its use in irrigation and environmental services. Given available technologies (knowledge) that allow substitution between these services, the shaded area under the curve E_wI_w that bounds the attainable and efficient social opportunity set, represents potentially available benefits from different combinations of water use. Before the policy change was introduced, water was mainly directed to irrigation while environment was the residual claimant, a position depicted by Q.

[Figure 2] Welfare effects in water allocation

In this case, under prolonged drought conditions water use would gradually approach a situation corresponding with I_w at the lower right corner. At this point, irrigation receives all water at the expense of the environment, and consequently irreversible losses to society (social, economic and environment) would occur. To prevent irreversible losses the share of water resources between all water users needs to be considered (Krutilla, 1967). This can be shown by a shift in water use from Q *to* Q^* reflecting a change in social indifference curves. In Figure 2, I and I^* represent changed social preferences communicating the need for this shift in policy, while P and P^* represent the relative price of water resulting from this shift. This shift in policy results in an economic reallocation to attain a new socially efficient output bundle. Moreover, changes in the relative value of inputs and outputs under new social preferences will also influence the way water is used in future production systems, creating a spiral of policy-induced technological change leading to an outward shift in the social opportunity set E_wI_w. However, complexity in natural resource systems, social and individual preferences, and the manner in which policy changes affect choices and patterns of behaviour have the potential to create multiple equilibria, because such behaviour is sensitive to random events

(Marshall, 2013). Well-designed public policy needs to reflect not only the objectives of society, but also any trade-offs associated with constraining the hydrologic and economic dimensions of a system across scope, scale, time and space dimensions.[4] A single policy can create unintended consequences in social, economic and environmental domains outside its design brief on a local, regional, national and international scale.

For instance, reallocation of MDB irrigation water to environmental uses has generated significant debate about the potential vulnerability of regional communities dependent on irrigation income. Analysis indicates that communities dependent on irrigation income for the bulk of their rural economic activity are expected to adjust (EBC et al., 2011), with spatial impact variations resulting in some regions being more heavily exposed than others (Stenekes et al., 2012). The availability of alternative rural economic activities and the level of take-up will depend on many factors including: access to support services; individual’s preferences, capabilities (knowledge, skills etc.); and resource endowment (Ecker et al., 2012). Further, the rate of technical change and random variables—such as climate, weather patterns and the efficiency of related policies such as water trading (Loch et al., 2012)—will influence the degree of farming-community activity impacts from alterations to water access resulting from policy change (Adamson et al., 2009; Loch et al., 2013). This information is contained in the social indifference curves, relative prices and the production possibility frontier depicted in Figure 2. Consequently, the new policy change induced social setting may mean new economic activities in some instances, and the termination of existing activities in others (Stenekes et al., 2012).

Economic and hydrologic analysis helps inform policy-makers of the nature and magnitude of the trade-offs stated above (Connor et al., 2014; DAFF, 2011; Wittwer, 2011). However, if policies are to improve social welfare a degree of certainty about these trade-offs is required before finalization. In the case of the MDB, such *ex ante* analysis was inconclusive or incomplete because relationships between environmental knowledge, ecosystem processes and expected patterns of interaction and

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[4] Scope describes the number of issues that are impacted by a policy, scale the institutional level at which those impacts occur and/or are managed, time the period over which the policy lasts, and space the area over which the policy is enacted.

impacts could not be estimated with any level of certainty (CIE, 2011). The available benefit estimates were particularly unreliable as they were subject to a range of uncertainties: that is, future states of nature and the influences of existing and proposed institutional settings (e.g. legal frameworks to create new, or protect existing, property rights). For these reasons, economic and hydrologic analyses may be controversial and only ever indicative of general directions and relative magnitudes of policy change impacts contingent on existing knowledge. Larger relative knowledge gaps create greater uncertainty about the future impacts of proposed policy change. In particular longer time horizons, together with non-market characteristics of most environmental water uses, imply significant uncertainties which should be reflected in policy-making economic choice criteria (Smith, 1979). So, in setting out water resource reallocation policy, what is the role for hydrology, economics and other sciences? Are there common areas of influence? We examine these questions below.

2.3 The role of science to inform policy

Populist public policy—that by definition appeals to the common interests and prejudices of ordinary people—can rapidly transition from one rationale to another based on fundamental shifts in public perception, invariably limiting growth (Rostow, 1959). Public policies driven by narrow political mandates are therefore vulnerable to changes in government if they fail to win popular support. Conversely, durable public policy requires investment in credible debate and subjecting facts to robust analysis to create transparent evidence. This involves considerable expenditure of time and other resources that policy-makers working within political exigencies do not often have access to. In the MDB example, hydrology played a pivotal role in understanding the nature of Basin water resources across catchments, as well as how irrigation use interacted with groundwater systems to cause unintended consequences such as salinity (e.g. Austin et al., 2010). Hydrologists and economists also worked together to identify and assess new opportunities for agricultural production, and helped determine cost-efficient ways to manage the impacts of water policy change on the environment (Khan et al., 2009a; Khan et al., 2009b; Qureshi et al., 2010).

The reform of MDB water policy to improve social welfare thus faced a practical reality to balance the political will needed to create change against the possibility of irreversible and negative consequences associated with an incomplete understanding. This included incomplete problem setting and under-appreciation of the limits of solutions against future states of the world. The challenge for hydrologists-economists is to work within these realities to provide robust strategic advice founded on careful analysis of states of the natural world. The need is to carefully inform policy-makers about how to safeguard against as yet unknown and unfavourable consequences from policy formulation choices, to help set appropriate courses of action in the interest of social progress. However, under increasing uncertainty about future states of the world, social welfare maximizing public policy may only provide what is perceived by economists as sub-optimal social outcomes, underpinned by what hydrologists would consider as lacking a complete understanding of the bio-physical constraints and feedbacks within complex adaptive systems (Ajami et al., 2008). Consequently, the contribution of science input to policy formulation is to guide social adaptation toward environmental concerns, which minimize unfavourable impacts of increasing consumption patterns by society. Economists in particular may gauge the success of a given policy change by the balance of perception between responses to questions of social welfare efficiency and equity (McConnell, 2010). Minimizing such complex risks in a world of unknowns remains an increasingly challenging task for scientists. But, in part, this challenge can be met through narrowing the decision errors associated with information asymmetry, including knowledge gaps and uncertainties related to resource conditions, and management regimes that are based on precaution. In these settings, the precautionary principle may provide a useful heuristic guide for decision-makers faced with the possibility of unfavourable surprises (Grant and Quiggin, In press).

