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Socio-hydrological water balance for water allocation between human and environmental purposes in catchments

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Abstract. Rebalancing water allocation between human consumptive uses and the environment in water catchments is a global challenge. This paper proposes a socio-hydrological water balance framework by partitioning catchment total evapotranspiration (ET) into ET for society and ET for natural ecological systems, and establishing the linkage between the changes of water balance and its social drivers and resulting environmental consequences in the Murray–Darling Basin (MDB), Australia, over the period 1900–2010. The results show that the 100-year period of water management in the MDB could be divided into four periods corresponding to major changes in basin management within the socio-hydrological water balance framework: period 1 (1900–1956) – expansion of water and land use for the societal system, period 2 (1956–1978) – maximization of water and land use for the societal system, period 3 (1978–2002) – maximization of water use for the societal system from water diversion, and period 4 (2002–present) – rebalancing of water and land use between the societal and ecological systems. Most of management changes in the MDB were passive and responsive. A precautionary approach to water allocation between the societal and ecological systems should be developed. The socio-hydrological water balance framework could serve as a theoretical foundation for water allocation to evaluate the dynamic balance between the societal and ecological systems in catchments.

1 Introduction

Human overuse of water resources has caused serious ecological degradation of water catchments worldwide. Water allocation between society and natural ecological systems is an increasing challenge for water managers, particularly for those subject to changing climate and socio-economic development (Falkenmark, 2003; Grantham et al., 2014). Future human well-being may be seriously compromised if we pass a critical threshold that tips catchment ecological systems from stable conditions.

In recent centuries catchment water management has sought optimization of catchment water balance to secure water supplies for human consumptive demands and to meet the increasing needs of human socio-economic development. This catchment water management paradigm has been supported by hydrological science which has improved the understanding of the partitioning of precipitation into evapotranspiration and surface runoff, based on the framework of water balance (Beven, 2011; Yang et al., 2008; Zhang et al., 2004). This water balance, derived from the principle of conservation of mass, is the most fundamental aspect of global and regional hydrological cycles (Oki and Musiake, 1995). It has been a useful tool for water planners and managers to maximize human water uses under the constraints of water extraction capacity. However, it gives little attention to the water demand for catchment ecosystems and to water sharing between the societal and ecological systems of water catchments. The water balance approach worked well when humankind's water development capacity was very limited,

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and human water consumption volumes took up small percentages of the total available water of catchments. However, when human water uses increase dramatically, and exceed a certain level at which catchment ecosystems are increasingly degraded, the conventional water balance approach is unable to support emerging water management issues such as allocating water between the society and the environment (Alcamo et al., 2007; Kiguchi et al., 2014; Turner et al., 2007; Zhou et al., 2014a).

There have been several attempts at exploring human–water systems with the co-evolutionary approach (Geels, 2005; Kallis, 2011; Pataki et al., 2011). All these studies used "thick description" rather than explanatory approaches and therefore are unable to provide quantitative bases for water allocation between the society and environment. Socio-hydrology is emerging as a new discipline aimed at understanding the co-evolutionary dynamics of human–water systems to underpin sustainable water management (Sivapalan et al., 2012). From its very beginning it was argued that socio-hydrology must be a quantitative science. Since 2012 increasing numbers of studies in socio-hydrology have been reported in several case study areas, such as the Tarim River basin and Heihe River basin in western China and the Murrumbidgee River basin in eastern Australia (Di Baldassarre et al., 2013; Srinivasan, 2015; Elshafei et al., 2014; van Emmerik et al., 2014; Kandasamy et al., 2014; Liu et al., 2014; Lu et al., 2015). Kandasamy et al. (2014) traced the history of the Murrumbidgee catchment, an agricultural water catchment in the Murray–Darling River basin, Australia, and found a swing phenomenon of water sharing between agricultural water use and riverine environments. Elshafei et al. (2014) in the same catchment developed a prototype framework for socio-hydrological modelling to identify key feedback loops between the human–water relationship by specifying six key functional components including catchment hydrology, population, economics, environment, socio-economic sensitivity and collective response. This framework combined the strengths of previous attempts with rich descriptions of the human–water co-evolution and formal hydrological modelling. However, the modelled results did not correlate well with observed irrigation areas. In addition, although it was already a necessary simplification of an extremely complex coupled system, this framework is still too complex for water catchment managers to use. Lu et al. (2015) quantitatively analyzed the evolution of human–water relationships in the Heihe River basin of northern China over the past 2000 years by reconstructing the historical catchment water balance by partitioning precipitation into evapotranspiration and runoff. Their study analyzed the impacts of societies on hydrological systems but did not explicitly link the water balance to its drivers. While these studies have made great contributions to observing, understanding and predicting human–water cycle dynamics in catchments, there is still no clear analytical or empirical framework for water allocation between human use and the environment.

We argue that determination of water allocation between human societies and catchment environmental uses is the first basic task of socio-hydrology as it is the critical linkage between economic development and ecological sustainability of catchments. The aim of this paper is to propose a simple socio-hydrological water balance framework on terrestrial ecosystems for allocating water between the society and catchment ecological systems. Water management in the Murray–Darling Basin over more than the past 100 years is taken as a case study. It is expected that this study will provide an empirical case for understanding historical human–water relationships and supporting sustainable catchment management under changing climate and socio-economy conditions in the future.

2 A simple conceptual framework for socio-hydrological water balance

We will define a simple socio-hydrological water balance framework in a standardized way to describe changes in socio-hydrological water balance, establish linkages between the drivers that cause changes, and to describe the resulting consequences of these changes on catchment societal–ecological systems. The framework is expected to explain feedback between stresses and strains of catchment societal–ecological systems.

