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Recasting catchment water balance for water allocation between human and environmental purposes

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Abstract

Rebalancing water allocation between human consumptive uses and the environment in water catchments is a global challenge. The conventional water balance approach which partitions precipitation into evapotranspiration (ET) and surface runoff supports the optimization of water allocations among different human water use sectors under the cap of water supply. However, this approach is unable to support the emerging water management priority issue of allocating water between societal and ecological systems. This paper recast the catchment water balance by partitioning catchment total ET into ET for the society and ET for the natural ecological systems, and estimated the impacts of water allocation on the two systems in terms of gross primary productivity (GPP), in the Murray–Darling Basin (MDB) of Australia over the period 1900–2010. With the recast water balance, the more than 100 year water management in the MDB was divided into four periods corresponding to major changes in basin management: period 1 (1900–1956) expansion of water and land use by the societal system, period 2 (1956–1985) maximization of water and land use by the societal system, period 3 (1985–2002) maximization of water diversion for the societal system, and period 4 (2002–present) rebalancing of water and land use between the societal and ecological systems. The recast water balance provided new understandings of the water and land dynamics between societal and ecological systems in the MDB, and it highlighted the experiences and lessons of catchment water management in the MDB over the last more than 100 years. The recast water balance could serve as the theoretical foundation for water allocation to keep a dynamic balance between the societal and ecological systems within a basin for sustainable catchment development. It provides a new approach to advance the discipline of socio-hydrology.

1 Introduction

Human activity has caused ecological degradation of water catchments worldwide. Water allocation between the human society and natural ecological systems is an increasing challenge for water managers, particularly under 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 the past centuries, catchment water management has sought the optimization of water balance for human consumptive demands and to secure water supplies to meet the increasing needs of human socio-economic development. This catchment water management paradigm has been supported by hydrological science which has been improving 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 optimize water allocations among different human water use sectors under a cap of maximum water extraction, but it is blind to water sharing between the societal and ecological systems of water catchments. It worked very well when humankind's water development capacity, and water consumption volumes, were far smaller than the cap of the human water use. However, when human water demand increases dramatically and goes beyond a certain level, this conventional water balance approach is unable to support emerging water management issues such as allocating water between the society and the environment in catchments to address increasingly degraded ecosystems (Alcamo et al., 2007; Kiguchi et al., 2014; Turner et al., 2007; Zhou et al., 2014).

Integrated river basin management (IRBM) has been widely promoted by both water academics and practitioners since the 1980s and has become a mainstream water management strategy (Downs et al., 1991; Mitchell, 1990; Pahl-Wostl and Hare, 2004;

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Zakaria, 2004). It is defined as “the process of coordinating conservation, management and development of water, land and related resources across sectors within a given river basin, in order to maximise the economic and social benefits derived from water resources in an equitable manner while preserving and, where necessary, restoring freshwater ecosystems” (GWP, 2000). Despite its popularity the definition of IRBM continues to be broad and vague, and the theoretical framework underpinning IRBM, e.g. how water and land should be integrated in catchments, is far from a practical guide for its application (Biswas, 2004; Hering and Ingold, 2012).

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). Since 2012 increasing numbers of studies in social-hydrology have been reported in several case study areas, such as the Tarim River Basin in western China and the Murrumbidgee River Basin in eastern Australia (Elshafei et al., 2014; van Emmerik et al., 2014; Kandasamy et al., 2014; Liu et al., 2014). While these studies have made great contributions to observing, understanding and predicting water cycle dynamics in catchments, there are no clearly defined theoretical guidelines for water allocation between human and the environment.

The aim of this paper is to recast catchment water balance for allocating water between the human society and catchment ecological systems to support sustainable catchment management using a socio-hydrological approach. We consider water management in the Murray–Darling Basin over the past over one hundred years as a case study. It is expected that this study will advance socio-hydrology and directly guide future water allocation for catchment management.

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2 Materials and methods

2.1 Study area

The Murray–Darling Basin (MDB), located in southeast 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 in the MDB are very diverse, from the rainforests of the cool eastern uplands, the 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 held meaning for Indigenous Australians for over 50 000 years and for European settlers for over two hundred 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 yr^{-1}) 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 (Fig. 1). The surface water flows of the Murray–Darling rivers have decreased markedly and water volumes discharged into 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 the unprecedented growth in agricultural production but with increased human use of water resources, 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

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a state of crisis, characterised by highly degraded natural systems, compromised ecological functions, and intense conflict and competition between users of scarce supplies (Wei et al., 2011).