3 Information needs for effective policy

Effective and efficient policy interventions require a good understanding of the factors that make the status quo unsatisfactory, and the benefits and costs associated with options available to alter the status quo. In water policy, such information includes: knowledge of the relevant hydrologic, economic and social systems; values for the supply and demand of public goods; and the likely costs and benefits to government and other affected parties of various policy options. As discussed above, this information is often available with high levels of uncertainty.

3.1 System knowledge requirements

Water resource systems are particularly complex and variable in many parts of the world (Connor et al., 2012), and under future climate change variability of global water supply is expected to increase dramatically (IPCC, 2012). As such, policy-making and subsequent implementation can become problematic where the behavioural scope for adaptive systems, as well as scope for failure among non-adaptive entities, increases significantly. Water system complexity can further magnify considerably where resources flow across political boundaries, and where water supply and demand varies over seasons, sites and across use categories. When the knowledge of hydrological attributes governing these systems is incomplete and the suitability for consistent decisions is compromised by large and uncertain margins of error (Preston and Jones, 2008) much of the data used for hydrologic and economic assessments of both production and conservation water uses will have weaknesses, making *ex ante* evaluations of policy change ambiguous. Again, the MDB provides useful examples of the implications of this inadequacy relating to hydrologic, economic, ecological and institutional variables employed in policy analysis, and efforts undertaken by authorities to uphold public confidence on the policy development process (MDBA, 2010; MDBA, 2012; Young et al., 2011). This experience also highlights the nature of binding practical constraints that affect policy development in complex areas such as water resources.

3.1.1 Hydrologic variability

Water availability is dictated by the hydrologic cycle. The MDB river system with a combined length of 440,000 km is regarded to have the second most variable water flows in the world (McMahon and Findlayson, 1991). This includes the Darling River, Australia's most variable river system (Khan, 2008). Rainfall is summer-dominant in the northern area and winter-dominant in the south (Figure 3). The majority of rainfall occurs in the Basin's south-east (900-1200mm/pa), and rapidly declines over western and north-western areas (100-400mm/pa) (ABS, 2008).

[Figure 3] Long-term rainfall variability in the MDB (Leblanc et al., 2012)

As such, converting rainfall to runoff in the MDB is complicated, particularly under anticipated climate change impacts (Schrobback et al., 2011). However, estimates used for planning and policy suggest that, on average, rainfall contributes 22,925GL of runoff that combined with 2,373GL of groundwater resources and 1,118GL of inter-basin transfers, delivers 26,418GL of water resources annually (MDBA, 2012). Figure 3(c) also depicts a 9-year running mean (black line) and the two lowest inflow mean runs on record (red lines) for the MDB. Over-reliance on such averages, often derived from models of varying complexity and accuracy, to describe highly variable water systems in the face of further uncertainties such as climate change renders policy evaluations based on such data almost fictional (Adamson et al., 2009). The magnitude of this problem increases rapidly for MDB hydrologic baseline data owing to: acknowledged measurement errors; difficulties in accounting for conveyance losses, landscape modification and interactions with use patterns; unreliable and incomplete environmental water requirements; and complex storage rules that govern river flow management (Young and McColl, 2009). Coupled with the difficulties and uncertainties attached to monitoring actual water uses, this information asymmetry leads to a high level of ambiguity in choosing model-based scenarios to guide planning, implementation and monitoring of policies across the MDB.

3.1.2 Economic variability

Approximately 10 per cent of Australia’s population resides within the Basin, while an additional five per cent of the national population in Adelaide (the capital city of South Australia) rely on water resources from the Murray River (ABS, 2008). Agriculture is one of the largest economic activities, representing 80 per cent of land use. While only two per cent of this land area is irrigated (by 40 per cent of Australia’s total irrigators), nearly 60 per cent of Basin water resources are diverted for agricultural and urban use. These diversions (Figure 4) have resulted in diverse economic growth, but significant reductions in discharge to the sea from 13,000GL under natural conditions to around 5,000GL at present (MDBC, 2006).

[Figure 4] MDB water diversions by state and year: 1996 to 2011 (Adamson et al., 2011)

MDB irrigated agricultural water use broadly falls into two categories: perennial crops that require relatively secure access to seasonal water supplies; and annual crops that have more flexible water needs. Figure 4 also provides an illustration of water supply variability in the MDB; notably a significant reduction in diversions that occurred in response to an extended (Millennium) drought between 2001/02 and 2009/10. Adaptation in response to this event highlights scale issues that might be considered in a hydrologic-economic model of the Basin. That is, all water users in the Basin used a range of adaptation mechanisms to protect their investments and livelihoods from historically low levels of water availability. A range of voluntary, regulated (quantity), and price-based mechanisms introduced at varying scales across the Basin supported these adaptation decisions. These included, individual farm level activities such as water trade, feed purchasing and changes to watering patterns; water allocation reductions and caps on trade activity at the district/regional level; and suspension of water plans, drought assistance and income support at the state and national level (Mallawaarachchi and Foster, 2009; Wheeler and Cheesman, 2013).

3.1.3 Ecological variability

The MDB is also highly variable as an ecosystem, accommodating a range of habitat and species with varying dependence on land and water resources. For example, there are more than 30,000 wetlands scattered over 25,000 km^2. Basically, MDB water resources play an important role in supporting environmental sites and their attendant flora and fauna species in three ways. First, base-flow water in river systems provides continual supply as refugia support through dry periods. Second, occasional high-flows contained within riverbanks periodically inundate extended riverine areas providing habitat, replenishing groundwater reserves, and flushing salts, sediments and nutrients from river systems. Third, large over-bank flood events periodically re-connect ephemeral wetland or floodplain waterholes to the river systems providing important fauna breeding sites and habitat expansion to support species diversity, as well as system flushing on a larger scale (Loch et al., 2011).

Each year the Murray-Darling Basin Authority (MDBA) identifies important environmental watering activities or priorities that will influence Basin-scale outcomes. Achieving a level of coordination between environmental water holders and managers at different scales is critical to ensuring optimized Basin results. For instance, the MDBA has set a total of ten priorities for 2013-14, focusing on the watering needs of important areas. These priorities complement and exist in parallel with other watering activities happening at local and regional levels (MDBA, 2013). The scientific and administrative challenge involved in determining volumes of water required to maintain an optimal balance in these complex ecological systems—and the optimal timing for their application—is well beyond the grasp of hydrology and economics, and involves a high level of uncertainty.