We will follow the principle "as simple as possible but no simpler" (in Einstein's words) to minimize the numbers of variables and parameters to develop a framework, and apply a timescale of more than 100 years to it. We focus on an agricultural water catchment where water is limiting agricultural production, and where ongoing agricultural development of land and water resources has led to increased human use of water, significant modification of catchment vegetation conditions, and a strong human imprint on the water cycle.

2.1 Describing the socio-hydrological water balance

The conventional water balance, derived from the principle of conservation of mass, provides an effective framework for studying hydrological cycles and evaluating the hydrological response of a catchment to climate and land use changes (Oki and Musiake, 1995; Zhang et al., 2001, 2004). It is described by the following equation

$$P = \mathrm{ET} + R + G + \mathrm{d}S/\mathrm{d}t, \tag{1}$$

where P, ET, R, G and $\mathrm{d}S/\mathrm{d}t$ are precipitation, evapotranspiration, surface runoff, recharge to groundwater and the change in soil water storage, respectively. They are the basic elements of a catchment water balance.

Equation (1) has been commonly applied in the partitioning of precipitation into evapotranspiration and surface runoff in catchment water resource planning and management for balancing water supply and water demand by a society. Based on this equation, we propose a socio-hydrological water balance to seek a balance of water allocation between societal and ecological systems within a water catchment. Precipitation is mainly lost as evapotranspiration in most water catchments directly arising from precipitation and transformed from runoff. Thus, water use in societal and ecological systems at water catchments can be expressed as the partitioning of evapotranspiration in societal and ecological systems. The socio-hydrological water balance is expressed as follows:

$$P = \mathrm{ET_s} + \mathrm{ET_e} + R_{\mathrm{out}} + \mathrm{d}G/\mathrm{d}t + \mathrm{d}S/\mathrm{d}t, \quad (2)$$

$$\mathrm{ET_e} = \mathrm{ET_{eP}} + \mathrm{ET_{eR}} + \mathrm{ET_{eG}}, \quad (3)$$

$$\mathrm{ET_s} = \mathrm{ET_{aP}} + \mathrm{ET_{aI}} + \mathrm{ET_H} + \mathrm{ET_{oth}}, \quad (4)$$

$$D_\mathrm{R} + D_\mathrm{G} = \mathrm{ET_{aI}} + \mathrm{ET_H} + \mathrm{ET_{oth}}, \quad (5)$$

where P is precipitation, $\mathrm{ET_s}$ and $\mathrm{ET_e}$ are the evapotranspiration from the societal and ecological systems, respectively, R_{out} is the outflow into sea, $\mathrm{d}G/\mathrm{d}t$ is the change in groundwater storage, and $\mathrm{d}S/\mathrm{d}t$ is the change in soil and surface (reservoir) water storage. Partitioning of ET into societal and ecological systems is mainly defined by land use. The native vegetation areas which maintain ecological function are considered as the ecological system. Ecological system evapotranspiration ($\mathrm{ET_e}$) includes evapotranspiration from precipitation, surface runoff and groundwater in native vegetation areas, expressed as $\mathrm{ET_{eP}}$, $\mathrm{ET_{eR}}$ and $\mathrm{ET_{eG}}$, respectively. Societal system evapotranspiration ($\mathrm{ET_s}$) comprises evapotranspiration in croplands and grasslands arising from precipitation ($\mathrm{ET_{aP}}$) and irrigation ($\mathrm{ET_{aI}}$), and water directly consumed by society, namely water use for households ($\mathrm{ET_H}$) and other industries ($\mathrm{ET_{oth}}$). Water diversions from surface runoff (D_R) and groundwater (D_G) supply irrigation water to croplands and grasslands as well as water for use by households and industries. The remaining surface runoff is used for ecological purposes, i.e. the environmental flows in the ecological systems ($\mathrm{ET_{eR}}$) and outflows to the sea (R_{out}).

2.2 Estimating the impact of changes in the socio-hydrological water balance on the societal–ecological systems

The societal and ecological systems of water catchments interact through changes in water allocations between the environment and human systems. Many indicators can be used to assess the impacts of changes in socio-hydrological water balance on the catchment societal–ecological systems. For example, the baseflow index at a specific cross section of the river can be chosen to characterize the catchment riverine ecological system, and agricultural output values per unit of water and water availability per person can reflect the catchment societal system. As our study focus is a semi-arid agricultural water catchment, and water consumption from households and industries is very small in comparison with the total available water, we focus on the impacts of water allocation on native vegetation systems, croplands and grasslands. We therefore use the changes of gross primary productivity (GPP), the total energy assimilated from each of the three vegetation systems, to measure the impacts of water allocation on them.

2.3 Interpreting the evolutionary processes of human–water relationships with changes in the socio-hydrological water balance, its drivers and resulting consequences

We interpret the evolutionary processes of the human–water relationships from the perspective of the socio-hydrological water balance, its drivers and resulting consequences. The socio-hydrological water balance equations described above partition precipitation into water use by society and ecological systems expressed as evapotranspiration, which are direct users of precipitation and water diversion from runoff. Catchment socio-hydrological partitioning is therefore strongly affected by climate and human activities. In conventional hydrology there are a number of studies that have assessed the impacts of climate change on catchment water balance. Socio-hydrology is more interested in social drivers. The hydrological cycle is responding to human activities, i.e. land use change such as deforestation, afforestation and urbanization that are the consequence of policies and investments made in the past. Population is one of the most dramatic and dynamic economic variables and is very commonly chosen as a social driver to represent society development. Technological developments also influence the relationship between humans and catchment ecosystems. A range of technologies involving streamflow prediction, water storage, water distribution, river regulation, ET measurement and farm irrigation practices could be considered for assessment of the impacts of technology on catchment socio-hydrololical water balance but water storage capacity and water diversion are key factors influencing catchment water balance and were chosen as technology indicators.

