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Why groundwater matters: an introduction for policy-makers and managers

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ABSTRACT
In many parts of the world the combined pressures of population growth and a drying climate have resulted in the proliferation of water focused policies which aim to increase the resilience of socio-ecological systems. Until recently, these policies often reflected surface water centric views of water resources, with groundwater receiving scant attention. In this paper we provide an introduction to the importance of groundwater for water-dependent socio-ecological systems and why it needs to be better incorporated into environmental water management policies. Specifically we highlight the key role of groundwater in buffering the environment and socio-economic activities against drought. We also outline some of the key challenges that face policy-makers and managers implementing groundwater management policies. These include dealing with groundwater resources that are spatially and temporally mismatched with surface water resources; transboundary governance issues; challenges between focusing on either preventative or restorative actions and most importantly limited knowledge about groundwater resources and groundwater–ecology relationships. We hope that the information in this paper will assist in the development of sustainable surface-groundwater water management policies, as well as highlight important challenges that should be considered before implementing groundwater related policies.

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Introduction

Population growth and climate change present a suite of complex, multi-faceted challenges for water policy and governance arrangements. Within three to four decades it is projected that, worldwide, billions of people will have to survive in river basins under severe water stress (OECD 2012). This presents a classic 'wicked problem' for those trying to balance the water requirements of people, environments and economies. In response to such projections and the consequences of severe water stress triggered by recent droughts, many governments have developed policies which aim to increase the resilience of socio-ecological systems to water scarcity (e.g. Medd and Chappells 2007; Stringer et al. 2009; MDBA 2012; California Department of Water Resources 2013). These policies, while progressive and immensely successful in some instances, have

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often been developed within a largely surface water centric (i.e. focused on and concerned mainly with surface water) framework (Tomlinson 2011).

This surface water focus, combined with not being able to easily observe groundwater systems has frequently lead to groundwater being overlooked. Furthermore, groundwater has also frequently been viewed as an infinite resource and is thus often poorly managed (e.g. Nevill 2009; Tomlinson and Boulton 2010; Castle et al. 2014; Khair, Mushtaq, and Reardon-Smith 2015). Poor knowledge and management of groundwater resources has in some instances also resulted in the shifting of unsustainable water use practices from surface water to groundwater (e.g. Khair, Mushtaq, and Reardon-Smith 2015). As a consequence, many groundwater aquifers are now being utilised unsustainably (Gleeson et al. 2012a, 2012b).

In the Murray-Darling Basin (MDB), Australia and other parts of the world (e.g. southwest United States, Castle et al. 2014) there has been increasing recognition that addressing unsustainable groundwater use and moving towards sustainable groundwater management requires a more integrated perspective than the historically surface water centric policy framework is able to deliver (Tomlinson 2011). Sustainable groundwater management here refers to the use of groundwater over a specified timeframe that allows acceptable levels of stress and protects groundwater dependent economic, social and environmental values (Department of the Environment and Heritage 2004; Gleeson et al. 2012b). Alongside the management of surface water, sustainable groundwater management requires explicit recognition of the importance of groundwater and its connectivity with surface water.

Recent initiatives in Australia have recognised the importance of surface-groundwater connectivity and the Australian Government's National Water Initiative (National Water Initiative 2004; National Water Commission 2014) specifically highlights the 'conjunctive management of surface water and groundwater resources: so that the connectivity between the two is recognised, and connected systems are managed in an integrated manner'. Within the MDB, principles of environmental watering are also determined with explicit regard to groundwater resources and their connectivity with surface waters (MDBA 2012). These are examples of environmental water management policies that explicitly recognise the importance of groundwater for holistic and sustainable water resource management. As water resources become more heavily utilised and polluted, delivering on integrated surface-groundwater integrated policies, such as these, will become increasingly important globally.