As a major environmental objective (Priority 10 - MDBA 2013), 650GL of water must reach the Coorong wetlands at the mouth of the Murray-Darling River in a calendar year. The Coorong is an iconic wetland of significant environmental and cultural heritage, and its health is a metric ingrained into the public debate. When Murray River inflows decrease, the risk of salt intrusion from seawater rises dramatically, threatening Coorong ecosystem health and species habitat. As such, barrages have been built to prevent Coorong salt-water intrusion during low-flow events. In the Millennium drought water levels in Lake Alexandrina—the largest lake in the Coorong system—fell below sea level (i.e. all values below zero are lower than the ocean) as illustrated in Figure 5. Complicating this issue further, attempting to meet minimum Coorong flow targets during drought periods may not be hydrologically or economically feasible or optimal, when available water would need to be shared between critically endangered wetland habitat (e.g. Chowilla Wetlands) across the entire MDB.

[Figure 5] Flows to Coorong, 2000 to 2013 (pers. comm. A. Ahmad, MDBA 2013)

3.1.4 Institutional variability

Finally, the MDB incorporates parts of four Australian states and the entire Australian Capital Territory (ACT). As these states maintain ownership of water resources under the Australian Constitution, a wide range of variation has emerged in the legal, governance and administrative arrangements for water management in the MDB. Despite a federal authority (MDBA) to coordinate management of the river system, significant differences still exist in: water sharing planning processes; water trade rules and approval processes; approaches to low-supply (drought) management; prioritization of reallocation efforts; policy responses; and the collection, analysis and dissemination of information. Further, in many parts of the Basin catchment boundaries do not fully align with political boundaries, serving to increase the degree of complexity presented to hydrologists and economists tasked with informing public policy. How then do hydrologists and economists typically approach this problem?

3.2 Guiding the uncertain search for environmental quality

Hydrologists and economists both consider water resource systems as interconnected stocks and flows that define the boundaries of its availability and suitability for social uses across different domains, as abstracted in the hydrologic cycle (Figure 6).

[Figure 6] Large-scale (a) and small-scale (b) hydrologic cycles (Mason et al., 2003)

Economists relate this supply-side information—along with the rules of access and utilization specified by policies and information on society's willingness to pay for services derived from water, where available—as prices paid and received to determine feasible allocation options that permit beneficial utilization patterns in profitable water exploitation and conservation. As these utilization patterns influence social well-being and affect wider ecosystem functions, the economic system then becomes part of a broader socio-ecological system linked through the hydrologic cycle at one scale, and organizing entities such as farmers, river managers or water supply authorities at another scale.

As discussed, hydrologists and economists have historically played a key role in trying to articulate the nature of this interaction, including inherent water resource supply variability and associated information uncertainty surrounding water resource systems (e.g. Skurray et al., 2012). In this role, a close nexus between hydrology and economics is found in their shared use of available data, the specification and application of complex modelling methodologies, and their approaches to dealing with uncertainty in both these areas. Hydrology, economics and a host of other disciplines are well equipped to assist in reducing uncertainty in response to long-run policy requirements, provided they make the best use of often divergent but related information sets to that end. This invariably involves learning to deal with scale, subjectivity and high stakes (Alexander et al., 2010; Moglia et al., 2012).

3.3 Data issues

Effective water management principally entails adequate comprehension of the variability inherent in each component of the connected supply system. Arguably, one of the highest stake responsibilities of the hydrologist-economist is to provide a number that goes into policy formulation. The complexity of any conjunctive water use system, which draws on surface and groundwater and relies on return-flows from irrigation and other uses, means that the inherent variability around target numbers is quite often lost once leaving the hands of the analyst. Simplicity requirements for mass communication usually demand a single number, whereas complexity dictates that such numbers are often meaningless. Yet, single values, drawn from seemingly unrelated distributions, then become the building-block upon which further analysis is conducted and public opinion gauged; regardless of its reliability or whether limiting assumptions are clearly (and most discouragingly, especially when such limitations are emphatically) acknowledged. The MDB example provides ample evidence for this practical aspect of public policy-making.

Despite a century of water reform, the necessity of obtaining coherent and consistent data was a central part of the *Water Act* (2007) to overcome shortcomings in MDB information sets. As individual states or territories retain responsibility for the management and collection of data for the river sections within their political boundaries, significant water resource data fragmentation, disparate calibration techniques and varied modelling approaches prevented an understanding of available water resources, how data was used, and how the possible implications of climate variability and climate change were assessed (Horne, 2012; Sandeman, 2008). Inconsistent data sets across state/territory agencies often provided a key barrier to transparency in the formation of policy decisions at a federal scale. For example, state and territory political boundaries are subdivided into surface water management areas and groundwater management areas that do not align. Meanwhile, the management of these areas was based on models, from which allocation and delivery decisions were subsequently drawn, as well as final audits to ensure compliance with objectives were conducted. In some unique cases the modelling methodologies, data standards, reporting errors and inherent model biases created difficult issues to resolve. In an attempt to address such issues, the CSIRO sustainable yields project had the unenviable task of merging available data into a consistent framework, using hydrological boundaries to define their catchments. Despite their best efforts, inevitable limitations in the data occurred. They can be attributed to: misconstrued complexity of the issues; unreliability in the underlying data sets; and the timeframe set to achieve requisite outcomes

(Young et al., 2011). Fundamental improvements in the data and estimation of the sustainable water yield occurred. But an original emphasis on the complexity, variability and uncertainty associated with the water recovery recommendation (range) was lost once it was compressed to a single recovery target number (i.e. 3,200GL).[5]

3.4 Modelling issues

The estimation of future MDB sustainable diversion limit (SDL) figures is not simply dependent on available data and how that data is collected, but also on the modelling methodologies used to estimate water supply and water requirements (Penton and Gilmore, 2009). If SDL estimates are optimized for efficiency, then redundancy and flexibility must also be encapsulated in both the estimations of supply and the demand for alternative uses to accommodate future unknowns. As Young and McColl (2009) discuss, design of institutions incompatible with highly variable hydrological system realities compound the need for continual policy reform. Future water supply is not a fixed number, nor has it been in the past. ‘Machine-learning’ directed (modelled) historic Basin water use figures, however, provided comfort to policy-makers and (some) confidence to modellers. But the complex association between rainfall, run-off and groundwater recharge cannot be described within a single variable (Chiew et al., 2011). In addition, landscape changes such as forestry (Schrobback et al., 2011), water harvesting (MDBA, 2012), and adaptation measures by all water users including the natural environment, in response to known and unknown triggers will vary beyond grasp. Infiltration rates, ecosystem requirements and the ability of water to reach river systems, as acknowledged in the models, are only one of many possible representations equally probable in an unknown distribution. Despite these realities, an often-adopted approach is to separate target figures from system variability and uncertainty in order to parameterize secondary models following a hierarchy of aggregation. In given cases, a simple normal distribution will be attributed to the final catchment level numbers, thereby exposing the solution to ‘black swan events’ (Taleb, 2007) where modelled outcomes fail to deal with the distribution tails (Chichilnisky, 2010). Inevitable failure to