2.2 Recasting catchment 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 equation

$$P = \mathrm{ET} + R + G + \mathrm{d}S/\mathrm{d}t \quad (1)$$

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 catchment water balance. Equation (1) has been commonly applied in the partitioning of precipitation into evapotranspiration and surface runoff in catchment water resources planning and management for balancing water supply and water demand by society. However, it has not been applied to partition precipitation into water use by societal and environmental purposes. Here, we recast the conventional catchment water balance to seek the balance of water allocation between societal and ecological systems within a water catchment. The new catchment water balance is expressed as follows:

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

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

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

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

where, P and $\mathrm{d}S/\mathrm{d}t$ are the same as those in Eq. (1), $\mathrm{ET_s}$ and $\mathrm{ET_e}$ are the evapotranspiration from the societal and ecological systems, respectively, R_{out} is the outflow

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into sea, and $\mathrm{d}G/\mathrm{d}t$ is the change in groundwater storage. Partitioning of ET into societal and ecological systems is mainly determined 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 coming 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) serve irrigation in croplands and grasslands and water use in society, the remaining surface runoff is used for ecological purposes or flows into the sea (R_out).

The annual ET from precipitation for the croplands, grasslands 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, respectively, using the annual datasets of water balance and land use at a spatial resolution of 0.05° in the remote sensing images. The water diversion was divided into four parts, including ET from irrigation in croplands and grasslands, for households and other industries. Water uses by the 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 used for irrigation, with a ratio of 4 : 1 between croplands and grasslands, according to the water use data on Australian farms (ABS, 2014b).

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 change in soil water storage were the same as those in the conventional water balance.

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2.3 Estimating the impact of water allocation on the societal system and ecological system in water catchments

The impacted sectors of water allocation on the societal and ecological systems in the MDB include native vegetation system, croplands, grasslands, the households, and other industries. As the water consumption from the last two items was less than 1 % of the total in the MDB, we focused on the impact of water allocation on native vegetation system, croplands and grasslands. We used the gross primary productivity (GPP), the total energy assimilated from these three systems, to measure the impacts of water allocation on them. Water use efficiency (WUE), 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). WUE was calculated as the ratio of GPP over ET, and was assumed to be constant in a certain region (Yang et al., 2013). We supposed that WUE is negatively correlated to ET per unit area because of diminishing marginal WUE (Eq. 6). The relationship between GPP and ET could be expressed with a quadratic function which passes 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 $\mathrm{ET_t}$ is the total ET in $\mathrm{mm\,yr^{-1}}$ (short for $\mathrm{mm\,H_2O\,m^{-2}\,yr^{-1}}$) for croplands, grasslands and native vegetation areas, $\mathrm{GPP_t}$ is the total GPP in $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, and $\mathrm{WUE_t}$ is the water use efficiency in $\mathrm{g\,C\,mm^{-1}\,H_2O}$ for all the vegetation types. 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 given as follows:

$$\mathrm{GPP_t} = -9.9455 \times 10^{-4} \cdot \mathrm{ET_t^2} + 1.8718\mathrm{ET_t}. \tag{8}$$

The relationship between GPP and ET in Eq. (8) was firstly used to estimate total GPP in the MDB from 1900 to 2010. It was then used to determine the relationship between

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GPP and ET for each vegetation type for the period 1900–2010 with the 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

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

$$\mathrm{GPP}_{in} = \mathrm{WUE}_{in} \cdot \mathrm{ET}_{in} = a_i \cdot \frac{\mathrm{ET}_{in}^2}{\mathrm{AR}_{in}} + b_i \mathrm{ET}_{in} \tag{11}$$

where i refers to crop ($i = 1$), grass ($i = 2$) and native vegetation ($i = 3$), respectively, and n is the year from 1900 to 2010. AR_{in} is the area ratio and $\frac{\mathrm{ET}_{in}}{\mathrm{AR}_{in}}$ is the ET per unit area of the vegetation i at the year n. 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 hence 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.

2.4 Data sources and processing

The annual water balance elements in $\mathrm{mm\,yr^{-1}}$ of the MDB from 1900 to 2010 including precipitation, evapotranspiration, surface runoff, deep drainage and change in soil water storage were obtained from the water balance dataset “Run 26j”, which was produced by the Australian Water Availability Project (AWAP). In the AWAP a simple and robust water balance model was developed to simulate the terrestrial water balance of the Australian continent with model-data fusion methods to combine measurements and model predictions (Briggs et al., 2009). The AWAP achievements include a long-term historical monthly time series of dataset "Run 26j" (1900 to 2010) of the conventional water balance elements at a spatial resolution of 0.05°.

