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Socio-hydrologic drivers of the Pendulum Swing between agriculture development and environmental health: a case study from Murrumbidgee River Basin, Australia

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Abstract

This paper presents a case study centered on the Murrumbidgee river basin in eastern Australia that illustrates the dynamics of the balance between water extraction and use for food production and efforts to mitigate and reverse consequent degradation of the riparian environment. In particular the paper traces the history of a pendulum swing between an exclusive focus on agricultural development and food production in the initial stages and its attendant socio-economic benefits, followed by the gradual realization of the adverse environmental impacts, efforts to mitigate these with the use of remedial measures, and ultimately concerted efforts and externally imposed solutions to restore environmental health and ecosystem services. The 100 yr history of development within Murrumbidgee is divided into four eras, each underpinned by the dominance of different norms/goals and turning points characterized by their changes. The various stages of development can be characterized by the dominance, in turn, of infrastructure systems, policy frameworks, economic instruments, and technological solutions. The paper argues that, to avoid these costly pendulum swings, management needs to be underpinned by long-term coupled socio-hydrologic system models that explicitly include the two-way coupling between human and hydrological systems, including evolution of human values/norms relating to water and the environment. Such coupled human-water system models can provide insights into dominant controls of the trajectory of their co-evolution in a given system, and can also be used to interpret patterns of co-evolution of such coupled systems in different places across gradients of climatic, socio-economic and socio-cultural conditions, and in this way to help develop generalizable understanding.

1 Introduction

Water resource management decisions we make, be they infrastructure or policy related, produce positive or negative impacts that in many cases can last a long time.

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Therefore, in the emergent Anthropocene, given the growing demand for water resources to satisfy increasing human populations, there is an urgent need for water resources management decisions to be based on predictions over long (decadal to century) time scales. However, in order to make predictions of future water resources we need reasonable models of how future human societies will demand, use and supply water. But the difficulty in predicting this is compounded by the fact that humans do not normally organize themselves just to optimize access to or utilization of water resources; instead, the reality is that humans use and/or manage water resources so as to maximize the overall well-being of some or all members of society. Such human well-being could be framed in several ways, depending on local circumstances: it could be drinking water supply to cities, or it could be water for food or hydropower production, or it could be protection from floods or it could be protection of water quality or ecosystem health.

Consequently, hydrologic predictions over long timescales cannot escape from the twin problem of predicting how human societies themselves will evolve with respect to water in its many manifestations. The challenge this poses for prediction is clearly illustrated in the case study from Australia presented in this paper, where the hydrology is governed by the physical (natural and human-induced), socio-economic and institutional structures but these are in turn shaped by changing values and norms of the population regarding water and the environment.

Australia has had a long history of promoting agricultural development through harnessing its water resources, making it a defining feature of the country's social identity. Agriculture development has brought significant economic benefits to Australian society, contributing to national economic growth, regional development and secure food supplies. However, it is becoming clear that these societal and economic benefits had been achieved at significant environmental cost, through mounting pressure on, and degradation of, the riparian environment, impairment of water quality and reduction of biodiversity. These problems have been exacerbated by recent prolonged droughts and

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also increased demands for water, food and other amenities for a growing population, posing major challenges for water management.

A vivid example of these water management challenges is the crisis situation that has unfolded in recent times in the Murray-Darling Basin (MDB) in eastern Australia (Roderick, 2011). The crisis over water use in the MDB revolved around the competition for water resources between humans and ecosystems. The balance of water utilisation within the MDB remained strongly in favour of water use for irrigated agriculture for 75 yr. The degradation of the environment resulting from the long period of intensive irrigated agriculture, and failure of several efforts to mitigate their negative environmental impacts contributed to a change of community attitudes, which in the end forced the hand of government to act in a decisive manner and impose a solution to achieve environmental outcomes (MDBA, 2010). The balance has now decisively shifted in favour of the environment, reflected not only in the relative amounts of water allocated for human and environmental uses, but also in investments in water infrastructure and changes to human settlement patterns. However, the proposed cutbacks to water allocation for irrigation, as part of the Government imposed solution to alleviate environmental degradation, threaten the economic livelihood of rural Australia, which was behind the heated debate that followed the Government intervention.

Gleick and Palaniappan (2010) describe the situation that prevails in the MDB in terms of “peak ecological water”, which they defined as the “point beyond which the total costs of ecological disruptions and damages exceed the total value provided by human use of that water.” In coming decades, as human populations and economies grow further, it is likely that such problems could become increasingly prevalent in other parts of the world as well. Finding the delicate balance between competing water needs of humans and ecosystems in the management of water resources is becoming an urgent need worldwide.

The rapid changes that the water cycle and the environment are likely to experience as a result of natural climatic variability and increasing anthropogenic changes require that prediction and management frameworks must account for not only the effects of

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climate variability and human interferences on hydrologic variability, but also how hydrologic variability and associated environmental changes and possible degradation in turn influence the human responses and behavior changes. In the past these feedbacks were not included in the hydrological predictions that underpinned traditional integrated water resource management (IWRM). Recently, Sivapalan et al. (2012) have proposed a socio-hydrologic framework that permits the study of coupled human-water system dynamics, including inherent bi-directional feedbacks between the two sub-systems. Indeed, socio-hydrology accounts for a balancing of economic and environmental well-being, with consideration for changing social norms or community attitudes in respect of the environment.

This paper will present the history of how the water crisis unfolded in the MDB, and a socio-hydrologic interpretation of the co-evolutionary dynamics of the coupled human-water system. In particular, it will chart the history of water utilization within the MDB, but with a particular focus on the Murrumbidgee, a major sub-catchment of the MDB and the most significantly impacted. The paper will highlight the dynamics of human-water interactions that resulted in the "pendulum swing" in relative water allocations between humans and ecosystems, and the natural and societal factors that contributed to this pendulum swing. Understanding the causes of the pendulum swing in the Murrumbidgee river basin within a quantitative and universal socio-hydrologic framework may provide useful lessons for other river basins around the world that may be undergoing similar development.

2 Location of study, data and methods

The Murray-Darling Basin (MDB) is Australia's most iconic river system and is defined by the catchment areas of the Murray and Darling Rivers and their many tributaries (Fig. 1). The MDB extends over 1 million km^2 of south-east Australia, representing approximately one-seventh of Australia's landmass. The MDB displays a varied landscape, from semi-arid ephemeral river systems in the north to highly regulated

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river systems in the south. It supports a great number of plants, animals and ecosystems that are both nationally and internationally significant, including 95 inundation-dependent fauna species, and more than half the nation's native fish species. The economic success in the MDB is a direct result of historical efforts by MDB States (New South Wales, Queensland, Victoria and South Australia) and the Commonwealth Government to harness its water resources for agriculture. This is exemplified by the fact that it supplies some 40 % of Australia's food needs and supports a resident population of 2.1 million people. In 2006 more than 920 000 people were employed across the MDB within the agricultural industry, contributing an average of $ 15 billion per annum to the Australian economy (MDBA, 2010).

The Murrumbidgee river basin, one of the largest sub-basins within MDB (Fig. 1), is located in the south-east of the MDB, and has a population of over 540 000. Although only representing approximately 8 % of the MDB's area, the Murrumbidgee Basin accounts for 22 % of the surface water diverted for irrigation and urban use. It contributes 25 % of NSWs' fruit and vegetable production, 42 % of NSW's grapes and half of Australia's rice production. Agricultural production within the Murrumbidgee is valued at over $ 1.9 billion annually (Murrumbidgee CMA, 2006, 2012).

One of the goals of this paper is trace the history of the "pendulum swing" between an exclusive focus on agricultural development and food production in the initial stages and its attendant socio-economic benefits, followed by the gradual realization of the adverse environmental impacts, efforts to mitigate these with the use of remedial measures, and ultimately concerted efforts and externally imposed solutions to restore environmental health and ecosystem services. This goal is sought through a critical review of the substantial literature that existed in the form Government and consultants' reports, and additional new quantitative trend analysis of several hydrological and social variables that contributed to or reflected the pendulum swing.

The trend analyses reported in this paper were carried on primary data sourced from several Australian Government agencies: NSW State Water Corporation, Australian Bureau of Statistics, and the Australian Department of Sustainability, Environment,

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Water, Population and Communities. The trends in the data of water use, agricultural production, and environmental flows are correlated with the history of development of agriculture, government policy and investment, social issues, and environment conditions within the Murrumbidgee catchment. The results of the trend analyses are used to support or confirm the narratives presented in previously published (including Government) reports. Guided by these trends and narratives, a secondary goal of the exercise is the development of a perceptual model of the coupled socio-hydrologic system operating within the Murrumbidgee basin, framing it in terms of the two-way coupling of social and hydrologic systems. Furthermore, a perceptual model that has wider applicability across climatic and socio-economic gradients is also sought through generalizing the drivers, and interactions and feedbacks, in a manner that has wider applicability.