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[5] Jones et al. (2002) provide an earlier MDB example for the dangers associated with recommendations on recovery target ranges, despite clear communication of their variability. Once again, target figures were typically used as ‘sound-bites’ for different purposes by varying stakeholder groups, including governments.

perceive new lows and highs results in ‘dumb farmer’ model responses to the data provided (Chugh and Bazerman, 2007). In fact, MDB irrigators adapted quite readily to environmental, political and economic incentives during the Millennium drought (Wheeler and Cheesman, 2013), providing further evidence of the need to structure modelling approaches carefully and accurately.

A secondary weak aspect of the MDB recovery target was driven by the separation of several conjunctive management issues. The separate treatment of surface and groundwater resources allowed the MDBA to present future increases to groundwater access without wider public discussion or debate. However, this separation has significant hydrological and economic consequences. Not only are MDB water managers failing to recognize non-linear relationships between surface and groundwater resources (Chiew et al., 1992), but differential influences of climate change on surface and groundwater systems are also being ignored (Pulido-Velazquez et al., 2011). Failure to recognize the hydrological complexity of this target and the separation of interconnected resources also creates problems when implementing policy solutions, in particular future water management plans. Not only does the Basin Plan (detailed in section 4) assume all water-users are passive to new information but it assumes that individuals are incapable of adopting appropriate management solutions to accommodate new policy settings. This violates the fundamental principles of adaptation.

In this case, failing to understand the hydrological, economic, environmental and social implications of alternative policy tools—as well as their sensitivity to risk and uncertainty—not only creates a second best solution, but may potentially compromise the efficiency of MDB irrigators to adapt. Such outcomes are exacerbated by uncertainty about future climate states, which have a strong influence on all system characteristics. The greater the complexity of a given water resource system, the higher the probability that fatal policy constraints toward achieving effective, efficient and socially acceptable water policy solutions will be realized. Where this occurs, an inevitable cycle between policy design, social opinion and rigorous analysis can occur as political ambitions transition from one policy reform process to another.

3.5 Risk and uncertainty

Risk and uncertainty appear frequently in policy discussions, but often with incomplete clarity. This observation needs to be understood to avoid confusion amongst disciplines such as hydrology and economics. Risk always relates to a consequence of an event. Knight (1921) describes risk as one end of a continuum where the probabilities of events are based on actual physical data, and uncertainty as the other end of that continuum where events cannot be assessed using probabilities, as no knowledge about those events exist. Public choices typically fall between the two extremes, with water policy characterized by increasing uncertainty (Mallawaarachchi et al., 2012). Rising uncertainty may involve increased (reduced) consumption of resources during relatively good (bad) periods (Grant and Quiggin, 2005), but may also be eliminated in a policy-making or modelling process through the implementation of 'ideal' data processing techniques and experimental evidence (Nestorov, 2001). This process is bounded, however, by limits to possible improvements on existing knowledge (epistemic) and informational gaps that are non-reducible owing to natural variability (Merz and Thieken, 2005).

In the context of hydrologic-economic modelling, improvements may be achieved via addressing efforts to structure complex system representations, improvements to probability assessments, increased data gathering and information management, and sensitivity analysis (Mallawaarachchi et al., 2012). Similarly, economic models may be improved through better design, reduced parameter uncertainty, appropriate subjectivity or assumptions, and attention to likely computational error. Typically, simple models work best where they both explain the data presented but also allow underlying theory to expand (Ruth and Hannon, 1997). An obvious problem for policy credibility and expert peer scrutiny is derived from the application of simple models to complex system arrangements. However, the appropriateness of including expert information and advice into public policy outcomes depends on: the scale and application of the assessment tools; the scope of the economic agents involved; and the timeframes considered (Mallawaarachchi et al., 2012). The combination of scale, scope and temporal issues typically provides a complete set of realized outcomes as a single decision. Further, as the number of feasible and infeasible solutions to a single problem increases we also expect exponential growth in the possible solution set (trade-offs). In turn, a policy-maker's awareness of—and capacity to deal with—large solution sets influences the probability of resource misallocation, resulting in negative externalities or opportunity costs that reduce net social and private welfare. Again the Basin Plan process is a case in point. This leads to the question of how hydrologists and economists should seek to effectively and efficiently inform robust public policy.

4 Robust public interventions

Achieving robust policy objectives necessitates a clear distinction between ambition, and practical application or implementation (Walker et al., 2013). The implementation stage (i.e. devil is in the detail), in particular, illustrates when a clear division between the policy process, policy detail and subsequent outcomes emerge. For example, policy *process* develops overarching goals, legal settings and funding sources or parameters. Policy *detail* involves how the policy will be enacted and introduced at the grass-roots level, and it is at this stage that the clarity of intent must prevail. If the overarching process goals curtail the strategic direction of the original intent and the use of appropriate instruments (i.e. the tools used to achieve the outcomes), then the policy is likely to be a second-best outcome.

The MDB provides us with a final useful example for this discussion. As we have seen, in a pluralistic society led by differential access to processing capacity for utilizing available information, public management of MDB water resources have generated increasing concern and policy scrutiny in recent decades. Further, while MDB natural resource systems are typically complex, unstable and variable, in contrast effective and efficient water resource policy demands transparency, stability and consistency (Mallawaarachchi et al., 2012). This need arises from the purpose of public policy in enhancing organizational efficiency and effectiveness (Marshall et al., 2013). The Basin Plan implementation process impinged directly on how its objectives must be achieved, in part due to a lack of data. Below we discuss the Basin Plan and two major water reallocation incentives related to its implementation: *Restoring the Balance* (RtB) a $3.1 billion fund to purchase water rights from willing irrigators, and *Sustainable Rural Water Use and Infrastructure* (SRWUI), a $5.8 billion fund to modernize existing irrigation infrastructure and implement capital works for environmental assets.