We firstly describe the feedbacks between humans and water on a yearly basis, then classify the evolutionary processes of the human–water relationships into distinct phases according to the relative size of the human water use and ecological water use. During each phase we analyze the co-evolution of population, water storage and diversion, human water use and their impacts on societal and ecological systems. Briefly, we aim to answer the question of how climatic and social drivers have interacted in catchments to produce historical socio-hydrological partitioning and its resulting consequences on the catchment environment.

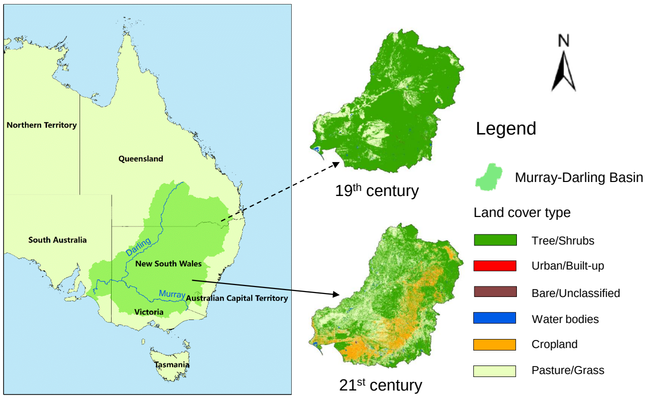

Figure 1. Location map and land cover changes of the Murray–Darling Basin.

3 Application of the socio-hydrological water balance framework in the Murray–Darling Basin

3.1 Study area

The Murray–Darling Basin (MDB), located in south-east Australia, is the largest river system in Australia. It is about 1 million km^2, covering three-quarters of New South Wales, more than half of Victoria, all of the Australian Capital Territory, and significant portions of Queensland and South Australia (Fig. 1). As one of the largest and driest catchments in the world, the climatic conditions and natural landscapes of the MDB are very diverse, from the rainforests of the cool eastern uplands, temperate mallee country (dryland dominated by multiple-stemmed eucalyptus species) of the south-east, inland sub-tropical areas of the north, to the hot, dry semi-arid and arid lands of the western plains (MDBA, 2010). The MDB has been a significant place for Indigenous Australians for over 50 000 years and for European settlers for over 200 years. It directly supports around 10 % of the Australian population (more than 2 million people) who live in the basin, and more than 1.3 million people who live outside the basin also depend on its water resources. The basin has around 65 % of Australia's irrigated land and accounts for about 39 % (AUD 15 billion per year) of Australia's gross value of agricultural commodities (MDBA, 2010).

Two centuries of European settlement, starting with grand dreams of taming the rivers, greening the desert and making land productive, has transformed Australian water catchments. Approximately 50 % of native forests and 65 % of native woodlands have been cleared or extensively modified in the MDB (Fig. 1). The surface water flows of the Murray–Darling rivers have decreased markedly and water volumes discharged into the Murray's estuary decreased from 29 000 GL yr^{-1} in the 1890s to 4700 GL yr^{-1} at present. The dramatic development of land and water resources has led to unprecedented growth of agricultural production, but with increased human use of water resources, and there has been significant modification of landscapes and a strong human imprint on water cycle dynamics. The MDB has been changed into a highly human impacted and managed river system, and the MDB's water resources and associated ecosystems are in a state of crisis, characterized by highly degraded natural systems, compromised ecological functions, and intense conflict and competition between users of scarce supplies (Wei et al., 2011).

3.2 Data sources and processing

We use a 100-year time frame (1900–2010) that represents a period over which dramatic changes in climate, population, water and land use, ecological conditions, economic reform, management regulation and technological innovation have occurred in the MDB. The annual water balance components (in mm yr^{-1}) of the MDB from 1900 to 2010, including precipitation, evapotranspiration, surface runoff, deep drainage and changes in soil water storage were obtained from the water balance results produced by the Australian Water Availability Project (AWAP). AWAP developed a simple and robust water balance model to simulate the terrestrial water balance of the Australian continent by model–data fusion methods that combined measurements and model predictions (Raupach et al., 2009). The AWAP results include a long-term historical monthly time series (data set "Run 26j", 1900 to 2010) of the conventional water balance components at a spatial resolution of 0.05°. This data set has been widely used in research and for management of water catchments in Australia.

The annual GPP in g C m^{-2} yr^{-1} of the MDB from 2000 to 2010 were summed from the monthly GPP data provided by the Numerical Terradynamic Simulation Group, University of Montana. This group processed the GPP product "MOD17A2" (2000–2010) from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 8-day intervals with 1 km spatial resolution into a monthly time series of GPP at a resolution of 0.05°. These data were considered as the observed GPP in this study.

The land use data are very important for the analyses in this study. As ET and GPP data for each of the three vegetation types over the last century were not available, we used the land use data sets, i.e. the History Database of the Global Environment (HYDE 3.1 version) to estimate ET and GPP for each vegetation type. HYDE 3.1 provides long-term estimates of global human population and built-up areas (croplands and grasslands used for livestock) at a spatial resolution of 5′ since the Holocene (10 000 BC to AD 2000) (Klein Goldewijk et al., 2011). The database of population, cropland and grassland areas is available every 10 years from 1900 to 2000, and for 2005. The annual changes in land use were normally small, and therefore the annual data sets at a resolution of 0.05° of the population and the area ratios of cropland, grassland and native vegetation areas in the MDB from 1900 to 2010 were obtained from HYDE version 3.1 with resampling and linear interpolation in ArcGIS. This is reasonable for the purposes of this study. We did not consider crop factors changes because this research is based on modelled data rather than field investigations.