This paper is intended as a brief introduction into the importance of groundwater and is targeted at policy-makers and managers, both in Australia and abroad, with little background in groundwater. In this paper we highlight the importance of groundwater and integrated surface-groundwater management policies for socio-ecologically sustainable water management. We outline the importance of groundwater for water-dependent socio-ecological systems and why it is essential to incorporate it into environmental and water management policies. We also discuss some of the challenges that will need to be overcome before sustainable water management policies in which groundwater receives more than lip-service, can be successfully implemented. Throughout we focus mainly on groundwater flows, not quality. Groundwater quality is important and can complicate surface-groundwater policies, but these factors are beyond the scope of an introductory paper such as this. While the concepts and problems presented throughout are of international relevance, in many places we focus on the MDB in Australia. The MDB, provides numerous examples for exploring management and policy issues surrounding groundwater, having recently undergone a long period of water scarcity comparable with projections of climate change (CSIRO 2008) and significant basin wide water reforms (e.g. MDBA 2012). We do not give a detailed overview of the history of groundwater policy developments in the MDB as this has been previously covered by Nevill (2009).

In simple terms groundwater is water in the subsurface of the earth. For the purpose of this paper we regard groundwater as water that saturates the fissures and pores within the earths subsurface (in both unconfined and confined aquifers) and includes soil water and deeper vadose zone water (after Giordano 2009 and Green et al. 2011). Areas where groundwater sits within the earth's surface are known as aquifers and these can range from confined to unconfined (Hiscock 2005). Confined aquifers are usually overlain with impermeable rock, which prevents water directly interacting with the earth's surface. Unconfined aquifers allow water to move easily between the subsurface and the surface, and as such are of great interest when considering surface-groundwater connectivity.

Groundwater has two distinguishing characteristics that differentiate it from surface water resources and are important considerations for socio-ecological systems. First, the temporal dynamics of groundwater systems are generally considerably slower than those of surface water systems. This means that changes to groundwater can be slow to manifest and have much longer lasting hydrological impacts than changes in surface water flows. For example, if the time it takes an aquifer to recharge (the process of water moving from the land surface into groundwater aquifers) is slow, it can take a very long time to reverse groundwater extraction impacts (> 1000s of years), meaning that the impacts of groundwater decline can be long lasting (Alley et al. 2002) irrespective of efforts to reverse it. In contrast, the impacts of surface flow declines will generally reverse quickly following an increase in rainfall or decrease in extraction. It is important to note that the range of temporal responses of groundwater systems varies widely. For example, shallow riverine alluvium groundwater aquifers, which are often important for groundwater dependent ecosystems (GDEs), respond to groundwater extraction or rainfall changes over relatively short time scales (e.g. within a year to a few decades). As such, groundwater extraction beginning in the mid-1960s in the Condamine River Alluvium Aquifer in the north of the MDB, has seen water table declines of up to ~25 m in some areas over the past few decades (Dafny and Silburn 2014; Kath et al. 2014a).

Secondly, groundwater quality can differ markedly from that of surface waters. Groundwater often provides water that differs in salinity, oxygen, temperature (Power, Brown, and Imhof 1999), heavy metal pollutants (McKay and Moeller 2001) and nutrient content, and as such its loss may be disproportionately negative (or positive if groundwater quality is poor, for example, saline or contaminated with heavy metals) compared with changes in surface water. As a result of these properties, groundwater connections play a unique role in socio-ecological functioning that in many cases is not fulfilled by surface waters.

We stress that the characteristics of groundwater outlined above are provided to give only a general overview of how groundwater differs from surface water. The groundwater characteristics outlined in this paper are by no means applicable to all aquifers, as groundwater dynamics can vary widely in different landscape and hydrogeological settings (Winter et al. 1998).

Groundwater's importance for sustaining water-dependent ecosystems

Our knowledge about the sensitivity of freshwater habitats to changes in surface water flows has been steadily accruing over recent decades and in many cases we now have good knowledge about the important role that managed stream flows play in maintaining these ecosystems (Poff and Zimmerman 2010; Acreman et al. 2014). Research on flow–ecology relationships is increasingly highlighting that freshwater systems not only require managed stream flow regimes, but also carefully maintained links to groundwater (Boulton and Hancock 2006).