The annual GPP in $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ 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 Gross Primary Production (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 annual datasets at a resolution of 0.05° of the population and the area ratios of croplands, grasslands and native vegetation areas in the MDB from 1900 to 2010 were obtained from the History Database of the Global Environment (HYDE 3.1 version) with resampling and linear interpolation in ArcGIS. 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, croplands and grasslands area is available every 10 years from 1900 to 2000, and 2005.

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

3 Results

3.1 The recast water balance in the MDB

The changes of elements in the conventional and recast water balances in the MDB from 1900 to 2010 are shown in Fig. 2a and b. It can be seen from the conventional water balance that on average about 95 % of precipitation was consumed as evapotranspiration. The evapotranspiration almost equalled or even exceeded precipitation in drought years, resulting decreases in surface runoff and soil water storage (Fig. 2a). The recast water balance shows a different perspective (Fig. 2b). It can be clearly seen that evapotranspiration from societal use kept on increasing and surpassed that from ecological system after the 1950s, showing a stark historical trend of the co-evolutionary dynamics between the societal and ecological systems during the history of the MDB for an over one hundred-year period. The conventional water balance reveals the pattern of partitioning precipitation into evapotranspiration and runoff over the years, and the recast water balance indicates the dynamics of water allocation between the societal and ecological systems.

More specifically, ET from croplands, grasslands and native vegetation areas were closely associated with their land areas. This happens because more than 95 % of the ET came from precipitation directly (Fig. 3a and b). The ET ratio of native vegetation areas was as high as 0.86, and the ratios for croplands, grasslands were only 0.02 and 0.12 in 1900, respectively. The expansion of agriculture totally changed the dominance of native vegetation in the MDB, and the ratio of native vegetation areas to the total decreased to about 0.4 after 1975, and continued to be this ratio until 2005. ET from croplands kept increasing during the last century, accompanied by the expansion of croplands, especially of the irrigated croplands. However, grasslands increased at first, then decreased a little owing to it being converted into croplands after the mid-1970s. ET from the societal and ecological systems achieved almost an equal ratio in the mid-1950s, and then maintained a ratio of 3 : 2 during the late 20th century. The ratio of ecological ET increased a little in the early 21st century, due to the implementation of

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mitigation measures such as the Sustainable Diversion Limits and return of water to the environment.

In addition to the dramatic expansion of agricultural land, the increase of ET from societal use also came from surface water diversion (Fig. 3c). The ratio of societal ET from water diversion increased from only 0.01 to as high as 0.05 over the past century. The continued growth of water storage capacity supported water diversion (Fig. 3d). The water diversion dramatically decreased during the "Millennium drought" (1997–2009).

3.2 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 and Fig. 4a. For the whole MDB, the coefficient of determination (R^2) was 0.97, and the root mean square error (RMSE) was only 2 % of 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 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 measures to estimate the impacts of water allocation on the societal and ecological systems in the MDB. It should be noted that the RMSE for grasslands is relatively large due to a little bit of overestimation of GPP, as shown in Fig. 4a.

As result of changes in water allocation, the trends of GPP ratios for the three vegetation types were similar to those of the ET ratios because of the strong relationship between GPP and ET. GPPs 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. Both ET and resulting GPP ratios of the ecological system declined from more than 0.8 to about 0.4 over the period 1900–1975, and those of the societal system went just the opposite (Figs. 3b and 4b). This clearly indicates that changes in water allocation between societal and ecological systems would utimately bring about the changes in catchment GPPs. Thus, water allocations and resulting GPP between the societal and ecological systems could reveal the impact of water and land management within a basin.

4 Discussions

4.1 Revisiting catchment water management in the MDB during 1900–2010 with the results from the recast water balance

The relationship between human and the environment in the MDB has been changing over time, which is reflected in changes in land use, water allocation, and resulting GPP between societal and ecological systems. In view of the recast catchment water balance, the co-evolutionary history of the socio-ecological systems in the MDB could be divided into four stages (Fig. 5).