3 Results: how the Pendulum Swung in the Murrumbidgee

3.1 Murrumbidgee Basin as human-water system

The Murrumbidgee river basin is a highly human impacted and managed system. Over the past 100 yr, the basin has been almost fully transformed through the introduction of human built infrastructure (e.g. dams and weirs) to support expansion of irrigated agriculture. The irrigation infrastructure, such as dams and weirs, as well as irrigation schemes add to or overlie landscape features associated with natural river basins, such as hillslopes, wetlands, riparian areas and river networks. The human induced structures have altered the flow dynamics that would normally result from external climatic drivers (i.e. precipitation), in effect diverting much of the water that would have otherwise flowed down the river network to the ocean (and periodically inundated precious wetlands and riparian areas) now to targeted irrigation areas, from where it would be utilized by agricultural crops towards crop yield, and eventually returned to the atmosphere as transpiration.

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The above description refers to just the hydrologic dynamics in this human-managed landscape. However, in the intermediate term, this dynamics is accompanied by other slower dynamics that has to do with human decisions of the area to be put under irrigation, types of crops that will be grown, and about when and how much to irrigate. How much land is put to agriculture and the choice of crops are normally decentralized decisions that depend on externalities such as commodity prices, availability (i.e. in the dams) and price of water for irrigation, as well as the climate itself (which determines the demand for irrigation). How much water is available (i.e. stored in dams) and at what price depend upon climate over the previous few years, but increasingly also upon how much water may be allocated to the environment in the form of environmental flows. The allocation of water between agriculture and environment is governed by economic benefits of agriculture and the value placed by society on the environment, including water quality and biodiversity. This competition for water between irrigated agriculture and the environment is mediated in the political arena, on the basis of arguments by the rural lobby (acting on behalf of the irrigators) and by the green lobby (acting on behalf of the environment). The relative strength of the green and rural lobbies guides government decisions to purchase water rights from the irrigators, and to support the environment through construction of specialized infrastructure geared towards protecting or enhancing the environment.

Figure 2 is a schematic describing the organization of the coupled human-water system specific to Murrumbidgee, along the lines presented above. Clearly, as seen in Fig. 2, human management of the water system over the last 100 yr has resulted in a system of enormous (apparent) complexity, spanning both physical infrastructure and the economic, policy and legal frameworks governing water availability, use and pricing. In fact, the system is even more complex than is shown in Fig. 2 due to the fact that the human-water interactions and feedbacks occur in a distributed manner within the basin at a range of space and time scales. The complexity of the linkages shown in Fig. 2, which is the end result of a century of human management of the system, is a far cry from what might have existed when agriculture first developed within the

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Murrumbidgee 100 yr ago. An understanding of how this complexity grew over time to become what it is today can inform the development of models of coupled human-water systems, and will give us the insights and a predictive capability that may help to avoid similar management crises from developing in river basins in other parts of the world.

3.2 Pendulum swing in water utilization

Published studies have documented how the balance in water utilization between agriculture and the environment, and associated infrastructure development, have evolved over the last 100 yr. A synthesis of previously published reports and the results of new quantitative analyses carried out for this study resulted in the evolutionary history that is presented schematically in Fig. 3, which organizes the history in terms of the relative emphasis placed on agricultural development and environmental health, and is divided into four distinct Eras:

- Era 1: circa 1900–1980: development of irrigation and associated infrastructure
- Era 2: circa 1960–1990: gradual appearance of environmental degradation
- Era 3: circa 1990–2007: awareness of broader environmental impacts and a focus on consensus strategies and policies to achieve sustainable management
- Era 4: circa 2007–present: failure of the consensus model and emergence of a directed government strategy to achieve environmentally sustainable outcomes.

We next present a summary of the results of the synthesis presented in Fig. 3, followed subsequently by detailed description of how and why these happened, including substantiation by the results of quantitative analyses.

Era 1 saw rapid growth of agriculture infrastructure. Growth of human population and agricultural production followed into Era 2. By the end of Era 2 there was increasing awareness of environmental degradation, but these were addressed through "band-aid" solutions. Era 3 saw appreciation of broader environmental impacts, and led to

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exploration of a range of strategies aimed at their mitigation. As environmental degradation continued unabated, Era 4 saw a major switch in emphasis towards environmental health, with both agricultural production and population growth both showing sharp reverses, and increased investment in infrastructure aimed at enhancement of the environment. In this paper the switch from the earlier emphasis on agriculture development to a new emphasis on environmental health, shown in Fig. 3, is referred to here as a *pendulum swing*. In the next few sub-sections, we present a more detailed description of the changes that happened within the Murrumbidgee river basin over the past 100 yr.

3.2.1 Era 1 (1900–1980): expansion of agriculture and associated irrigation infrastructure

Aboriginals had lived sustainably in the Australian landscape for thousands of years. The situation changed with the settling of Europeans, who displaced aboriginals, cleared forests and native grasses, introduced new grasses, cereal crops, cattle and sheep. They built farm dams and introduced irrigation schemes for intensive cultivation and more productive use of lands on the floodplains. These efforts were supported by government investment in irrigation infrastructure (e.g. dams and weirs) and government coordination in the sharing of waters. Government investment in, and coordination of, irrigated agriculture was motivated by several factors.

Firstly, the development of agriculture was representative of the pre-eminence of agriculture in the Australian economy in the early to mid-20th century. The Murrumbidgee, along with the MDB, became Australia's food bowl, growing and processing a significant fraction of all fruits and vegetables. For example, during the first half of the 20th century, agriculture accounted for up to 35 % of the Australian economy and 70–80 % of Australia's exports (Productivity Commission, 2005). Secondly, there was the official government policy of populating the interior. Indeed, increasing the population in western NSW was one of the objectives of the NSW Government expenditure on irrigation (Wilkinson, 1997). In keeping with this policy, following World War 1, returning

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soldiers were settled in the area, with the numbers being boosted by new immigrants from Britain. However, peopling the interior, as government policy, was abandoned during the 1950s and 1960s (Wilkinson, 1997). Thirdly, irrigation allowed the expansion of agriculture away from riparian lands where people initially settled to more marginal lands lying further away from the river. Australia suffered from frequent severe droughts and irrigation gave more certainty of water supply to these lands than was possible with rain-fed agriculture. The certainty of water supply through irrigation resulted in more intensive agriculture production and cultivation of more profitable crops.

Much of the agricultural expansion commenced in about 1902 and continued until about 1980 with significant government funding and coordination (Wilkinson, 1997). A series of dams and weirs were built from about 1910 to about 1970. Irrigation activity invariably followed, with a significant expansion of the area under irrigation which continued up until about 1980. Expansion of agriculture and irrigation then led to a substantial growth of population within the Murrumbidgee, which hit a peak in 1990 and in the case of rice production was severely influenced by the drought between 2000–2010. Agricultural productivity also expanded dramatically, hitting a peak around 2000. The expansion of irrigated agriculture, associated infrastructure, size of the human population, the resulting agricultural productivity and measures of environmental degradation over the last 100 yr (1910–2010) are presented in summary form in Fig. 4a–h.

An indication of the nature of growth of agricultural activity can be obtained from the details presented in Figs. 1 and 4a–h. As early as 1843 much of the land along the Murrumbidgee River had been settled by European colonists who used the water for grazing stock. Within the Murrumbidgee irrigation activity commenced in 1902 in the area around Hay (Turral et al., 2009). Construction of the Burrunjuck Dam commenced in 1907, followed by the construction of diversion weirs and irrigation delivery canals. The Murrumbidgee Irrigation Area (MIA) commenced in 1912 and quickly expanded (incorporating the Yanco Irrigation Area, 1912; Mirrool Irrigation Area, 1924; Wah Wah Irrigation District, 1930; Benerembah Irrigation District, 1933; and Tabbita Irrigation District, 1933). Construction of more dams to increase storage capacity occurred in tandem

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(e.g. enlargement of Burrinjuck Dam during 1939–1956; Blowering Dam, 1968; Tantangara, 1960; Talbingo, 1971). The Lowbidgee Flood Control and Irrigation District (LFCID) was established 1945. It is located at the downstream end of the Murrumbidgee river basin, upstream of Balranald. The Maude and Redbank weirs facilitated the flooding of the Lowbidgee irrigation area during the winter/spring. The Coleambally Irrigation Area (CIA) area was established in 1960 (Wilkinson, 1997; Lewis, 2012).