Shallow groundwater underlays and connects to almost one-third of the lands surface (Fan, Li, and Miguez-Macho 2013). Across the lands surface, many highly valued rivers, wetlands, lakes, riparian and floodplain areas are connected to groundwater (Boulton and Hancock 2006). In the MDB numerous rivers, streams lakes and wetlands are connected to groundwater (e.g. large sections of the Darling and Murray Rivers) and all represent ecosystems dependent on the surface expression of groundwater (CSIRO 2008; BOM 2014). Alongside these groundwater connected streams there are often extensive floodplain and riparian forests, which are examples of ecosystems dependent on the subsurface presence of groundwater (e.g. River red gum (*Eucalyptus camaldulensis*) forests on the Murray River, Condamine River floodplains and semi-arid riparian areas, in the Namoi catchment of the MDB; Cunningham et al. 2011; Kath et al. 2014b; Fu and Burgher 2015). Some groundwater systems, on which floodplain ecosystems are dependent, are also localised and recharged by flood events rather than rainfall and are thus intricately linked to surface water.

The environmental water requirements of a number of these ecosystems were used to propose environmentally sustainable level of diversions for river basins within the MDB (CSIRO and SKM 2010; Swirepik et al. 2015). While the policy intent was that environmental water requirements are established with regard to the groundwater dependency of the ecosystems, this has been hampered by a lack of knowledge about groundwater–ecology relationships and of the interactions between surface and groundwater.

Groundwater's importance for water-dependent socio-economic policies

Globally groundwater is a key source of water for many human activities. Approximately 25% of all water withdrawals for human uses are from groundwater with estimates that groundwater makes up 50% of the world's potable water supply (Giordano 2009). Agriculture is also often highly dependent on groundwater. Since the 1960s agricultural groundwater water use has been steadily increasing in many countries (Giordano 2009). In many places, the stable and predictable water sources provided by groundwater play a key role in supporting the economies of agricultural communities. In Spain, which has climates comparable to the MDB, groundwater irrigation is estimated to be five times more valuable, and provide three times as many jobs as surface water irrigation (Llamas and Custodio 2003).

In the MDB there a wide range of human activities that are highly dependent on groundwater. To support these activities, upwards of 1832 GL/year of groundwater was extracted within the MDB during 2004/2005 (CSIRO 2008). In the MDB, groundwater is used for a range of activities including irrigated agriculture, drinking water for livestock, mining, urban and rural water supply, as well as industrial and manufacturing uses. This diverse range of uses and absence of alternative supplies means that groundwater is of high economic value. A recent study of groundwater value in Australia has estimate that the use of approximately 3500 GL of groundwater each year has a direct value-add value of $4.1 billion dollars, and a total economic contribution of $6.8 billion dollars (Deloitte Access Economics 2013). At this rate of groundwater use to economic return, groundwater use in the MDB would have a total economic contribution of around $3.3 billion dollars per annum. While this figure is a rough approximation and should be treated with caution, it does indicate the high importance of groundwater to the socio-economic viability of MDB communities.

Beyond, its economic value, groundwater can also be of cultural importance. Although, receiving relatively little attention in the MDB, investigations in other areas of Australia have highlighted that groundwater is central to many peoples culture. In Western Australia, the Nyungar peoples culture, identity and spirituality is intricately linked with groundwater and GDEs (McDonald, Coldrick, and Villiers 2005). The close association the Nyungar have with groundwater is also common for Aboriginal people in other parts of Australia (McDonald, Coldrick, and Villiers 2005). Policies for managing, groundwater socio-ecological systems in the MDB thus require an appreciation of not only its importance for the environment and socio-economic activities, but also its cultural value.

Groundwater's importance for drought resilience

Additional to the general importance of groundwater for socio-ecological systems its unique properties make it acutely important for water resource management in drought. The stable and slow flowing nature of groundwater aquifers often mean that they are only minimally impacted by short term precipitation drought events. As a consequence, in times of low rainfall when rivers, creeks and dams may be short of water, groundwater provides a critical source of water for socio-ecological systems. Because of this buffering ability, many groundwater fed-habitats also act as climate change refugia by decoupling freshwater habitats from variability and / or short term declines in precipitation or increases in temperature (Davis et al. 2013; Smettem et al. 2013). As such groundwater will likely become even more important for areas predicted to become dryer and subject to more intense droughts.