In addition, data for water diversion (1923–2010), outflows into the sea (1900–2010) and water storage (1900–2002) were provided by the MDB Authority. Social and economic data, including water accounts (2008–2010) and water use on farms (2002–2010) were available from the Australian Bureau of Statistics.

3.3 Describing the socio-hydrological water balance in the MDB

The socio-hydrological water balance was estimated according to Eqs. (2) to (5), i.e. partitioning ET into societal and ecological systems, including ET from the precipitation and that from runoff. The annual ET from precipitation for the cropland, grassland and native vegetation areas were partitioned into three parts by multiplying the average ET by the area ratios of the three land use types for each grid, and then aggregating the separated ET of all the grids in the MDB, using the annual water balance data sets from the AWAP and the annual data sets produced for each of the three area ratios from HYDE 3.1. This method was performed with the assumption that the three vegetation types shared the ET in each grid according to the ratios of their areas.

The annual ET from runoff referred to water diversion in the societal system and environmental flows in the ecological system. The water diversion data were divided into four parts, including ET from irrigation in croplands and grasslands and water use for households and industries. Water use by households and other industries were assumed to be proportional to population, and the ratios were set to be 0.078 and 0.153, respectively, according to the water account data (ABS, 2014a). The remaining water diversion was ascribed to irrigation, with a ratio of 4 : 1 between croplands and grasslands, according to water use data of Australian farms (ABS, 2014b). The environmental flows were calculated by subtracting surface water diversion and outflows into the sea from surface runoff.

In the MDB, groundwater diversion and evapotranspiration from groundwater for native vegetation are generally small compared to other elements and were not considered. Therefore, groundwater recharge and changes in soil water storage were the same as those in the conventional water balance.

3.4 Estimating the impact of water allocation on the societal system and ecological system in the MDB

The impacted sectors of water allocation on the societal and ecological systems in the MDB include native vegetation, croplands, grasslands, households and industries. As the water consumption from the last two items was less than 1 % of the total in the MDB, we focused on the impacts of water allocation on native vegetation, croplands and grasslands. We used GPP to measure the impacts of water allocation on them. Water use efficiency (WUE), defined as the ratio of carbon gain to water loss in terrestrial ecosystems, has been used to estimate annual GPP because of the linear relationship between GPP and ET at a regional scale (Beer et al., 2007). However, a linear relationship between GPP and ET was not the best expression, as evaluated in many studies (Zhou et al., 2014b). In order to improve the estimation of GPP, we assumed that WUE is negatively correlated with ET per unit area because of diminishing marginal WUE when GPP was limited by other controlling factors, such as solar radiation and nutrients (Eq. 6). The relationship between GPP and ET could be expressed by a quadratic function which passes through the origin (0, 0). The relationship between annual GPP and ET is given in Eq. (7).

$$\mathrm{WUE}_t = a \cdot \mathrm{ET}_t + b, \tag{6}$$

$$\mathrm{GPP}_t = \mathrm{WUE}_t \cdot \mathrm{ET}_t = a \cdot \mathrm{ET}_t^2 + b\mathrm{ET}_t, \tag{7}$$

where ET_t is the total ET per unit area in $\mathrm{mm\,yr^{-1}}$, GPP_t is the total GPP in $\mathrm{g\ C\,m^{-2}\,yr^{-1}}$ and WUE_t is the water use efficiency in $\mathrm{g\,C\,m^{-2}}$ per mm water. The parameters a and b were determined with the observed GPP from 2000 to 2010 when data were available, and the result, with a correlation coefficient of 0.99, was

$$\mathrm{GPP}_t = -9.95 \times 10^{-4} \cdot \mathrm{ET}_t^2 + 1.87\mathrm{ET}_t. \tag{8}$$

The relationship between GPP and ET in Eq. (8) was used first to estimate total GPP in the MDB from 1900 to 2010. It was then used to determine the relationship between GPP and ET for each vegetation type for the period 1900–2010 with an optimization method. The optimization minimized the root mean square deviation between the total GPP estimated in Eq. (8) and the sum of GPP of the three vegetation types. The objective function is expressed as follows:

$$F = \min \sqrt{\frac{\sum_{n=1900}^{2010} \left(\mathrm{GPP}_{tn} - \sum_{i=1}^{3} \mathrm{GPP}_{in} \right)^2}{111}}, \tag{9}$$

where

$$\mathrm{WUE}_{in} = a_i \cdot \frac{\mathrm{ET}_{in}}{AR_{in}} + b_i, \tag{10}$$

$$GPP_{in} = \mathrm{WUE}_{in} \cdot \mathrm{ET}_{in} = a_i \cdot \frac{ET_{in}^2}{AR_{in}} + b_i \mathrm{ET}_{in}, \tag{11}$$

where i refers to crop ($i = 1$), grass ($i = 2$) and native vegetation ($i = 3$), and n are the years from 1900 to 2010. Since the unit for ET is $\mathrm{mm\,yr^{-1}}$ in this study, AR_{in}, i.e. the area ratio is used, and $\frac{\mathrm{ET}_{in}}{\mathrm{AR}_{in}}$ are the ET per unit area of the vegetation i in year n. The area ratio is omitted from Eq. (6) because it equals 1 for the whole basin. The parameters a_i and b_i were calibrated according to Eq. (9) using the data from 1900 to 2010. The total GPP and the GPP of each vegetation type were therefore compared with observed data to verify the effectiveness of the parameters in Eq. (11). The observed GPP of the three vegetation types were partitioned using the same method as the partitioning of ET from precipitation.