The investment in infrastructure (dams, weirs, supply canals, etc.) facilitated the growth of the whole community and the agricultural industry. Agricultural production within the Murrumbidgee included rice, wheat, soybeans, canola, citrus, vegetables and vines, as well as sheep and cattle. The first commercial crop of rice was harvested in 1924 and subsequently rice production grew rapidly (Lewis, 2012). In the early years rice was a very profitable crop compared to other grains. Over the next 30 yr the rice industry grew significantly, leading to the construction of rice mills in the area around Leeton and Yanco, which generated greater employment. Similar growth also occurred in other sectors, such as the wine industry, with extensive support and supply chain development in the local community. Figure 4d shows the growth in rice production, which is used here as a surrogate for overall agriculture production.

However, the agricultural expansion described above did not happen uniformly across the Murrumbidgee river basin; in fact, there was a spatial aspect to it. Agriculture started in riparian areas near the outlet of the basin, and then with the onset of irrigation expanded to areas away from the river (non-riparian lands) and, aided by the construction of dams further upstream, migrated to upstream regions. This expansion also benefited from the government policy of populating the interior. Sivapalan et al. (2012) presented a cartoon figure that illustrated the upward expansion of agricultural development (in terms of growth of irrigation infrastructure and area put under irrigation) within the Murrumbidgee, which is reproduced in Fig. 5.

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3.2.2 Era 2 (1960–1990): onset of environmental degradation and band-aid solutions

The balance in water utilisation over Era 1 was in favour of agriculture development, with heavy government investment and supported by government policy, yet there was no consideration, nor even any apparent awareness, of the requirements of the environment. However, the situation began to change with the appearance of several environmental problems.

The first was the problem of saltwater intrusion. As water consumption in the MDB increased and as flow in the rivers decreased, intrusion of seawater was felt up to 250 km upstream from the mouth of the River Murray. This impacted landowners and farmers along the lower reaches of the river who strongly advocated construction of barrages to keep the water fresh in the lower reaches of the River Murray. Work on the barrages was completed in 1940.

The second problem was salinization of lands due to irrigation. As part of agricultural development deep rooted native vegetation was replaced by shallow rooted annual crops and pastures which changed the water balance and raised groundwater levels. For example, before the introduction of rice, the groundwater table within the Murrumbidgee Irrigation Area (MIA) was 20 m below the land surface. By 2001 the water table had risen to within 2 m of the surface. Rising water tables dissolved salts that were already present in the soil profile and brought them to the surface (GWG, 1996). This was compounded by the application of irrigation water resulting in both salinisation and waterlogging. The damage due to salinity was widespread, with adverse impacts on the environment of rivers and wetlands, built infrastructure, and agricultural productivity.

Mitigation measures to tackle salinity were implemented in the Murray-Darling Basin. These included controlling rice production, introducing efficient irrigation practices, implementing efficient delivery and usage of town water, and expanding tree planting. Since 1988, the NSW, Victoria and South Australia governments, together with the Commonwealth Government, have funded the construction of salt interception

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schemes (SIS) to reduce salinity in the Murray River. The SISs are large scale groundwater pumping and drainage projects that intercept saline groundwater flows and dispose them, usually by evaporation.

Salinity was not the only issue to impact the region. The summer of 1991–1992 saw the occurrence (over 1000 km in the Murray-Darling) of one of the worst blooms of blue-green algae recorded anywhere in the world (MDBMC, 1994). Sewage treatment plants were the cause of excess nutrients in the river and significant investment was made by the Governments to upgrade wastewater treatment plants to reduce the nutrient loads. Irrigation areas were identified as having another large impact on nutrient loads and further measures were adopted to decrease nutrient runoff.

Figure 3 does recognize the initiation of infrastructure targeted towards alleviating salinity and algal blooms (e.g. barrages, SIS schemes and upgrading of sewage treatment plants). There were also attempts to institute policy changes that affect the utilization and sharing of waters, through extending the role of the Murray-Darling Basin Commission (MDBC) (MDBC, 2011). These mitigation measures, especially those to combat salinity, failed to reverse the degradation as they did not address the fundamental causes of the rising water tables caused by irrigation practices. Despite the emergence of environmental problems and some efforts at remediating them, there was continued rapid growth of agriculture production and population (see Fig. 4c and d), and the balance of water utilisation remained with agriculture (see Fig. 3). A holistic catchment wide approach considering human influences and environmental requirements were not yet given proper recognition until the beginning of Era 3.

3.2.3 Era 3 (1990–2007): establishment of widespread environmental degradation

As seen in Fig. 4a and b, investment in irrigation infrastructure (e.g. dams and weirs, and irrigated areas) was largely complete by 1970, and growth of irrigation area was largely complete by 1980. However, irrigation water utilization continued to increase until 2000 (see Fig. 5a), although this growth was moderated somewhat by the 2000–

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2010 drought. The growth of water utilization was also mirrored in the growth of agricultural production (e.g. as reflected by growth of rice production, Fig. 4d). This increase in agricultural output was achieved by strong productivity growth (per hectare) and a decline in the agricultural work force. This was in part a result of a heavy reliance on mechanisation, an increase in corporate farming practices and a movement of labour to other sectors of the economy. The population in the Murrumbidgee which grew rapidly until 1990 began to decline (see Fig. 4c), which is partly attributed to the changing profile of agriculture. Agricultural share of the Australian economy started to decline from the 1950's to its present value of just 4 % and Australia's reliance on agricultural exports declined to about 20 % (Fig. 4g) (Productivity Commission, 2005).

The rapid growth in water utilization for agriculture also meant a reduction of residual flow (i.e. environmental flows) in the river. This is illustrated in Fig. 4f, which shows the reduction in Murrumbidgee river flows that reaches the outlet near Balranald (see Fig. 1 for locations) over the period 1900 to 2011, expressed as a fraction of the river flow at Wagga-Wagga. The flow reduction can be directly attributed to water utilization for irrigation (see Fig. 4e) sourced from the Murrumbidgee River and utilized mainly in the MIA, CIA and LFCID irrigation areas. By 2011 the fraction of flow reaching Balranald has dropped to a mere 10 % (on average). The reduction of flows significantly reduced the frequency and duration of inundation of wetlands in the riparian areas near the river, and in this way began to impact ecosystem health of these riparian environments, including the fauna and flora that depended on these wetlands.

For example, Fivebough Swamp and Tuckerbil Swamp are Ramsar designated wetlands. Both are located near Leeton, within the MIA (Fig. 1). Other significant wetlands in the Murrumbidgee are the Lowbidgee Floodplain, located within the LFCID, and the Mid-Murrumbidgee Wetlands, which are riparian wetlands between Wagga Wagga and Carrathool, each of which cover significant areas. Changes to the wetland areas within the Lowbidgee were assessed by Kingsford and Thomas (2004), who estimated that between 1902 and 1998 some 232 276 ha of wetlands (out of the 303 781 ha that existed in 1902) have been lost or degraded.

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Trend analyses of the number of species of different water bird groups and their overall abundance were carried out using annual aerial surveys between 1983 and 2000 across the Lowbidgee floodplain, Fivebough Swamp, and the Paroo overflow lakes (Table 1, taken from Kingsford and Porter, 1994). Paroo lakes are located in the north west of NSW in an area relatively free from agricultural development. This analysis showed a significant reduction in water birds in parts of the Murrumbidgee that experienced significant loss or degradation of wetlands, relative to those that did not (e.g. Paroo lakes). Similar to water birds, the native fish community within the Murrumbidgee Basin has also been severely depleted. A survey by Gillian (2005) showed that 8 of the 21 native fish species were either locally extinct or survive at very low abundances. In addition to the loss of native species, a large number of invasive fish species have become dominant, both in terms of number (71 %) and biomass (90 %).

With the realization of the severity of the environmental degradation, which was proceeding unabated, several measures were instituted to control the environmental degradation. These covered the entire spectrum of new infrastructure, policy changes and also economic measures. For example, no new licenses for water extraction were issued after 1986, even though the proportion of flow allocated to irrigation continued to expand on the basis of existing licenses (Turral et al., 2009). In 1993, the MDBC introduced a temporary cap on further expansion of water extraction, which was made permanent in 1997 (MDBMC, 2000). Another initiative of the NSW state government was to construct fishways which would allow fish to pass barriers within the rivers, which was now required of all significant upgrade or renewal works undertaken in the rivers used for irrigation. As result, since 1985, 27 fishways have been built.