Several recent studies have highlighted the environmental importance of groundwater's drought-buffering characteristics. In California, USA, researchers have shown how both meadow vegetation and certain tree species are protected from the impacts of drought by having access to groundwater (Elmore et al. 2006; Mclaughlin and Zavaleta 2012). Areas where plants have access to groundwater act as drought refugia, or in other words, areas where the impacts of drought are less severe than they are for the rest of the plant community. The loss of groundwater from such areas could therefore greatly increase the overall impact of a drought on these ecosystems.

The potential importance of refugia in buffering ecosystems against drought impacts and climate change more generally has been explicitly recognised in policies. For example, to ensure that water-dependent ecosystems are resilient to climate change, there are specific objectives in the MDBA plan (MDBA 2012) which focus on refugia protection. In other parts of the world, predicted dryer climates under climate change (Dai 2011) suggest that such refugia protection policies could be globally important.

In the same way that groundwater access may buffer ecosystems (or provide refugia habitats) against drought impacts, it provides an important buffer for agricultural and urban water supplies for human uses (Llamas 2000; Iglesias et al. 2007). As groundwater is less susceptible to short term changes in rainfall it can help agricultural communities through drought periods. In many parts of the world this buffering role of groundwater may even protect the need for farmers to migrate if a drought were to threaten agricultural production (Kulkarni, Shankar, and Krishnan 2011). In the Campaspe catchment in the southern MDB, agricultural activities during drought are maintained by increasing groundwater use (El Sawah et al. 2013). Likewise in Spain, the 1990–1995 drought highlighted the role of groundwater for mitigating drought effects for both agricultural and urban populations (Llamas 2000; Iglesias et al. 2007). The loss of groundwater could therefore be of great concern for many socio-economic activities and make them more vulnerable to drought impacts. Nonetheless, Nevill (2009) has argued that in the MDB, groundwater resources, which could have been reserved specifically as a drought buffer against climate variability, have been used to the possible future detriment of both human and environmental values.

Consequences of overlooking groundwater – groundwater decline

Given the importance of groundwater for socio-ecological functioning, especially its importance for drought resilience, not appropriately incorporating groundwater into water policy and governance is likely to have numerous consequences. The most significant of these consequences manifest through groundwater decline.

Globally, the unsustainable extraction of groundwater has led to dramatic declines in groundwater levels (Gleeson et al. 2012a). Groundwater decline has occurred in China, India, Pakistan, Mexico, Spain, most countries in North Africa and the Middle East, as well as areas of the United States of America (USA), south and central America, Southern Africa and Australia (Gleeson et al. 2012a). In many instances, groundwater decline is triggered by a restriction in surface water resources, directing attention to groundwater as an alternate source (Khair, Mushtaq, and Reardon-Smith 2015). Such restrictions in surface water resources can be caused by increases in demand, restrictions to allocations, or changes in climate (e.g. drought or shifts in rainfall patterns). In much of Africa and the Americas, southern Europe, the Middle East, Southeast Asia and Australia, an increased frequency of drying and drought events predicted from future climatic change could reduce surface water supplies and dramatically increase the rate of groundwater use and thus magnify groundwater decline (Dai 2011). This means that alongside climate change, the unsustainable extraction of groundwater and consequent groundwater decline is an important global environmental and social issue (Llamas and Martínez-Santos 2005).

In areas of unsustainable groundwater extraction, adverse effects on the environment can be expected. Globally, there are numerous examples highlighting the negative effects of groundwater decline on the environment. These include reductions in streamflows and lake levels causing local species loss, a loss or change in vegetation communities, land subsidence and seawater intrusion. In the southwest of the USA, reductions in groundwater have been linked with the degradation of riparian habitats (Busch and

Smith 1995; Stromberg, Tiller, and Richter 1996). In the Mojave Desert, USA, groundwater pumping of regional aquifers has caused water table declines and the direct loss of Devils Hole Pupfish (*Cyprinodon diabolis*) habitat (Karam, Parker, and Lyons 2012; Mora et al. 2013). In fens of East Anglia, United Kingdom (UK), groundwater abstraction has been linked with declines in vegetation and invertebrate species (Harding 1993). In the San Joaquin Valley, California, around 750,000 ha of land has experienced subsidence of up to 9 m as a consequence of groundwater extraction (Zektser, Loaiciga, and Wolf 2005).