4.1 The Murray-Darling Basin Plan

Arguments about the reallocation of MDB water resources have resulted in policy stagnation more often than not (Cummins and Watson, 2012). However, as noted, heightened public concerns spurred the Australian government to enact a national *Water Act* (2007) which, among others, provided for the creation of the Basin Plan to achieve large-scale water reallocation and implement sustainable levels of extraction. A target figure of 3,200GL of surface water will eventually be reallocated to the environment—although access to an additional 1,786GL of groundwater resources will be provided by way of economic and social compensation. Clear externality addressing objectives such as those in Basin Plan could assist in maximizing economic benefits (Pannell, 2009), but only if they are appropriately set and managed. Setting objectives and process improvements involve estimating the trade-offs associated with different water uses, and highlighting potential synergies and opportunities to maximize the social return from large-scale government investment in public goods (Mallawaarachchi et al., 2010). However, questions remain regarding the relevance of such process improvements as against communicating clear intent and meeting content requirements.

A notable concern with the Basin Plan is its reliance on averages and means. Under increasing rainfall variability and climate change uncertainty the real issue is one of future drought frequency. Where runoff patterns alter over time, flexible and adaptive long-run management solutions will be required to achieve effective and efficient reallocation of water resources across different states of nature that gives rise to different means and variance regimes. Further, additional uncertainties such as the rate of groundwater renewal (Crosbie et al., 2010), the impacts of land overutilization including salinity (Knapp and Baerenklau, 2006), and water interaction effects on ecological processes (Brunke and Gonser, 1997) in the MDB create complex optimization problems for policy-makers and hydrological-economic experts alike. Thus, future water supply not only has to deal with known variability creating short run scarcity, but also incomplete specification of climatic change impacts on supply reliability. Continued efforts to manage the uncertainty about MDB water resources and its productive uses (i.e. economic, environmental and social) are needed to meet the long-run policy objective of building resilience of Basin resources and communities to better face future shocks.

4.1.1 Restoring the Balance

Under the RtB program, full or partial water rights are purchased from willing irrigators, effectively transitioning what were consumptive property rights into environmental water holdings that are then managed by the Commonwealth Entitlement Water Office (CEWO). How to best acquire this resource for the common good is reasonably easy to model from a hydrologic-economic point of view. The water value of the property right is known within reasonably accurate bounds, and how this physical water asset flows through the rest of the river system can be reasonably determined. Beyond the policy process then, follows questions about how the CEWO best utilizes the asset to maximize net environmental gains. As such, to maximize the benefits from this program and ensure success, detailed knowledge about appropriate environmental benefit functions must be known. In this case, the spatial and temporal details of both the CEWO environmental goals and the nature of property rights must be known to determine its physical and economic characteristics (Adamson, 2012). Any failure to understand climatic impacts on environmental (common) property rights to provide future ecological water could leave the Plan incapable of providing water when it is required to maximize net social benefits.

4.1.2 CEWO management and resilience

At the time of writing, rules about how the CEWO will manage its water portfolio for the greater good are still being determined. There are, however, a few aspects to consider if the Basin Plan is to have lasting benefits for all water users. By providing the environment with a defined share of the available water assets, a common property is established which needs to be managed in perpetuity (i.e. the responsibility of the CEWO). As Ciriacy-Wantrup and Bishop (1975) argue, a public trust doctrine helps negate any externalities derived from resource exploitation. As the Plan intervention process is costing $10.87 billion, justification for this expenditure and preservation of the common good needs to be maintained. When setting the rules for common good resource use, merging hydrologic-economic lessons as discussed in the RtB section above could lead to significant cost-savings. Our estimates suggest that by knowing (properly defining) attendant MDB environmental goals and their real water cost—where the spatial and temporal characteristics of water rights are identified—intervention costs/ML fall to just over $1,030/ML; suggesting that approximately 70 per cent of the allocated funding could have been saved. Remaining funds could then be used to provide other benefits for the Basin community, or invested in additional services for the common good.

4.1.3 Sustainable Rural Water Use and Infrastructure

The SRWUI program is also an area where hydrologic and economic knowledge can provide useful common insights. Yet, it appears surprisingly absent in many discussions. A common misconception in Australia is that existing irrigation systems are inefficient. Studies that claim benefits from continued refinement of resource use generally fail to understand associated opportunity costs, in particular those arising from variability in water supply through time. This lack of recognition of critical systemic properties places the water efficiency investment at an increasing real risk of failure. If we were to invest in commodities like perennial horticulture, that must have a reliable supply of water through all states of nature, then the loss of capital investment is real if water cannot be supplied through a drought. The resultant need would then be excess capacity built into water storages, or for farming systems to adapt either through water trade or holding very large water licences. Without this adaptive capacity—and if the irrigator has not locked-in (confirmed) additional resources with a fixed price—they are then at the mercy of the market and any short-run upward price spikes will undermine business viability. Adamson & Loch (under review) found that subsidization of MDB capital to invest in increased water use efficiency not only removes water from the system, it also makes redundant existing system controls that are designed to mitigate risk under scarcity, and fails to account for beneficial return flows from previously inefficient practices. In other words, the cross-scale trade-offs in water use and allocation is misconstrued in the policy analysis. The result is that the water for the environment then comes at unnecessarily high social cost.

Experience therefore suggests that the primary source of apparent policy failure, or discomfort of the community about proposed changes, is that the policy problem is misconstrued. Hydrologists and economists can contribute to greater policy consistency by appropriately defining the supply and demand configurations that may fit within system characteristics. This will require independent science input to policy that may not come from existing arrangements where scientific organizations are not immune to behaviours of rent seeking. Irrespective of such anomalies in the information market place, clearly defining the policy issues to be managed and determining what evidence is available, relevant and useful to public policy-makers could help identify critical evidence gaps for effective public policy-making. Left unconstrained, developments in information technology mechanisms will allow better ways to communicate shared evidence meaningfully such that it informs and drives community values.