The most important changes happened in the policy and economic domains. The Council of Australian Governments (COAG) in 1994 developed a Water Reform Package which, for the first time, recognised that the environment was a legitimate user of water in its own right (Arthington and Pusey, 2003; Schofield et al., 2003; COAG, 1994). The NSW Government in 1997 followed suit with a set of reforms culminating in the Water Management Act (WMA) of 2000, the legislation underpinning the process to protect

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environmental flow. Under the WMA Act, Water Sharing Plans (WSPs) were developed that sought a balance between requirements of industry, agriculture, domestic use and the environment. Other key reforms introduced as part of these legislations included the separation of water titles from land, adoption of water trading arrangements and setting up of a water market, full cost recovery and removal of cross subsidies in the supply of water, and importantly, institutional arrangements to support these reforms (Schofield et al., 2003).

3.2.4 Era 4 (2007–present): remediation and emergence of the environmental customer

In spite of the increasing recognition of the water needs of the environment and several mitigation measures instituted during Era 3, these did not manage to reverse environmental degradation. Community concerns started to grow at the continued environmental degradation and the failure to develop viable solutions. Community concerns were highlighted strongly by the "green" lobby, which grew in influence since at least the 1990s. This, combined with strong fiscal position that Australia was in thanks to the mining boom, and the diminishing role of agriculture in the Australian economy (Fig. 4g), changed community attitudes towards the environment and strengthened the Commonwealth government's hand.

In 2007 the Commonwealth government announced a $ 10 billion national water reform package (later increased to $ 12.9 billion, Turral et al., 2009). It called for the states which are part of the MDB to transfer their constitutional powers over water management to the Commonwealth so that comprehensive MDB-wide reforms could be introduced. The main thrust of the $ 12.9 billion plan was to reduce the allocated water volume to agriculture in return for system and on-farm investments in water conservation. This has also added impetus to the need to account for surface water and groundwater flows, and to monitor and control the capture of runoff on farms. In all states, the ability to capture runoff in farm dams was restricted through new licensing requirements. The 2007 Water Act created an independent Murray-Darling Basin Authority (MDBA).

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It began to set sustainable diversion limits that can be taken from surface water and groundwater systems within the MDB. It also included an environmental watering plan to optimize environmental outcomes. The Act also established an Environmental Water Holder to protect and restore the environmental assets within the MDB (Fig. 4h).

As part of the Commonwealth government's $ 12.9 billion program significant projects within the Murrumbidgee River are now being implemented. These are aimed at upgrading infrastructure and operational processes. They include a suite of infrastructure works designed to minimize in-stream river losses either through improved metering of customers or reducing water flowing to places where it is not required. As part of these projects more detailed information on the cost of delivering water (in terms of evaporation and infiltration losses) to different parts of the catchment are being assembled. This will allow further policy development such as purchasing water licenses for the environment from areas that are more costly to deliver water to. Differential water pricing that will allow further efficiencies and transparency in the use of water is envisaged. Other projects include modification of bridges to allow passage of water to flood wetlands, and weirs to divert water to wetlands.

Several other mitigation measures that the Government has introduced are intended to reverse environmental degradation by reducing water allocation to agriculture in favor of flows to the environment. These are in four main areas: new policies (i.e. legislation to impose a solution, creation of the MDBA and the office of the Environmental Water Holder), new economic measures (e.g. massive funding, buying back of water licences, water trading), new technologies (e.g. incentives to change the type of crops grown, efficient farm irrigation), and new infrastructure (weirs to flood wetlands, modification of bridges, water efficiency projects).

The consequence of all of these actions is that irrigation infrastructure (in terms of area put under irrigation and associated infrastructure) that was moving upstream for the first 75 yr of agricultural development is now expected to move back downstream (Sivapalan et al., 2012). An example of this is that over the 2001–2009 drought period rice growers were able to make more money with less risk by selling their water

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in the water trading market rather than by growing rice. The sales of water by the rice growers helped downstream horticulturalists to keep their plantings alive, and new horticulturalists to move in to grow highly profitable produce, in areas downstream of the Murrumbidgee, e.g. Sunraysia and Goulburn regions of the state of Victoria and Riverland in the state of South Australia (NWI, 2010, 2011).

The mix of solutions imposed by Government during Era 4 was in part arbitrated by interactions and feedbacks between the affected local community and local stakeholders, and the increasing political influence of environmentally aligned political parties and lobby groups. In effect, the Government was responding to changing community attitudes, even though these normally tend to lag well behind the system changes. In any case, the net result is that the pendulum has now clearly swung back to the environment. As a result of the massive funding directed at environmental remediation and enhancement, it is expected that the population within the Murrumbidgee will decline further, and agriculture is expected to follow.

4 Discussion: lessons learned – need for new socio-hydrologic prediction frameworks

As we survey what transpired over the past century one can see that, in the short term (i.e. during an individual Era), it involved the implementation of IWRM, ostensibly using the best tools available, including hydrologic prediction tools. Yet in the long-term the problems only got worse and reached a crisis situation by the 1990s. This was firstly due to poor understanding or lack of awareness of environmental impacts; consequently, the environment was not valued enough. By the time the environment began to be valued, there were no analyses or prediction frameworks that could account for environmental feedbacks that impacted on human behaviour in respect of water.

Above all, the Murrumbidgee case study illustrates what could happen when the underlying preferences, i.e. what humans value, have changed over time and the prediction frameworks could not account for these changes. The values and norms relating

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to water and the environment have changed over the past century due to several factors: the realization of the damage to the environment is the first, but is not the only one. Another factor is the growth of the economy overall, and the diminution of agriculture and food exports as a fraction of the national and regional economy (Fig. 4g). Thirdly, tied to this, was the general growth of environmental awareness and growth of the "green" lobby. All of these together created the conditions for decisions to reallocate water to the environment. In other words, changes in norms and values were themselves a result of human-water system feedbacks.

The net result of all this is that the human-water system in the Murrumbidgee has witnessed an interesting long-term dynamics that could not have been seen a 100 yr ago, or even 50 yr ago. In the time domain this manifested as the growth of irrigation and its eventual turnaround (as shown in Figs. 3 and 4a–h): irrigation here stands variously for area under irrigation, amount of water utilized in irrigation, agricultural productivity, size of human population, and size of irrigation infrastructure. There is also a spatial aspect. Figure 5, reproduced from Sivapalan et al. (2012) indicates schematically that the growth of irrigation involved the upstream migration of indicators of irrigation. The eventual turn-around in irrigation then involved a downstream migration of the same. This complex dynamics, which we refer to as the pendulum swing, were the result of the two-way feedbacks between the hydrologic and human systems; in effect they can be considered as "emergent" dynamics. This emergent dynamics, which we call the pendulum swing, could not have been predicted using traditional hydrologic prediction frameworks.

The pendulum swing, meanwhile, has been costly to the environment, local communities and to Government. Yet, there is no guarantee that the imposed solution will fix the problem forever. Imposed solutions by Governments on complex inter-dependent systems such as this are seldom successful and the outcomes which manifest many years later seldom align with the original objectives or intentions. Indeed, it is not absolutely clear what the situation will be in another 50 yr for the people, and for the environment. It also raises several related questions: could the situation have been

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avoided in the first place? What would happen if the Government had not intervened? Could there be other alternative solutions? Now that Government has intervened, what does the future hold, for the people and the environment?

The Murrumbidgee experience teaches us that simplistic hydrologic predictive frameworks that link demand to population growth or economic growth will not be adequate in the long-term. Likewise, traditional economic frameworks that allocate water between multiple human users are also not adequate. These frameworks are elements of the integrated water resource management (IWRM) approach, which has as its focus controlling or managing the water system to reach desired outcomes for society and the environment. The Murrumbidgee case study has clearly demonstrated the weakness of the IWRM approach for sustainable water resource management over decadal to century time scales, due to the fact that it cannot account for the bi-directional feedbacks between hydrological and human systems that have been responsible for much of the complex, emergent dynamics witnessed in the Murrumbidgee.