Similarly, within the MDB recent studies have suggested that some species of tree, such as River red gum, may be negatively affected by groundwater decline. In areas of deeper groundwater in the Condamine catchment in the north of the MDB, there is a lower likelihood of large river red gum occurring and the condition of riparian and floodplain forest is poorer, suggesting that these species need groundwater tables maintained within a certain depth to survive over the long term (Kath et al. 2014a). Although, it should be noted that in southern parts of the MDB, it is not only groundwater levels, but also groundwater quality that is important for forest condition (Cunningham et al. 2011).

The inter-linked nature of social, economic and ecological systems means that groundwater decline and corresponding environmental consequences also threatens many human populations and livelihoods. India is one of the world's most intense users of groundwater. Groundwater use has been increasing at phenomenal rates in India to help support agricultural production (Kulkarni, Shankar, and Krishnan 2011). Concern about these high rates of groundwater extraction has been growing and it is estimated that 33% of India's land area and 35% of its population are now exposed to unsustainable levels of groundwater withdrawal (Kulkarni, Shankar, and Krishnan 2011). In rural areas where groundwater is often the primary, or only, source of drinking water, the implications of this could be catastrophic in the near future (Kulkarni, Shankar, and Krishnan 2011).

Challenges and barriers to implementing groundwater policies

Given the potential consequence of unsustainable groundwater use, several governments have delivered policies that aim to curtail groundwater decline. As is the case for large aquifers on a global scale (Gleeson et al. 2012b), throughout the MDB there are many aquifers where groundwater is extracted at unsustainable rates (CSIRO 2008). In these areas, policies that cap groundwater extraction have been designed to help move towards sustainable groundwater use (MDBA 2012). Recently, in over allocated aquifers in the MDB (e.g. in the Condamine, Border Rivers, Lower Namoi, parts of the Lower Macquarie, parts of the Lower Lachlan, the Upper Lachlan and the Mid-Murrumbidgee), reductions in groundwater use of between 46% and 69% have been proposed. More specific policy recommendations about how to address unsustainable groundwater decline that are applicable both in the MDB and internationally have also been made (Nevill et al. 2010; Christian-Smith and Abhold 2015). These include the metering of groundwater use, compliance programmes to stop unauthorised use and the pricing of groundwater (Nevill et al. 2010). Policy and governance arrangements that recognise the value of the aforementioned recommendations and more generally the importance groundwater for socio-ecological systems are emerging. The MDB Plan also acknowledges the need to consider groundwater derived base flow, surface–groundwater interactions and groundwater dependence of ecological systems when determining environmental water requirements (MDBA 2012). This is a step away from the historically dominating surface water centric water policies and paves the way for objectives for groundwater to be established for ecological outcomes.

While the need for socio-ecological relevant groundwater management policies may be well established and there is general community acceptance of this (see Mendham and Curtis 2014), there are several important barriers and challenges impeding their successful implementation. We briefly outline some of these below and pay attention to highlighting how policies and management of groundwater resources contrasts with those focused on surface waters.

Temporal and spatial scale

The temporal and spatial scales over which groundwater aquifers operate can differ markedly from surface water resources. Depending on the size of an aquifer, the time between when water extraction starts and when significant impacts on groundwater conditions are noticeable can take anywhere from a few seconds to millions of years (Sophocleous 2012). Policy and governance must be cognisant of the fact that responses to management vary dramatically depending on the size and nature of the aquifer. Smaller local and intermediate sized aquifers with shorter response times are more likely to be easily managed and responses observed within a policy cycle. In contrast, for larger regional scale aquifers with long time lags, a response to changes in management actions may not be detected within the lifetime of those implementing them. The long time lags of groundwater systems to management actions may also discourage implementation of difficult policies needed to manage larger aquifers sustainably (Sophocleous 2012). Furthermore, time-lagged responses between extraction and changes in groundwater conditions can give the false impression that waters are being managed sustainably (Cook and Lamontagne 2002).