5 Conclusion

Policy-making remains largely a craft, despite an increasing global trend toward the inclusion of expert scientific advice and input to policy formulation. Reasons for this include the political nature of policy-making that is subject to social vagaries, and a mismatch between individual and collective preferences that lead to trade-offs at multiple levels. The situation creates a clear role for knowledge brokers such as scientists, including hydrologists and economists in the policy formulation process; but they must be cognizant of the limits to their input. In water resource policy formulation, such limits are often dictated by uncertainty about the patterns of interaction among different elements of the social and natural resource systems that are governed for meeting human needs through policies and other social mechanisms. Our inability to predict ecosystem processes and future states of nature, and how individuals and firms react to those changes, present a continued need to refine and adapt our social policy mechanisms as new information comes to hand. The influence of such changes to institutional settings in natural resource management will remain difficult to gauge with certainty. Consequently, hydrologic-economic analyses may typically be controversial and only ever indicative of general directions and relative magnitudes of policy change impacts, contingent on existing knowledge. Thus, while larger relative knowledge gaps create greater uncertainty about the future impacts of proposed policy changes, conversely, durable public policy requires investments in credible social debate and subjecting scientific facts and robust analysis to create transparent evidence. In this setting, it is critical to acknowledge that the "new problems created by our improved scientific knowledge are symptoms of progress, not omens of doom. They demonstrate that Mankind now possess the analytic tools that are basic to … understanding the human condition" (Simon, 1973, p 277). Understanding the limits of these tools and allowing the developments in information technology to help share such limits will help us better adapt to the uncertainties before us.

We contend that effective public policy formulation can be achieved by reducing information asymmetry via strong evidence, expert analysis to verify that evidence, and an understanding of knowledge gaps. Such an approach provides a robust foundation for agreement on critical public interventions to achieve chosen social welfare objectives, with clear comprehension of societal capacity to fund and manage such objectives. However, under increasing uncertainty about future states of nature, social welfare maximizing public policy may only provide what is perceived by hydrologists and economists as sub-optimal social outcomes. Further, these outcomes may be viewed as lacking a complete understanding of the bio-physical and economic constraints, and feedbacks within a complex adaptive system. In these cases, failing to understand the hydrological, economic, environmental and social implications of alternative policy tools—as well as their sensitivity to risk and uncertainty—not only creates a second-best solution, but may potentially contravene the ability of water users to adapt.

Finally, in this paper we highlight that risk and uncertainty constraints appear frequently in hydrologic and economic policy formulation-input discussions, but often with incomplete clarity. We emphasize that this observation needs to be understood to avoid confusion amongst the two disciplines when working toward shared policy outcomes for river basins and water resource systems. Usefully, the consideration of scale, scope and temporal issues in tandem typically provides a means to achieve a complete set of realized decision outcomes. However, we also caution against the provision or specification of solitary outcomes, particularly in the form of single numbers (e.g. the MDB 3,200GL recovery target figure). The inherent problems with such an approach are discussed at several points within this paper, as well as the limitations and perverse outcomes that may arise. Inherently, this paper identifies that effective, well-integrated and useful input can be achieved from cross-disciplinary approaches such as hydrologic-economic assessments, which combine a shared understanding of natural and social systems. There is more common ground than not between the two disciplines, suggesting clear paths for future engagement in future water resource policy contribution.

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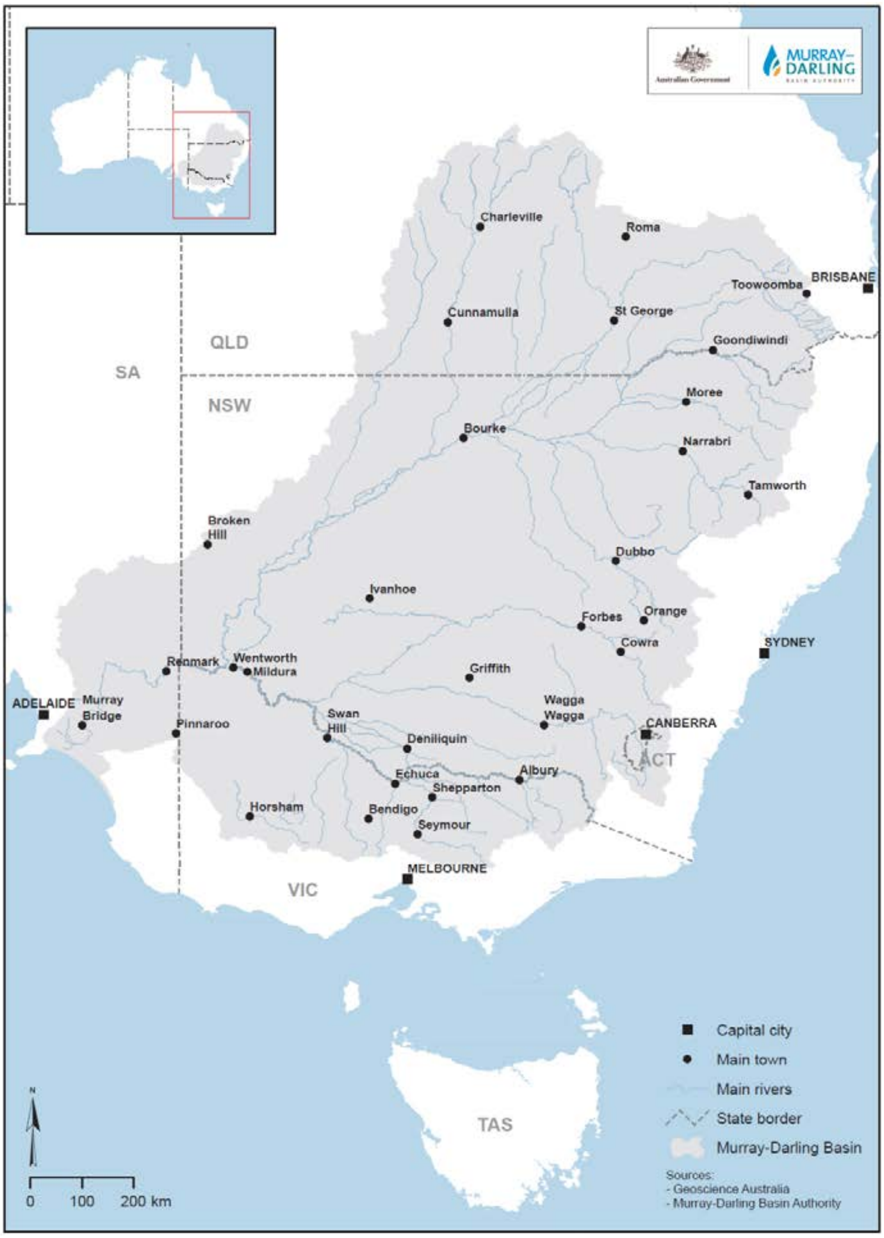