4 Results

4.1 The socio-hydrological water balance in the MDB

The changes in the components of the conventional and socio-hydrological water balances in the MDB from 1900 to 2010 are shown in Fig. 2a and b. The results for the conventional water balance showed that on average about 95 % of precipitation was consumed as evapotranspiration. The evapotranspiration almost equalled, or even exceeded, precipitation during drought periods, such as during the federation drought (1885–1902), the World War II drought (1937–1945) and the millennium drought (1997–2009), resulting in decreases in surface runoff and soil water storage (Fig. 2a). The conventional water balance reveals the pattern of partitioning precipitation into evapotranspiration and runoff over the years. The socio-hydrological water balance shows a different perspective (Fig. 2b). It can be clearly seen that evapotranspiration from societal use increased and surpassed that from the ecological system after the 1950s. After that time human water use played a more and more dominant role. The socio-hydrological water balance indicates the co-evolutionary dynamics of water allocation between the societal and ecological systems in the MDB for this 100-year period.

More specifically, ET from croplands, grasslands and native vegetation areas were closely associated with their land areas, and cropland ET showed less variation than ET of grasslands and native vegetation areas (Fig. 3a and c). This happened because more than 95 % of the ET came from precipitation directly. The ET ratio of native vegetation areas was as high as 0.86, and the ratios for croplands and grasslands were only 0.02 and 0.12 in 1900, respectively. The expansion of agriculture markedly reduced the dominance of native vegetation in the MDB, and the ratio of native vegetation areas to the total decreased to about 0.4 by 1975, and continued at this ratio until 2005. The ET from croplands increased during the last century, accompanied by the expansion of croplands, especially of the irrigated croplands, which were intensely managed by human activities. However, the area of grasslands increased at first, then decreased a little owing to their conversion into croplands after the mid-1970s. ET from the societal and ecological systems were almost equal in the mid-1950s, and then maintained a ratio of 3 : 2 during the late 20th century. The ratio of ecological ET to societal ET increased a little in the early 21st century, due to the implementation of mitigation measures such as the government-directed sustainable diversion limits which returned water to the environment.

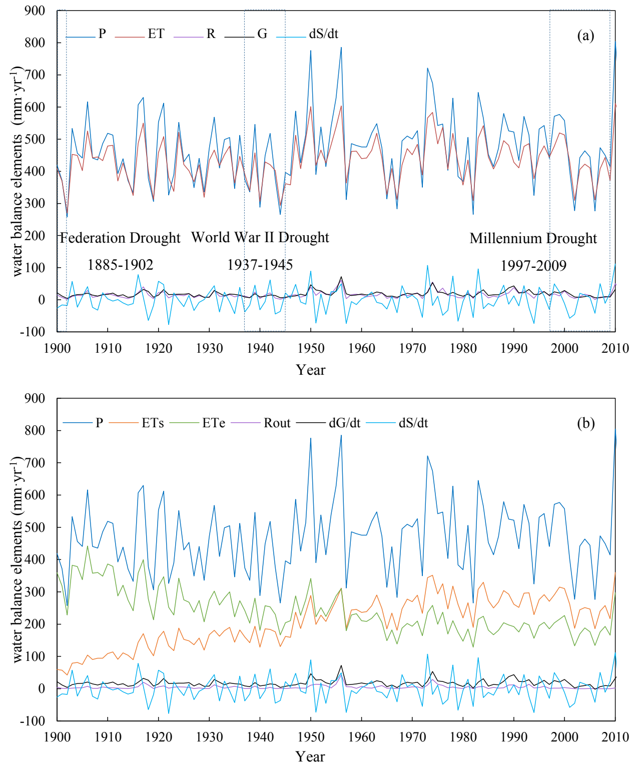

Figure 2. Water balance element changes in the MDB from 1900 to 2010 in the conventional water balance **(a)** and in the socio-hydrological water balance **(b)**.

4.2 The impact of water allocation on societal and ecological systems

The results and accuracy of GPP in the MDB obtained by the optimization method are shown in Table 1. For the whole MDB, the coefficient of determination (R^2) was 0.97, and the root mean square error (RMSE) was only 2 % of the average total GPP. In addition, the R^2 of the relationship between the estimated and observed GPP for each vegetation type ranged from 0.94 to 0.96, and the RMSE was about 6, 11 and 7 % of the average GPP for croplands, grasslands and native vegetation areas, respectively. Therefore, the optimization method for GPP estimation was effective, and the estimated GPP for each vegetation type and total GPP can be used as estimates of the impacts of water allocation on the societal and ecological systems in the MDB. It should be noted that the RMSE for grasslands was relatively large due to slight overestimation of GPP.

As a result of changes in water allocation, the trends of GPP ratios of the three vegetation types were similar to those of the ET ratios because of the strong relationship between

Table 1. The results and accuracy of GPP in the MDB obtained with the optimization method.