In addition to dramatic differences in response times, differences in the spatial extent of groundwater aquifers relative to surface water resources also pose challenges for the integrated governance of water resources. For example, surface water is typically managed on a catchment scale, whereas groundwater aquifers may span multiple catchments (Ross 2012). Alternatively there may be numerous distinct and unconnected (or complexly inter-connected) aquifers within one surface water catchment. Furthermore, catchments are easily delineated on a map and are an intuitive governance unit. Groundwater aquifers are less easily discerned, making the establishment of a sensible governance unit difficult. Challenges in managing these spatial mismatches are further complicated where multi-layered (i.e. vertically stacked) aquifers are present (Ross 2012), or if water quality differs between adjoining aquifers.

It is not only the differences in spatial extent of the aquifer that poses challenges but also the spatial variation in recharge character. Recharge sites for large regional scale aquifers can be some distance from the use or discharge of the groundwater. In such cases integration of land and water management policies to ensure the quality and volumes of recharge are suitably managed is required (Pringle 2001). In addition, many significant fresh groundwater systems are recharged by flood events rather than rainfall recharge and as such it is important to ensure that the quality of overland run-off from catchments will not pollute groundwater.

Together, spatial and temporal mismatches between surface and groundwater resources are key barriers to implementing policies for integrated surface-groundwater management. These differences must be considered carefully across multiple spatial and temporal scales. Indeed, in some instances spatial and temporal mismatches between surface and groundwater resources could be so great that the best policies and management actions will be those that take a discipline centric approach and treat surface and groundwater as separate resources.

Transboundary border management issues

The policy challenges associated with scale can be further complicated if aquifers overlap multiple socio-political boundaries (i.e. are transboundary). These transboundary issues can be either international or intra-national. International transboundary issues will obviously be more difficult to deal with because laws and socio-political conditions are likely to vary more (Blomquist and Ingram 2003). In north-central Middle East, including parts of the Tigris and Euphrates River Basins there has been rapid groundwater decline, which in part has been linked with transboundary water resource issues (Voss et al. 2013). Voss et al. (2013) argue that unilateral water resource management by numerous countries (Turkey, Syria, Iran and Iraq) has caused this, with upstream users extracting almost all surface waters and effectively leaving downstream users (i.e. Syria and Iraq) with no option but to deplete their non-renewable reserves of groundwater to support their people and economies.

While there are significant transboundary issues surrounding the integrated management of water resources, Blomquist and Ingram (2003) list several issues they believe could facilitate the resolution of transboundary groundwater management issues. These include (1) similar water allocation laws and regulations; (2) authoritative conflict resolution institutions and (3) adequate technical knowledge. In contrast factors that may exacerbate transboundary groundwater problems include (1) differences in culture; (2) differences in socio-political and economic conditions and (3) differences in how water is used (e.g. agricultural versus urban). Within the MDB, the role of the MDB Authority (and before it the MDB Commission and the River Murray Commission) in basin scale water resource governance has provided an opportunity to mitigate many potential transboundary issues that occur because of the multi-jurisdictional nature of the MDB (i.e. spans numerous states).

Prevention versus restoration

Policies and management actions aimed at ensuring the sustainable use of groundwater resources can be thought of in two broad ways (1) preventative and (2) restorative (or remedial) (Nelson 2013). In areas where groundwater extractions have historically been small, but future projections suggest increased use, then preventative actions are likely to be of greater priority. In contrast, areas where unsustainable groundwater extraction has been occurring for an extended period of time (e.g. >decades) and groundwater decline has already occurred (e.g. Gleeson et al. 2012a) then restorative policies and actions are likely to be the priority.

Preventative actions are likely to revolve around setting thresholds or change points beyond which no further groundwater extraction is allowed. These thresholds could be simple numerical ones, for example, there may be a policy stipulating no groundwater extraction is allowed within a specified distance of a groundwater connected stream or a groundwater (cap) based on total volumes, or relative to some reference point (Nevill et al. 2010; Nelson 2013). The latter option of a groundwater extraction cap based on volumes is the approach taken in the MDB. However, Nelson (2013) argue that while simple numerical thresholds can be easy to administer they are also relatively imprecise and furthermore, large-scale caps uniformly applied across aquifers, may result in highly variable outcomes. Preventative actions therefore need to be considered in concert with the previously discussed issues about the spatial and temporal variability of groundwater resources.