Figure 1: Murray-Darling Basin

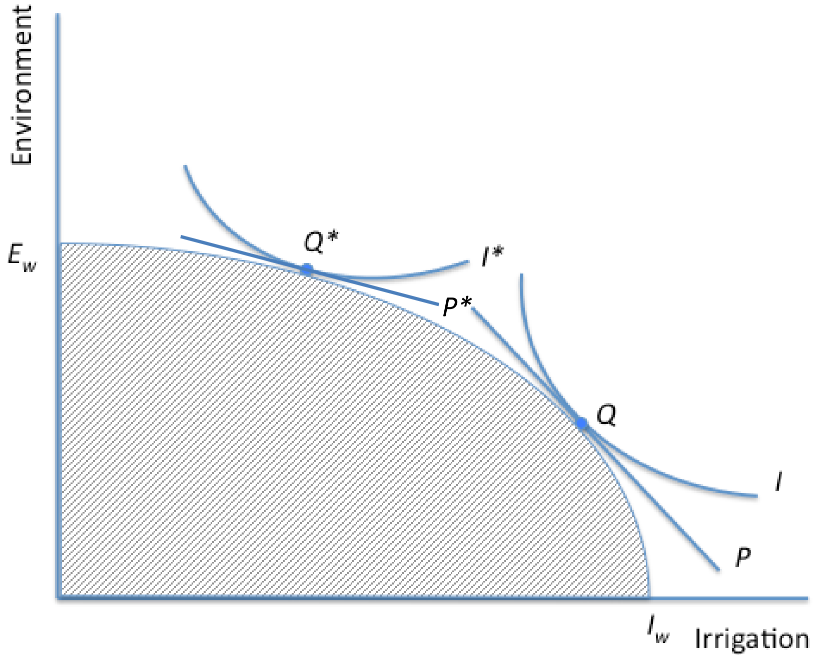

Figure 2: Welfare effects in water allocation

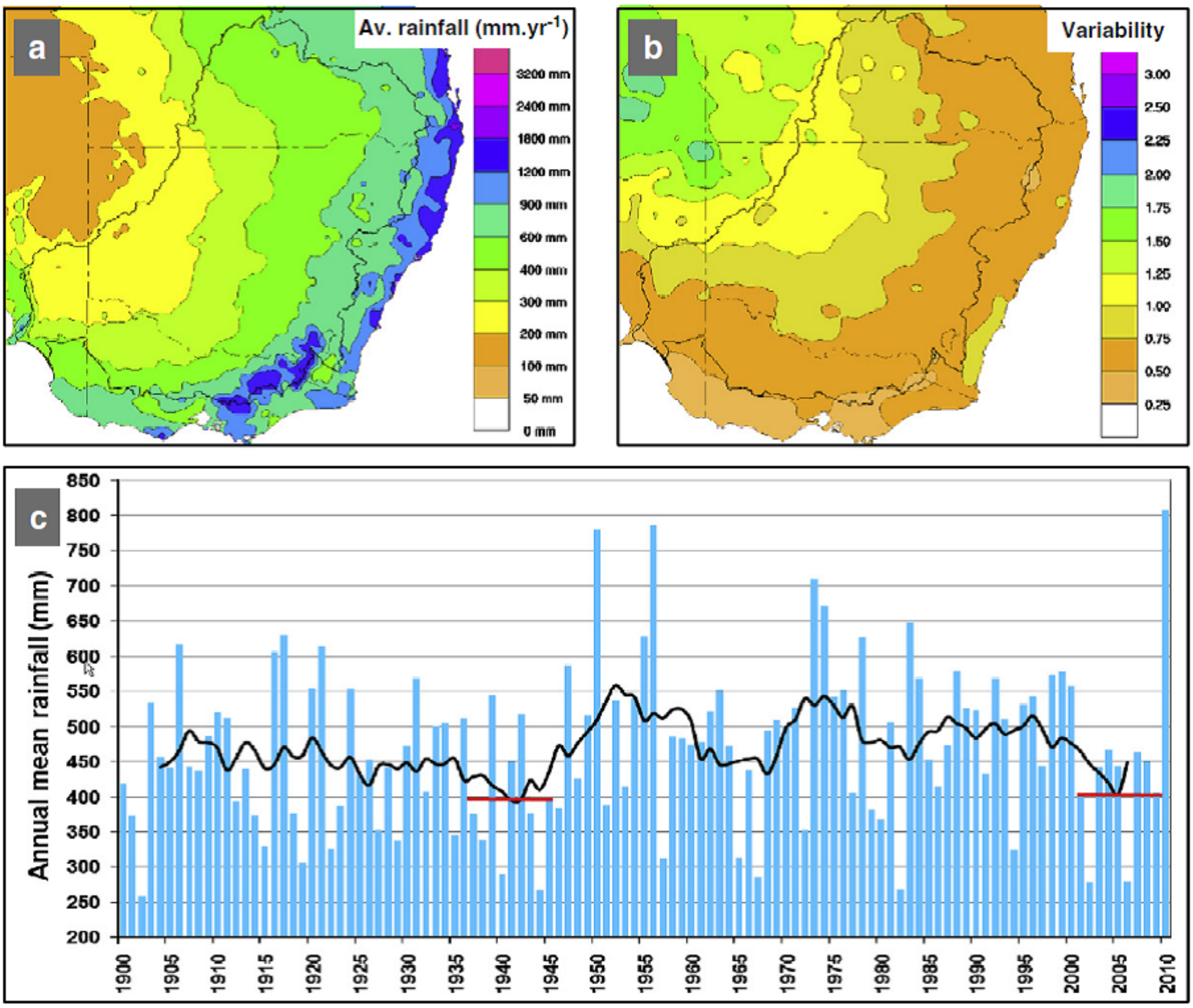

Figure 3: Long-term rainfall variability in the MDB

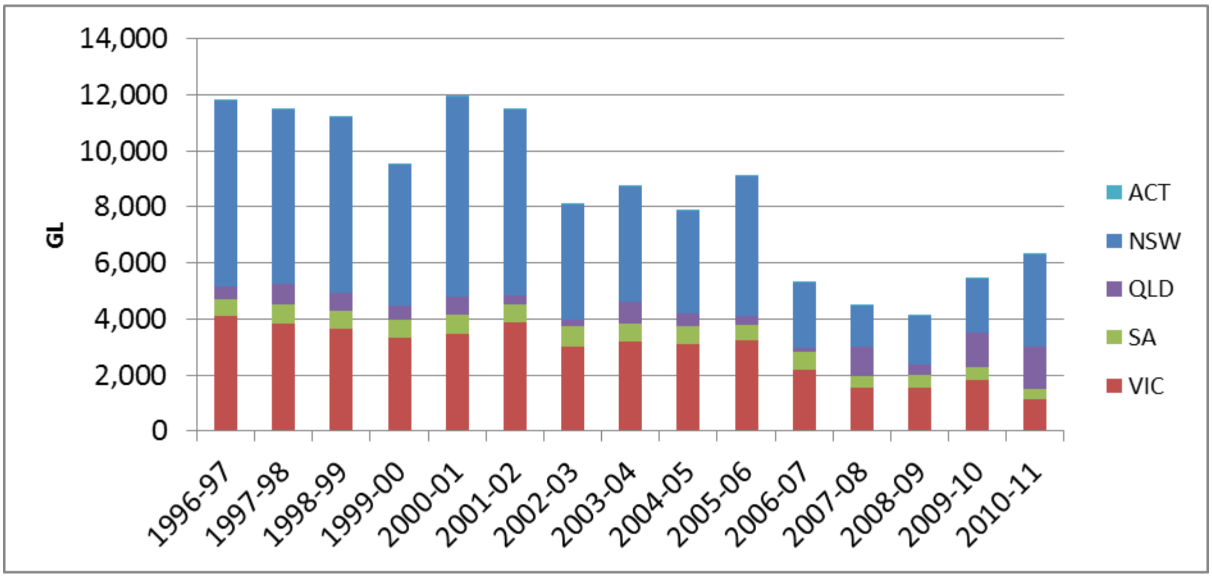