Vegetation type	GPP–ET function	R^2	RMSE ($\mathrm{g\,C\,m^{-2}\,yr^{-1}}$)
Crop	$\mathrm{GPP}_1 = -9.10 \times 10^{-4} \cdot \frac{\mathrm{ET}_1^2}{\mathrm{AR}_1} + 1.84\mathrm{ET}_1$	0.96	8.16
Grass	$\mathrm{GPP}_2 = -10.53 \times 10^{-4} \cdot \frac{\mathrm{ET}_2^2}{\mathrm{AR}_2} + 1.90\mathrm{ET}_2$	0.95	23.88
Native vegetation	$\mathrm{GPP}_3 = -9.71 \times 10^{-4} \cdot \frac{\mathrm{ET}_3^2}{\mathrm{AR}_3} + 1.86\mathrm{ET}_3$	0.94	19.55
Total	$\mathrm{GPP}_{\mathrm{total}} = \mathrm{GPP}_1 + \mathrm{GPP}_2 + \mathrm{GPP}_3$	0.97	13.99

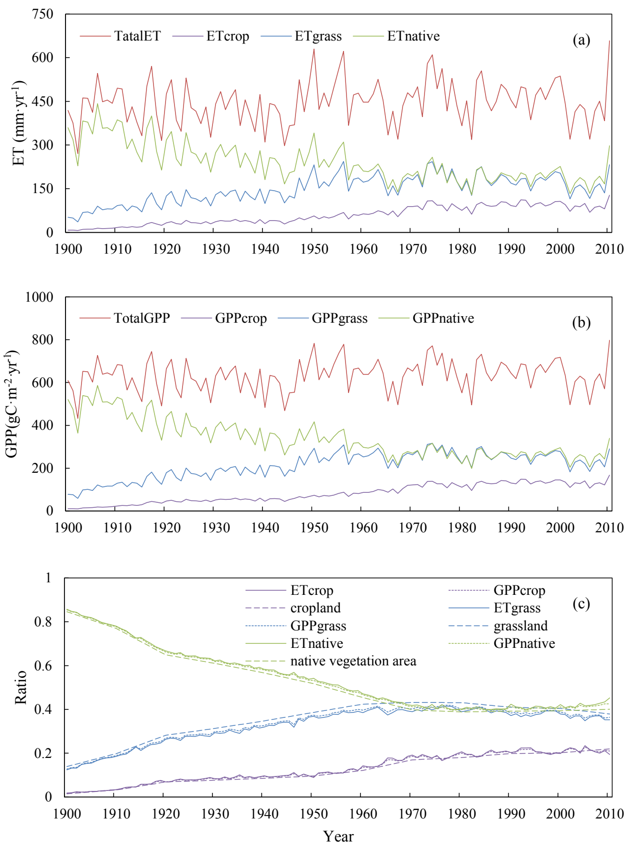

Figure 3. Time series of **(a)** ET, **(b)** GPP and **(c)** ratios of ET, GPP and land area for croplands, grasslands and native vegetation areas in the MDB from 1900 to 2010.

GPP and ET (Fig. 3b and c). The GPP of croplands and grasslands, which flow into society for socio-economic development, continued to grow over the last century, resulting in significant decreases in GPP of native vegetation areas, which maintain ecological function in water catchments. The GPP of croplands and grasslands increased from 10.5 and 78.0 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in 1900 to 133 and 298 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in 1978, respectively. The GPP ratios of the societal system increased from less than 0.2 to about 0.6 over the period 1900–1978, and those of the ecological system showed almost the opposite result (Fig. 3b). In the following 2 decades, the GPP ratios of the societal and ecological systems were maintained at about 0.6 and 0.4, respectively (Fig. 3c). It was not until the early 21st century that the GPP ratios of the ecological system recovered gradually, and reached 0.45 in 2010, because more water was used for the ecological system. This clearly indicates that changes in water allocation between societal and ecological systems would ultimately bring about changes in catchment GPP. Water allocations and the resulting GPP between the societal and ecological systems reveal the impacts of water and land management within a basin.

It should be noted that both ET and GPP more or less follow their respective land area ratios (Fig. 3c). This happens because the MDB lies in a semi-arid region where about 95 % of precipitation was consumed as evapotranspiration. The irrigated area only accounted for 2 % of the total land area and the crop patterns were relatively uniform.

4.3 Revisiting water catchment management in the MDB during 1900–2010 with the results from the socio-hydrological water balance

The relationship between human activities and the environment in the MDB changed over time, as is reflected in changes in water allocation, land use, and the resulting GPP. In view of the socio-hydrological water balance, the co-evolutionary history of the societal–ecological systems in the MDB can be divided into four stages (Fig. 4).

4.3.1 Period 1 (1900–1956): expansion of water and land use for the societal system

Indigenous Australians lived sustainably for over 50 000 years in the MDB and during this long period, when population size was small, water use for society was very small. After European settlement, economic development and water consumption by society began to expand. The first water diversion from the Murray for irrigation commenced in the 1880s, opening the door for irrigated agriculture.

There was rapid expansion of the development of the MDB represented by the substantial growth of agriculture land, and the population increased gradually during this pe-