In some cases, typically in well-studied aquifers with detailed information, specific thresholds based on modelled calculations of pumping impacts may be available. Such information would likely allow for locally specific groundwater pumping rules to be set. However, as Nelson (2013), highlights in many places locally detailed information is unavailable. Furthermore, the time and resources to gather such information may in some cases be unjustified, which means that pragmatic solutions will be required.

In the absence of preventative policies, restorative policies come to the fore. In general however, despite the potential to enact restorative policies (e.g. on the grounds of protecting ecosystems), this rarely occurs in practice (Nelson 2013). Nelson (2013) argues that aside from some emergency situations (e.g. salinisation) restoration is often politically and economically prohibitive. Indeed, in some extreme cases, high levels of groundwater extraction can cause aquifer collapse or salinity intrusion and remediation may be impossible (e.g. Katic and Grafton 2011). Such, catastrophic events could have significant socio-ecological implications, but the feasibilities of managing and reversing them is plagued by uncertainties (Tsur and Zemel 2004).

Lack of knowledge

Even in instances where the decision between choosing preventative and remedial policies may be relatively straightforward there is still likely to be considerable uncertainty about the justifiable accuracy and specificity of policies. This uncertainty can directly undermine policy-makers and managers confidence in specific actions aimed at managing groundwater. Aside from a few isolated and well-studied aquifers, information about groundwater conditions and surface-groundwater connectivity is almost universally poor (Evans 2007; Ross 2012). For example, information on the position, size and permeability of aquifers is often lacking, as is knowledge of water flows and quality and especially how these interact with surface waters (Nevill et al. 2010). A lack of knowledge or high uncertainty is likely to be a frequent barrier to implementing policies for sustainable groundwater use (MacKay 2006).

The barriers posed by a lack of knowledge are particularly evident in the establishment of the environmental water needs of the MDB. The Basin Plan clearly states that the environmental water requirements of key ecological assets need to be established having regard to groundwater derived base flow, surface–groundwater interactions and the groundwater dependence of the ecological systems (MDBA 2012).The implementation of this requires knowledge of groundwater hydrology, groundwater recharge from surface water and groundwater–ecology relationships. Without this there is a risk that policies will be either overly passive or aggressive (Ross 2012). If too passive the policy could lead to higher rates of extraction than are environmentally sustainable; if too aggressive they may needlessly stifle socio-economic activity.

Without access to suitable information, Nelson (2013) and Nevill et al. (2010) argue that groundwater policy-makers have three possible strategies. Firstly, they can assume that surface and groundwater are connected and thus develop integrated surface-groundwater policies for all areas; secondly, they can develop policies which require those wanting to use groundwater resources to show they will have minimal socio-ecological impacts; thirdly, they can use policies which require new license holders to collect data which would allow the impact of groundwater use to be assessed after a given time. These different options highlight potential paths for addressing the lack of information about groundwater resources that face policy-makers and managers. Nelson (2013) argues that such approaches are emerging slowly in different parts of the world. With groundwater resources coming under increasing stress in many parts of the world, it is likely that these and similar approaches for dealing with uncertainty will be key for managing groundwater resources into the future.

Conclusion

Groundwater is a critical source of water for the environment and a range of socio-economic activities. Historically, policies aimed at the sustainable use of water have overlooked groundwater. Instead a surface water centric view of water resources has prevailed. Recently, there has been recognition that a surface water focused perspective needs to be superseded by a broader and multidisciplinary perspective of water resources, which explicitly integrates groundwater. This has begun in parts of the world and will likely become the norm globally. However, while policy recognition of the importance of groundwater is a critical first step, it by no means guarantees sustainable water management. There are numerous barriers that must be overcome before this can be achieved. These barriers include, mismatches in the spatial and temporal scales that surface and groundwater operate across; the management of transboundary conflicts that are common in water stressed areas and a lack of basic knowledge about groundwater–ecology relationships. Failure to consider these challenges in the development, implementation and review of water resource policy means that the consequences of unsustainable groundwater use will continue and possibly intensify. In turn, the unsustainable use of groundwater will further increase the vulnerability of the environment and many human populations to future water scarcity and climate change.

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