Instead of the costly pendulum swing experienced in the Murrumbidgee, more incremental shifts may be possible with a properly developed coupled socio-hydrologic model that includes the bi-directional feedbacks between human and water systems. Such models can track the co-evolution of the physical (hydrological), human (social systems, infrastructure, agricultural), and environmental (biogeochemical, ecological) subsystems in response to external drivers (i.e. climate variables, market conditions, food prices), and the demand for water and food (i.e. governed by human population). Better yet, they can pave the way for self-organised solutions (Ostrom, 2009) that provide the resource productivity that humans aspire to that nevertheless are not detrimental to the health of ecosystems.

Figure 6 provides the essence of a new conceptual framework of a socio-hydrology model applicable to the Murrumbidgee river basin that naturally arose from historical (including quantitative) analysis of what happened. The development of such coupled models of socio-hydrological systems requires the formulation of inter-connected subsystems that co-evolve, albeit at different rates. Quantitative analyses of the drivers of

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the socio-hydrological system and trajectories of their co-evolution can provide the insights and parameterizations necessary to build such coupled models, especially relating to key feedbacks that influence possible trajectories of system co-evolution. Some aspects of natural systems, such as the surface hydrologic system, respond promptly to external changes to reach new equilibrium levels. This can be deemed as fast dynamics (Fig. 6). On the other hand, the evolution of human systems such as infrastructure development is more deliberate and occurs over a longer period of time. For example, irrigation infrastructure (e.g. water storages, irrigation systems etc.) within the Murrumbidgee developed over a period of 70 yr, governed by macro-economic conditions and political imperatives. The growth and dynamics of human populations in agricultural production follow the growth and dynamics of irrigated infrastructure, but with a multi-year delay. On the other hand, decisions humans make about the land area to be put to irrigation and the types of crops grown occur in the medium term, in response to medium-term variability in external drivers such as climate and commodity prices. Insights into these dynamics can be gained through careful analysis of available data, such as those presented in Figs. 3 to 4a–h. These insights have helped to develop a conceptual model of the Murrumbidgee socio-hydrologic system, as a distilled version of the complex picture presented in Fig. 2. This is presented in Fig. 6, and can form the basis of simple, lumped numerical models of the coupled human-nature system, which is work in progress (van Emmerik et al., 2013).

However, the trajectory of co-evolution of coupled socio-hydrologic systems presented here is not unique to Murrumbidgee. Similar cases of peak anthropogenic water or "water reallocation to nature" have been reported throughout the developed world, such as in the Rio Grande, Edwards Aquifer. Similar dynamics are also being reported in Western China in the Tarim Basin in Xinjiang Province (Liu et al., 2013). In the wider environmental literature the U-shaped relationship between GDP and environmental degradation shown in Fig. 4 has been referred to as the "Environmental Kuznets Curve" (EKC), suggesting the existence of a common organizing principle that could underpin a new generation of coupled models (Stern, 2004; Suri and Chapman, 1998). The EKC

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describes the gradual shift towards the recognition and treatment of sustained environmental degradation represents the increasingly egalitarian concerns of a society that is progressively more affluent and thus concerned with broader issues than simply those that are economic. The applicability of EKC, or other different organizing principle that underpins the pendulum swings, in the case of the Murrumbidgee basin is worthy of further investigation, but is beyond the scope of this paper.

The socio-hydrologic prediction frameworks such as the one presented above can also help interpret similarity and differences in behaviour between different places, and to interpret them in terms of climatic, socio-economic and socio-cultural factors. The development of coupled models of socio-hydrological systems everywhere requires a more generalised framework that is widely applicable. Cognisant of this, Fig. 7 is presented as the outcome of a further distillation from Fig. 6, through generalizing the drivers and the resulting interactions and feedbacks in a manner that has wider applicability across climatic and socio-economic gradients (Ostrom, 2009).

5 Conclusions

The complex dynamics witnessed in the Murrumbidgee river basin paper illustrates the challenge of predicting long-term hydrologic trajectories in coupled human-water systems. In particular, it showed that simplistic relationships such as between GDP and water use or extrapolation of past hydrologic trends to the future do not adequately capture the evolution of water systems. The Murrumbidgee case study suggests that hydrologic response in respect of relative allocation to humans and the environment is influenced by the underlying socio-economic and institutional structures, which are themselves shaped by societal values.

This paper has explored the history of water management in the Murrumbidgee river basin in eastern Australia, with a focus on efforts to mediate the competition for water between irrigated agriculture and the health of the riparian environment. The history of water management within the Murrumbidgee river basin over the past 100 yr was

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divided into four eras. In Era 1 (1910–1960) the focus was exclusively on development of agriculture with no awareness of, or attention paid to, environmental issues. Era 2 (1960–1990) was the period which saw the onset of environmental problems in the form of salinity. While the human response to salinity was immediate in terms of remedial infrastructure, it did not address the fundamental causes and therefore the problems persisted. Era 3 saw further widespread environmental degradation, with several mitigation measures implemented in the form of policy changes, infrastructure development, and the use of economic measures. These initiatives failed to reverse environmental degradation. Finally, Era 4 saw implementation of a mix of solutions, some drastic, imposed by Government to reverse environmental degradation: these seem to have set in motion an environmental remediation and emergence of the "environmental customer".

The history of conventional water management has given rise to complex emergent dynamics, involving a pendulum swing that expresses a dramatic change in emphasis from agricultural development and food production in the first 50 yr, which contributed to degradation of the environment, to sustained efforts to mitigate and reverse environmental degradation and restore ecosystem health. The pendulum swing is a result of several environmental and socio-economic factors: evidence of worsening environmental degradation, evolution of societal norms and values relating to the environment, and favorable economic conditions that emboldened the Government to act decisively. Nevertheless, the pendulum swing has been costly to the environment, the local communities and to the Government, and only arose because hydrologic prediction frameworks that supported conventional integrated water management did not include bi-directional feedbacks between the human and hydrological systems. The availability and use of such coupled models may have prevented widespread environmental degradation.

Although this case study described the particulars of the Murrumbidgee case study in great detail, the circumstances are not unique; rather, it typifies a trajectory that has been observed in several other cases. Several authors have reported the reallocation of water from anthropogenic to ecological uses. Indeed improved environmentaloutcomes

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as societies become wealthier, has been described in terms of a phenomenon called the "Environmental Kuznets Curve". This suggests that even though individual water systems in different places are extremely complex and unique, there is some hope that general organizing principles may still be found: this is left for further research.

Trajectories of co-evolution of coupled human-environment systems are governed by the nature of the interactions and feedbacks between the decisions of humans to utilize water resources to derive socio-economic benefits and by the adaptive capacity of the environmental systems. Clearly, to avoid costly pendulum swings, or to obtain more realistic predictions of the future, this paper has argued for the development of coupled socio-hydrological models with explicit inclusion of bi-directional feedbacks and the possibility of accommodating evolving norms and values relating to water and the environment. These models could help plot a path of how coupled human-water systems evolve under various scenarios, and in this way provide guidance for sustainable development, and the means to avoid costly pendulum swings. They can also provide the foundation for comparative studies across gradients of climatic, socio-economic and socio-cultural conditions.

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References

ABS: 100 years of change in Australian industry, 1301.0 – Year Book Australia, 2005, Australian Bureau of Statistics, http://www.abs.gov.au/AUSSTATS/abs@.nsf/lookup/1301.0feature+article212005 (last access: May 2013), 2005.

ABS: Australian Bureau of Statistics, http://www.abs.gov.au/, last access: May 2013a.

ABS: Australian Yearbook, Australian Bureau of Statistics, http://www.abs.gov.au/AUSSTATS/abs@.nsf/second+level+view?ReadForm&prodno=1301.0&viewtitle=Year%20Book%20Australia_2012~Latest~24/05/2012&&tabname=Past%20Future%20Issues&prodno=1301.0&issue=2012&num=&view=&, last access: May 2013b.

Arthington, A. H. and Pusey, B. J.: Flow restoration and protection in Australian rivers, River Res. Appl., 19, 377–395, 2003.

COAG: Council of Australian Governments water reform framework, Council of Australian Governments Australian Government Publishing Service, Canberra, Australia, 1994.

DSEWPC: Department of Sustainability, Environment, Water, Population and Communities Annual Reports, http://www.environment.gov.au/about/publications/annual-report/index.html, last access: May 2013.

DWR: Water distribution operations in irrigation areas and districts of NSW, New South Wales Department of Water Resources, Gutteridge, Haskins & Davey, Sydney, 1989.