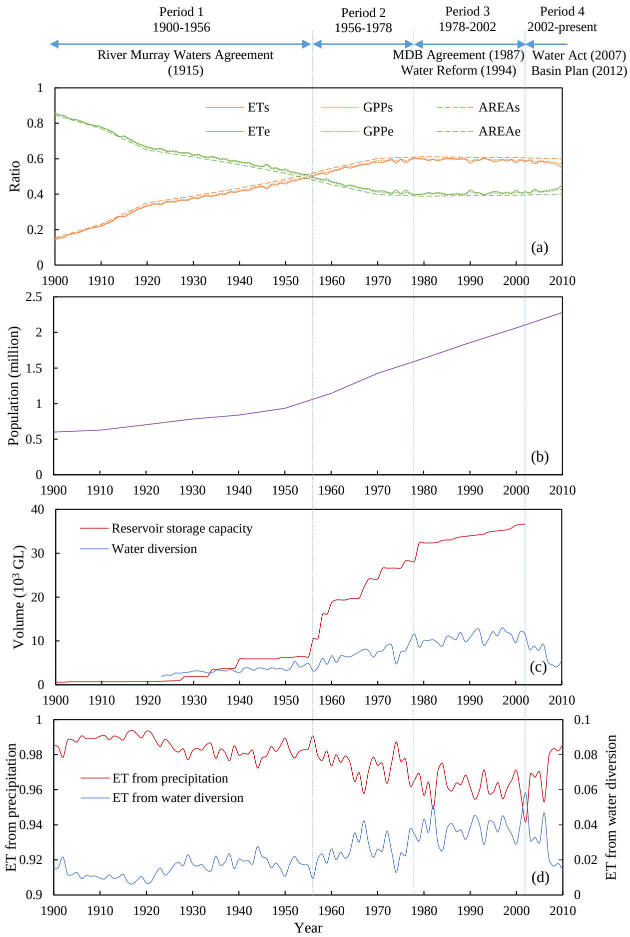

Figure 4. Time series of **(a)** the ratios of ET, GPP and land area for the societal and ecological systems; **(b)** population; **(c)** water diversion and reservoir storage capacity; and **(d)** the ratios of ET from precipitation and water diversion in the MDB from 1900 to 2010.

riod (Fig. 4b). The area ratio of the societal system increased considerably starting from 0.15 in 1900 to 0.52 in 1956, and the area of the ecological system declined to less than that of the societal system in the mid-1950s (Fig. 4a). The ET from the societal system exceeded that from the ecological system in 1956, and the GPP from the societal system also exceeded that from the ecological system in the same year (Fig. 4a). The growth of population and expansion of agricultural land were the major reasons for the expansion of water use by the societal system, accompanied by the construction of small dams and irrigated infrastructure (Fig. 4c). Therefore, 1956 should be considered as the critical year when land and water use for the societal system exceeded that for the ecological system for the first time.

4.3.2 Period 2 (1956–1978): maximization of water and land use for the societal system

Agricultural expansion continued during this period, especially irrigated agriculture, supported by water diversion (Fig. 4c). The vast investment in irrigation infrastructure supported the dramatic growth of agriculture and associated industries and the population of the MDB rapidly grew after 1956 (Fig. 4b). The storage capacity reached 28 233 GL in 1978 from a starting point of near zero with the construction of dams, weirs, barrages and irrigation delivery canals (Fig. 4c). Nearly 450 large dams and innumerable small farm dams were built, which gave rise to some of the highest levels of water storage per capita in the world – more than 3 times mean annual flow (Wei et al., 2011).

ET and GPP ratios of the societal system reached maxima in 1978 (Fig. 4a). The construction of a large-scale dam and irrigation infrastructure and expansion of agricultural land were the major reasons of water use expansion of the societal system during this period (Fig. 4c). However, it became increasingly evident during this period that environmental issues had arisen, e.g. blue-green algal blooms, rising salinity levels and degradation of wetlands, floodplains, lakes and red gum forests. By the end of this period, water became scarcer and more precious for the development of both societal and ecological systems and the competition between human consumption and environmental uses intensified.

4.3.3 Period 3 (1978–2002): maximization of water use for the societal system from water diversion

Surface water diversion increased and maintained nearly stable ratios of ET and GPP for society (Fig. 4a and c). The millennium drought (1997–2009) occurred in this period and is regarded as one of the worst droughts since European settlement (Murphy and Timbal, 2008). The millennium drought dried out the MDB's major river systems, and the water-dependent ecological assets such as the mid-Murrumbidgee Wetlands, and the Lowbidgee floodplain suffered significant degradation (Connor et al., 2013). The ET of the societal system from surface water diversion reached a maximum in 2002 in order to maintain the maximized societal system under severe drought, resulting in further exacerbation of ecosystem damage (Fig. 4d).

4.3.4 Period 4 (2002–present): rebalancing water and land use between the societal and ecological systems

This period saw a small decrease in the area of agricultural land, ET and GPP in the societal system for the first time since European settlement (Fig. 4a). The water diversion to society decreased. During wetter years, for example 2010, Australian governments took action to purchase water entitlements for the environment and implement irrigation efficiency programs to return water, about 2750 GL yr^{-1}, to the environment, and drive a transition to sustainable diversion limits after 2010. Within society, water trading and the introduction of upgraded irrigation infrastructure and technology, such as efficient low-throw sprinklers and drip/trickle irrigation methods, improved water productivity and facilitated the water reallocation between the societal and ecological systems (Wei et al., 2011).

5 Discussions and conclusions

This paper proposes a simple socio-hydrological water balance framework for allocating water between society and the environment to support sustainable water management of catchments. The framework shifts the understanding of catchment water balance from between human water demand and water supply to between human water use and ecological water use. It described changes in socio-hydrological water balance and established linkages between the drivers causing changes and the resulting consequences for catchment societal–ecological systems. The socio-hydrological water balance could serve as the theoretical foundation for maintaining dynamic balance between the societal and ecological systems within a catchment.

The management of water in the MDB over more than 100 years was divided into four periods using the socio-hydrological water balance framework. They include: period 1 (1900–1956), the expansion of water and land use for the societal system, period 2 (1956–1978), the maximization of water and land use for the societal system, period 3 (1978–2002), the maximization of water use for the societal system from water diversion, and period 4 (2002–present), the rebalancing of water and land use between the societal and ecological systems. This recognition of distinct periods of water management is very consistent with the results of Kandasamy et al. (2014) in the Murrumbidgee River basin, a subcatchment of MDB. The co-evolution of the human–water relationship in the MDB is the result of the interactions of climatic and social drivers in the basin. Three droughts, particularly the millennium drought, population increases and improvement of water storage are major driving forces. The growth of population played the overwhelming role in period 1 (1900–1956). Period 2 (1956–1978) was the result of a combination of population growth and water storage increases. In period 3 (1978–2002), the millennium drought acted as a trigger for the changes in the human–water relationship. Period 4 (2002–present) is a transitional period; population increase was no longer a driver for the increase of human water use. For the first time since 1900, water storage and water diversion were redirected to environmental purposes. The environmental consequences of both the millennium drought and social-economic development in the past were the major triggers for the management transition.