Figure 4: MDB water diversions by state and year: 1996 to 2011

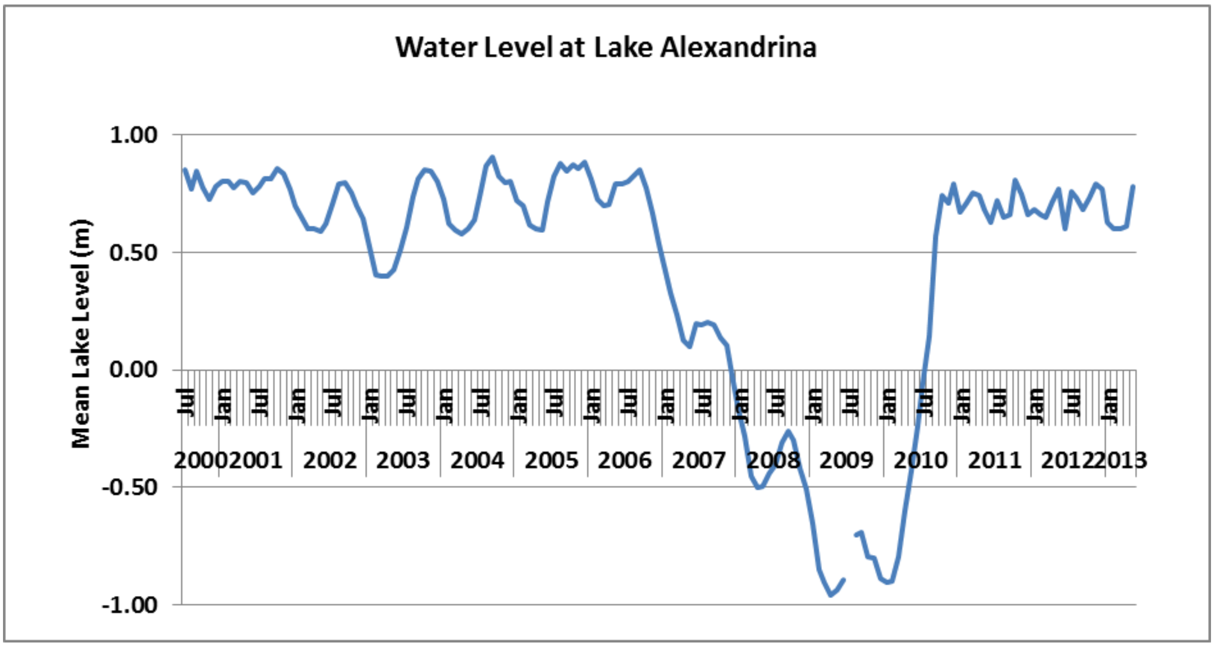

Figure 5: Flows to Coorong, 2000 to 2013

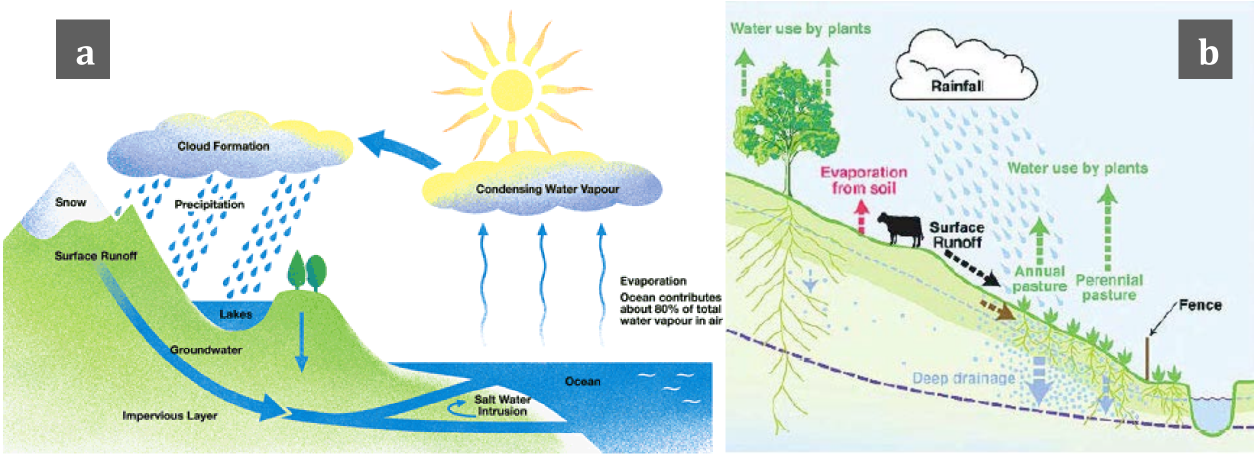

Figure 6: Large-scale (a) and small-scale (b) hydrologic cycles

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