Gilligan, D.: Fish communities of the Murrumbidgee catchment: Status and trends, NSW Department of Primary Industries – Fisheries Final Report Series No. 75, Cronulla Fisheries Centre, Sydney, Australia, 2005.

Gleick, P. H. and Palaniappan, M.: Peak water limits to freshwater withdrawal and use, P. Natl. Acad. Sci., 107, 11155–11162, 2010.

GWG: Murray-Darling Basin Status of Groundwater 1992, Groundwater Working Group Technical Report No. 2, Murray-Darling Basin Commission, Canberra, 1996.

Kingsford, R. T. and Porter, J. L.: Waterbirds on an adjacent freshwater lake and salt lake in arid Australia, Biol. Conserv., 69, 219–228, 1994.

Kingsford, R. T. and Thomas, R. F.: Destruction of Wetlands and Waterbird Populations by Dams and Irrigation on the Murrumbidgee River, in Arid Australia, Environ. Manage., 34, 383–396, 2004.

Lewis, G.: The Growers' Paddy – Land, Water and Co-operation in the Australian Rice Industry to the 1990s, available from: http://sydney.edu.au/business/__data/assets/pdffile/0008/155969/Lewis-GrowersPaddy-2012.pdf (last access: March 2013), 2012.

Liu, Y., Tian, F., Ni, G., Liu, D., and Sivapalan, M.: Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River Basin, Western China, Hydrol. Earth Syst. Sci. Discuss., submitted, 2013.

MDBA: Guide to the proposed Basin Plan: overview, Murray-Darling Basin Authority, Canberra, MDBA publication no. 60/10, MDBA, Canberra, Australia, 2010.

MDBC: A Brief History of the Murray-Darling Basin Agreement, Murray-Darling Basin Commission, Canberra, Australia, http://www2.mdbc.gov.au/about/historymdbc.html, (last access: December 2012), 2011.

MDBMC: The Algal Management Strategy for the Murray-Darling Basin: a component of the natural resources management strategy, Murray-Darling Basin Ministerial Council, Canberra, 1994.

MDBMC: A review of the operation of the cap: Overview report of the Murray Darling Basin Commission Ministerial Council, Murray-Darling Basin Ministerial Council, Canberra, 2000.

Murrumbidgee CMA: Murrumbidgee catchment action plan, Wagga Wagga, NSW: Murrumbidgee Catchment Management Authority, Wagga Wagga, Australia, 2006.

Murrumbidgee CMA: Our Catchment, Murrumbidgee Catchment: Rich and Diverse, http://www.murrumbidgee.cma.nsw.gov.au/about/catchment.aspx?print=1, last access: December 2012.

NWI: The impacts of water trading in the southern Murray-Darling Basin: an economic, social and environmental assessment, National Water Commission, Canberra, Australia, 2010.

NWI: Water trading in the rice industry, National Water Commission, Canberra, Australia, 2011.

Ostrom, E.: A General Framework for Analyzing Sustainability of Social-Ecological Systems, Science, 325, 419–422, 2009.

Productivity Commission: Trends in Australian Agriculture, Research Paper, Canberra, Australia, 2005.

Roderick, M. L.: Introduction to special section on Water Resources in the Murray-Darling Basin: Past, present, and future, Water Resour. Res., 47, W00G01, doi:10.1029/2011WR010991, 2011.

Schofield, B., Burt, A., and Connell, D.: Environmental water allocation: Principles, policies and practices, Canberra, Australia, Land and Water Australia, 2003.

Sivapalan, M.: Predictions under Change (PUC): Water, Earth and Biota in the Anthropocene, Research Report, Center for Water as a Complex Ecosystem, http://www.tandfonline.com/doi/pdf/10.1080/02626667.2011.580747, University of Illinois at Urbana-Champaign, 2011.
Sivapalan, M., Savenije, H. G., and Blöschl, G.: Socio-hydrology: A new science of people and water, Hydrol. Process., 26, 1270–1276, 2012.
Stern, D. I.: The rise and fall of the Environmental Kuznets Curve, World Development, 32, 1419–1439, doi:10.1016/j.worlddev.2004.03.004, 2004.
Suri, V. and Chapman, D.: Economic growth, trade and energy: implications for the environmental Kuznets curve, Ecol. Econom., 25, 195–208, 1998.
Thompson, S. E., Sivapalan, M., Harman, C. J., Srinivasan, V., Hipsey, M., Reed, P., Montanari, A., and Blöschl, G.: Understanding and predicting changing water systems: Use-inspired hydrologic science for the Anthropocence, Hydrol. Earth Syst. Sci. Discuss., submitted, 2013.
Turral, T., Connell, D., and McKay, J.: The Drama of Restraining Water Use, Chap. 12 in: River Basin Trajectories: Societies, Environments and Development, edited by: Molle, F. and Wester, P., CAB International, Wallingford, UK, 2009.
van Emmerik, T., Sivapalan, M., Savenije, H. H. G., Kandasamy, J., and Chanan A.: A simple coupled socio-hydrologic modeling of the pendulum swing between agricultural development and environmental health: Murrumbidgee river basin, Australia, Hydrol. Earth Sys. Sci. Discuss., in preparation, 2013.
Wilkinson, J.: Water for Rural Production in NSW: Grand Designs and Changing Realities, Briefing Paper No. 26/97, NSW Parliamentary Library Research Service, Sydney, Australia, 1997.

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Table 1. Annual trends in waterbird abundance in three wetland systems, including the Lowbidgee (1983 to 2001) (Kingsford and Thomas, 2004).

Wetland	Lowbidgee	Fivebough	Paroo overflow
Mean number of water bird species between:			
1983–1986	34	13	20
1998–2001	27 (−21 %)	12 (−8 %)	23 (15 %)
Mean population of water bird species between:			
1983–1986	139 939	6844	14 224
1998–2001	14 170 (−90 %)	911 (−87 %)	18 616 (31 %)

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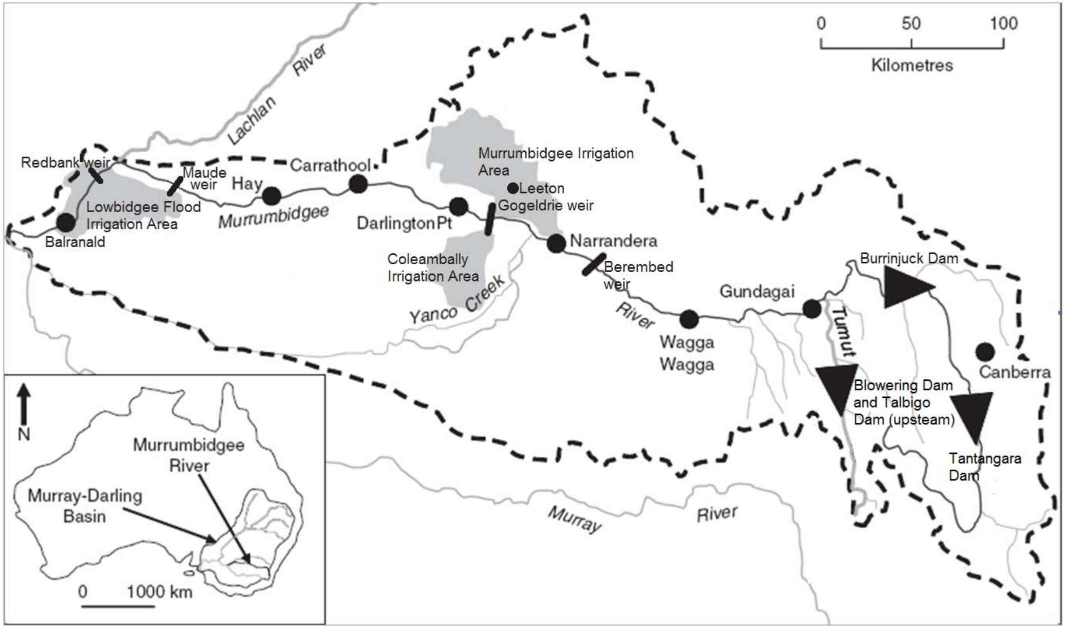

Fig. 1. Murrumbidgee Catchment within the Murray Darling Basin (adapted from: Frazier and Page, 2006). The Murrumbidgee Irrigation Area incorporates the the Yanco Irrigation Area, Mirrool Irrigation Area, Wah Wah Irrigation District, Benerembah Irrigation District, and Tabbita Irrigation District.