Two main lessons can be drawn from the analysis of co-evolutional processes of the human–water relationship in the MDB. Over the long history of water management reforms in the MDB, from the River Murray Waters Agreement in 1915 to the Murray–Darling Basin Agreement in 1987, attention was focused on water-sharing between the states of the basin to develop their economies; 1956 was the first critical period when water and land use for society for the first time exceeded that for the ecological system. Unfortunately, it was not given attention by catchment water and land managers at the time. When water and land use and GPP by society were maximized in 1978 and some serious environmental issues appeared, the governments of the basin started to take some actions on water resources management to address the emerging issues. In 1987 the Murray–Darling Basin Water Agreement was signed between the Commonwealth, New South Wales, Victoria and South Australia governments to promote and coordinate effective approaches to dealing with environmental problems, in particular salinity and water quality (MDBA, 2010). The millennium drought aggravated the tension between the societal and ecological systems, which caused water diversion for society to be maximized in 2002, resulting in serious degradation of ecosystems. The Water Act of 2007 recognized the importance of water allocation for environmental purposes. The Basin Plan, which aimed to balance societal and economic effects of reduced consumptive water to make water available for the environment, was proposed in 2010 and issued in 2012, and is the milestone of the rebalancing of the societal and ecological systems in the MDB. In the past, all these management changes in MDB were passive, responsive and contingent. A precautionary approach to water allocation between the societal and ecological systems should be developed based on the analytical understanding of the socio-hydrological water balance in water catchments.

The second main lesson is that land and water in catchments should be managed in an integrated way. Land use and hydrology are inextricably entwined in water catchments. A number of catchment deforestation studies indicate that catchment runoff is obviously increased after deforestation (e.g., Piao et al., 2007; Gallant and Gergis, 2011). Increasing cropping areas in the MDB since 1900 may have increased catchment runoff as a result of reducing native vegetative systems. The increased runoff, through water diversion, was then used for increasing irrigated cropping areas. Therefore, deforestation and water diversion have aggregated negative impacts on catchment ecosystems. While the research on the impact of these two interactive human activities on the catchment water cycle should be strengthened, without any doubts, more research should focus on their interactions.

Increasing concern for the ecological quality of the MDB has brought about a series of initiatives of purchasing water from irrigators for environmental purposes. For example, the target for surface water recovery for the environment under the Basin Plan is 2750 GL, of which 1500 GL was planned to be obtained through surface water buy-backs. These water volumes correspond with less than 1 % of the whole catchment ET and may improve the riverine ecological systems to some extent, but they have very little influence on the societal system. Therefore, only integrated land and water management could address ecological degradation at both riverine and catchment levels. The socio-hydrological water balance framework developed in this study provides new understandings of the water and land dynamics at catchments.

The lack of appropriate data is the major limitation of our study. First, the impacts of water allocation on the societal and ecological systems may be measured more precisely using other indicators if the data are available. For example, agricultural output per unit of water is more directly related to water use in the societal system. In addition to GPP of native vegetation systems, the size and quality of inland wetlands and riverine ecosystems and aquatic ecosystems should be considered to assess the impacts of water allocation on catchment ecosystems. We could not obtain data for observed ET and water productivity for the three vegetation types over a 100-year period in the MDB, and modelled water balance, MODIS GPP and interpolated land use data were used. In addition, there was an assumption that the three vegetation types share the ET and GPP according to their area, resulting in uncertainty for the partitioning of ET and GPP.

The proposed framework did not consider the change of societal values and norms as one of social drivers for changes in the socio-hydrological water balance. We argue that changes in societal values of water catchments, which define what we would like the water catchments to be, and changes in available technologies which determine the means to identify needs for changes and remediation practices, and their interactions, are key triggers for changes in the socio-hydrological water balance. Wescoat Jr. (2013) proposed incorporating societal values into socio-hydrological models. Van Emmerik et al. (2014) incorporated changing values and norms of a society by introducing environmental awareness as a co-evolutionary variable of system dynamics. Wei et al. (2015) empirically analyzed the evolution of newspaper reporting on water issues to reflect changing public opinions and social values in Australia since 1843. However, the metrics of societal values need to be further studied before they can be incorporated into the socio-hydrological modelling.

Water allocation between the society and catchment ecosystems is a real challenge for the coming decades in many parts of the world. Despite the uncertainties in long-term data sets and lack of knowledge about changes of societal values, the proposed socio-hydrological water balance could be used to understand the history of water allocation between the societal and ecological systems, i.e. how today's problems were created in the past, and which allocation may lead to more sustainable catchment management in the future. As there are fundamental differences in the hydrology, demography, social values, levels of economic development and capacity of water governance in areas such as the Yellow River basin in China, the Colorado River basin in the United States and the Ebro River basin in the Europe, which have similar management challenges as the MDB, application of the proposed water balance framework in these river basins can enable exploration of common research problems, as well as highlight regional differences and any unique responses. It will also enable the identification of important policies, institutional and/or cultural differences for this globally significant issue, and point to lessons that might not emerge from a single country study.

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