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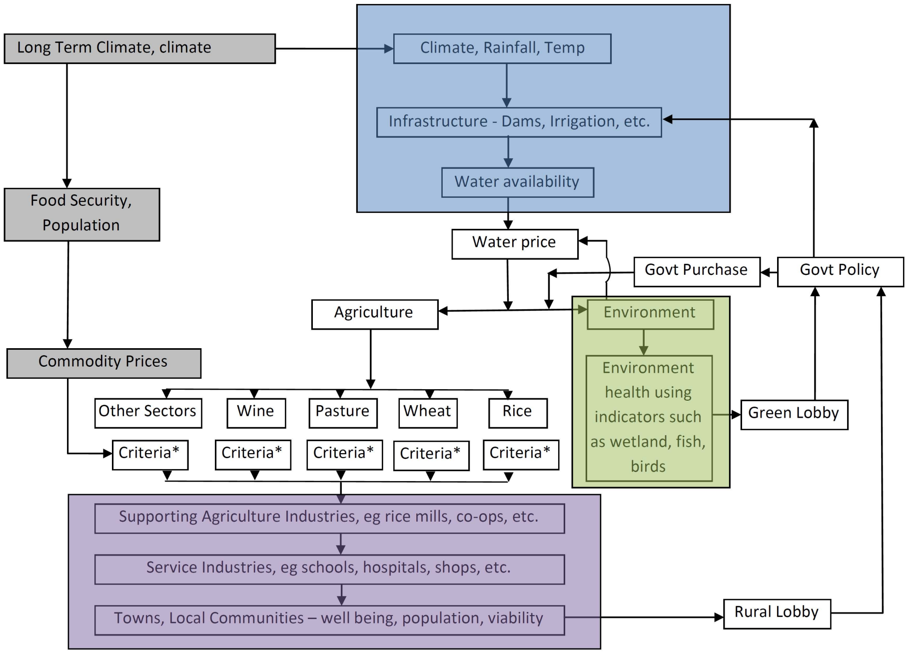

Notes

- Lumped model – location (space) not determined
- Time variable, catchment scale (i.e. location related to catchment)
- Criteria* – this refers to the criteria used by farmers to decide whether to grow crops that season (or sell their water license) and if so how much
- Grey shade refers to external driver
- Model available, NSW Dept of Water IQQM model
- Model available, NSW State Water – Economic input-output model
- Data available on Environmental Watering plan – no model available
- Variables – infrastructure, irrigated area

Fig. 2. Conceptual model for catchment scale competition for water utilisation between agriculture and environment using the socio-hydrology approach.

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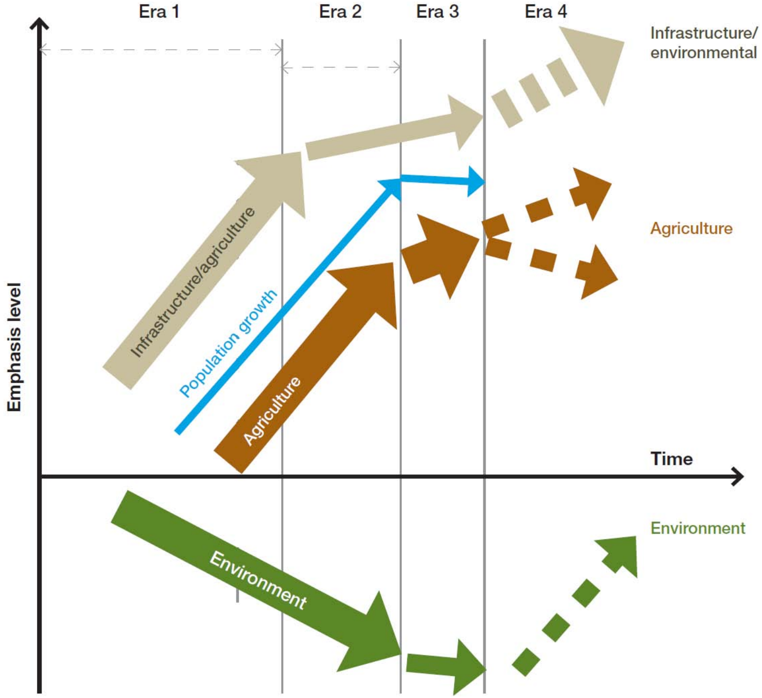

Fig. 3. The change in infrastructure, the environment, population and agriculture production in the Murrumbidgee through four eras: Era 1 1900–1960: the development irrigation and associated infrastructure, Era 2 1960–1990: a gradual appreciation of realisation of environmental degradation, Era 3 1990–2007: awareness of broader environmental impacts and a focus on consensus strategies and policies to achieve integrated and sustainable management, Era 4 2007–present: accepting the failure of the consensus model, with the emergence of a directed Commonwealth Government strategy to achieve environmental sustainable outcomes.

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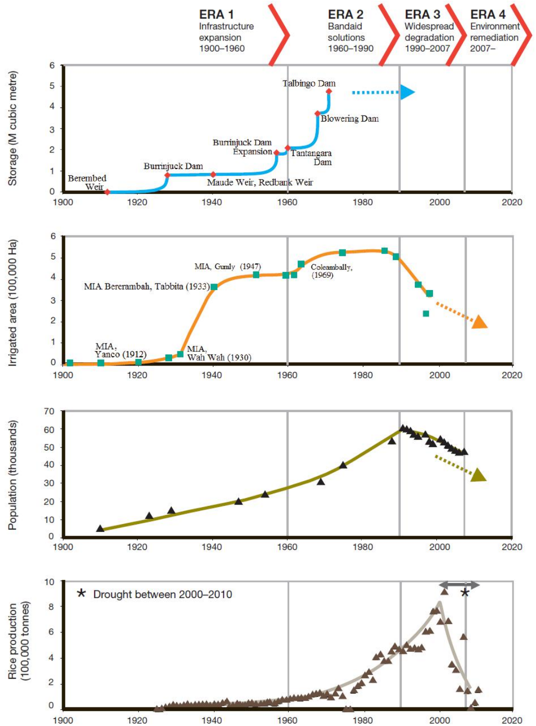

Fig. 4. **(a)** Development of storage in the Murrumbidgee Catchment (data sourced from NSW State Water Corporation). **(b)** Development of irrigation areas in the Murrumbidgee Catchment. See Fig. 1 for locations of irrigation area. Mirool, Yanco are in the Murrumbidgee Irrigation Area. Benerembah, Tabita, Wah Wah and Gumly are districts adjoin Murrumbidgee Irrigation Area but not shown in Fig. 1, Lowbidgee irrigation area not included (data sourced from ABS, 2013b). **(c)** Population growth in the Murrumbidgee. Between 1900 and 1980 the population was estimated from data available in ABS year book. From 1980 onward the estimate is for the population of Murrumbidgee less the population of Canberra and Wagga Wagga, (data sourced from ABS 2013a,b). **(d)** Rice production in the Murrumbidgee, (data sourced from ABS, 2013b).

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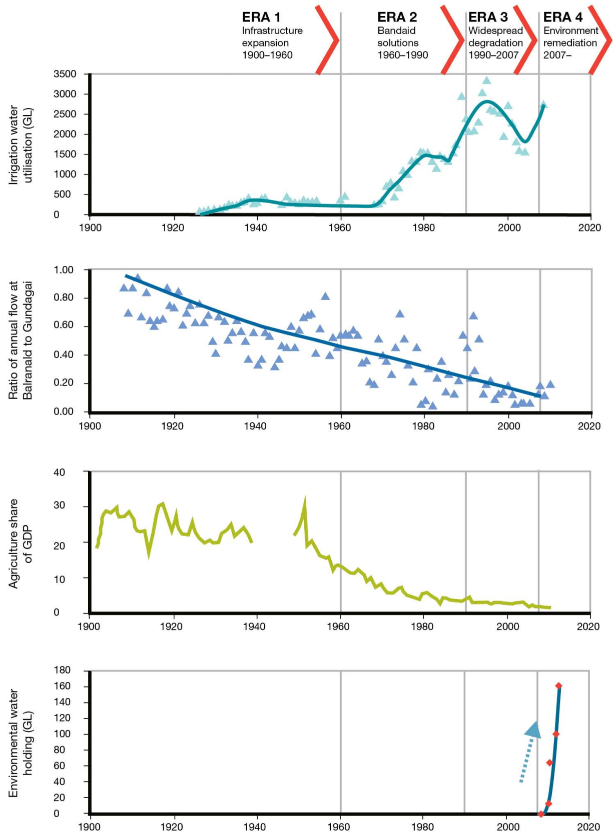

Fig. 4. **(e)** Irrigation flow utilisation in the Murrumbidgee Catchment (data sourced from DWR, 1989; ABS, 2013a; and State Water Corporation). **(f)** Ratio of annual flow in the Murrumbidgee at Balranald to the annual flow at Wagga Wagga, see Fig. 1 for locations of Balranald and Wagga (data sourced from NSW State Water Corporation). **(g)** The contribution of agriculture to the Australian economy expressed as a percent of GDP (ABS, 2005). **(h)** Environmental water holdings (water licenses) purchased by the Commonwealth Government and available to water sites of significant environmental value (wetlands, etc.) in the Murrumbidgee catchment,(data sourced from DSEWPC, 2013).

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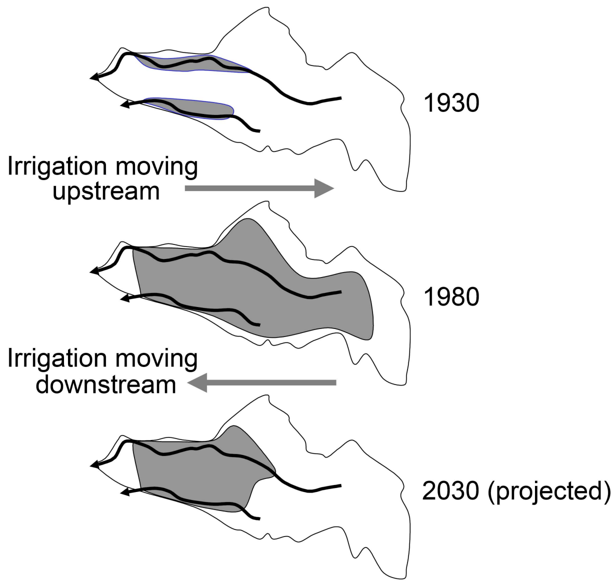

Fig. 5. Schematic of the evolution of the spatial patterns of irrigation (shaded area) in the Murrumbidgee. In the early 20th century irrigation moved upstream. Recently, the government has started buying water rights from farmers to protect the environment. Panel 3 is a projection based on cutting back irrigation upstream.

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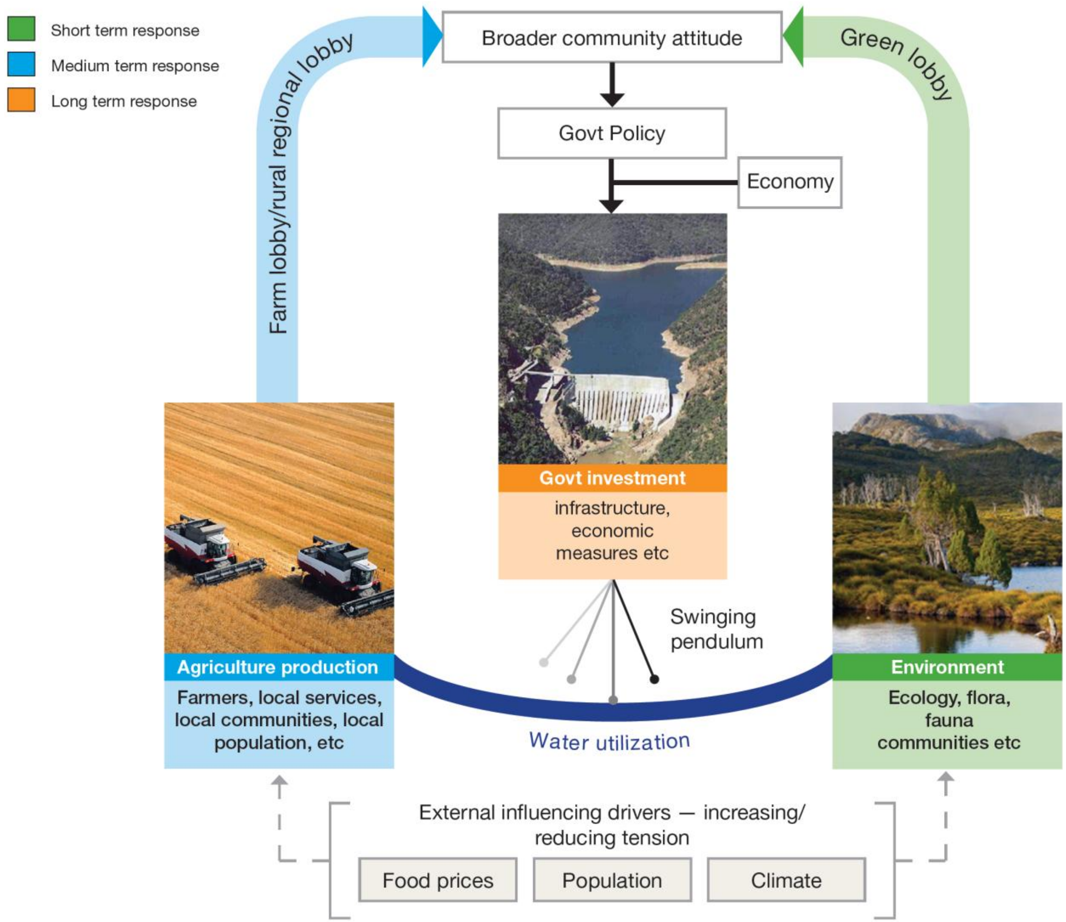

Fig. 6. Framework for socio-hydrologic modelling: interactions and feedbacks between human and environmental systems leading to new (whole system) dynamics.

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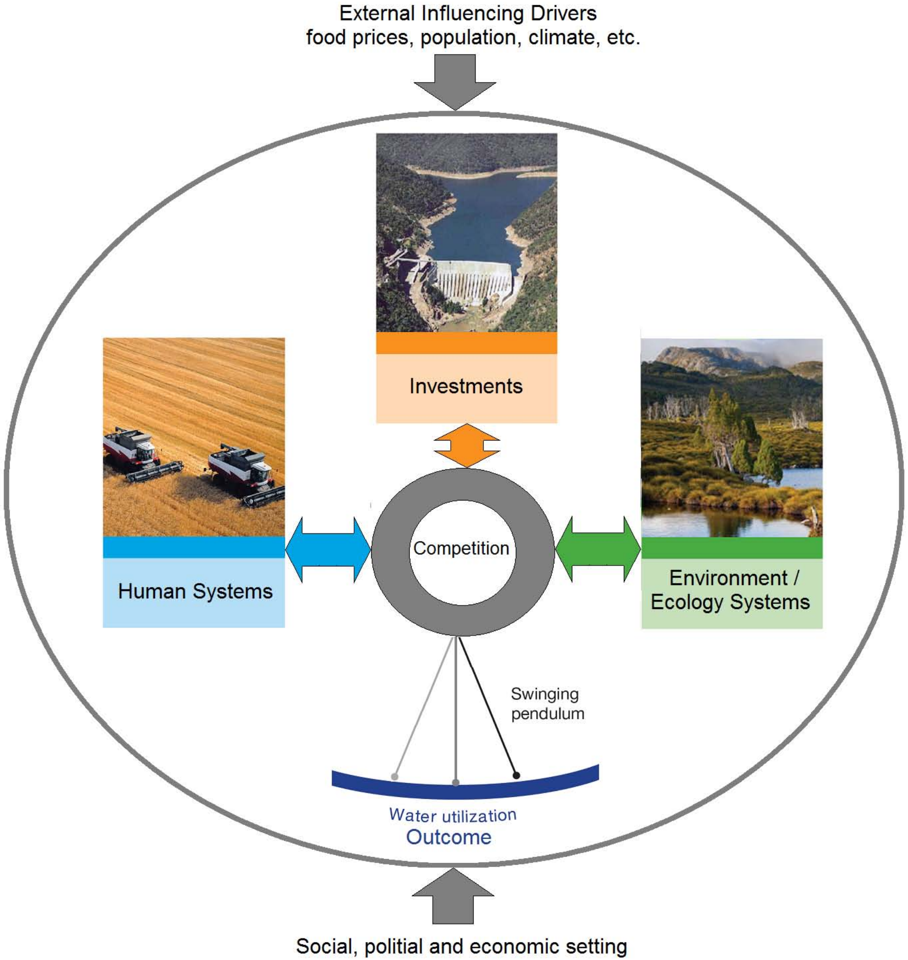

Fig. 7. Generalised framework for socio-hydrologic modelling: interactions and feedbacks between human and environmental systems leading to new outcomes.

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