4.1.1 Period 1 (1900–1956): expansion of 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. Since the settlement of Europeans economic development and water consumption for 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 in the MDB represented by the substantial growth of agriculture land (Fig. 3a). 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. 5). The ET from the societal system superseded that from the ecological system in 1956, and the GPP from the societal system also exceeded that from the ecological system at the same year (Fig. 5). The expansion of agriculture land was the major reason of expansion of the societal system, accompanied by the construction of a small size of dams and irrigated infrastructure (Fig. 5). Although we do not know the ideal ratios of ET and GPP of the societal system to ecological system in the MDB, 1956 should be the first critical period when land and water use for the societal system superseded that for the ecological system for the first time.

4.1.2 Period 2 (1956–1985): maximization of the societal system

Agricultural expansion went on during this period, especially irrigated agriculture, supported by water diversion (Fig. 3a). The vast investment in irrigation infrastructure supported the dramatic growth of the agricultural industries. The storage capacity reached 24 144 GL in 1970 from nearly zero with the construction of dams, weirs, barrages and irrigation delivery canals (Fig. 5). Nearly 450 large dams and innumerable small farm dams were built, which gives 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).

1985 was the year when ET and GPP of the societal system reached maxima. The construction of a large scale of dam and irrigated infrastructure and expansion of agriculture land were the major reason of expansion of the societal system during this period (Fig. 5).

The rapid expansion of agriculture strengthened the competition capacity of the societal system over ecological system, resulting in much more water consumption by society, and largely enhanced the GPP of society to provide for the increasing population in the basin (Fig. 5). However, it became increasingly evident that numbers of environmental issues appeared, e.g. blue-green algae blooms, rising salinity levels and degradation of wetland, floodplains, lakes and red gum forests. By the end of this period, water became scarcer and precious for the development of both societal and ecological systems and the stress between human consumption and the environment intensified.

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4.1.3 Period 3 (1985–2002): maximization of water diversion for the societal system

Water diversion increased as much as possible for maintaining a nearly stable GPP for society (Fig. 5). The millennium drought (1997–2009) occurred in this period and is regarded as one of the worst 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 exacerbated ecosystem damage (Fig. 5).

4.1.4 Period 4 (2002–present): rebalance of water and land use between the societal and ecological systems

This period saw a small decrease of agricultural land, ET and GPP in societal system for the first time since the European settlement (Fig. 5). The water diversion to society largely decreased. When wetter years for example 2010 explained part of these decreases, the Australian Government took action to purchase water entitlements for the environment and implement irrigation efficiency programs to return water, about 2750 $\mathrm{GL\,yr^{-1}}$, to the environment and drive a transition to the Sustainable Diversion Limits since 2010. Within the society, water trading and the introduction of upgraded irrigation infrastructure and technology, such as efficient low-throw sprinkler and drip/trickle irrigation methods improved water productivity and facilitated the water reallocation between the societal and ecological systems.

Over the long history of water management reforms in the MDB from the River Murray Waters Agreement in 1915 to Murray–Darling Basin Agreement in 1987, attention was focused on water-sharing between the basin states to develop their economies.

Although so far no research findings have indicated the sustainable ratios of ET and GPP of the societal to ecological systems in the MDB, 1956 should be the first critical period when water and land use for society for the first time superseded that for the ecological system. Unfortunately it was not given enough attention by catchment water and land managers. When water and land use and GPP in the society was maximized in 1985 and some serious environmental issues appeared, the Basin governments started to take some actions on water resources management to address these emerging issues. Two years later, 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 resulted in water diversion for society to be maximized in 2002, resulting in serious degradation of ecosystems. The Water Act in 2007 recognized the importance of environmental water. The Basin Plan, aimed to balance societal and economic effects of reduced consumptive water as required for the environment, was proposed in 2010 and issued in 2012, and is the milestone of the rebalance of the societal and ecological systems in the MDB. Therefore, the recast water balance approach is very useful to understand the co-evolution of the societal and ecological system in the MDB and highlight the experiences and lessons of catchment water management in history.

4.2 Implication of the recast water balance approach for integrated land and water management in catchments

The water balance and GPP changed considerably in the societal and ecological systems in the MDB during the period 1900–2010 as a result of land use and water use changes. GPP, closely related to water allocation, is absolutely the consequences of the land and water development of over the more than 100 years in the MDB. Therefore, GPP could be used as the outcome or objective of water and land management in water catchments. The persuit of growing GPP in society resulted in maxima of the

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societal system and water diversion for society and degraded ecosystems. The history of the MDB revealed the relationships of societal development and the consumption of water and land resources. With the knowledge of these relationships, water and land would be better managed, and the balance between the societal and ecological systems in the MDB could be kept in a better status.

We developed the relationships between the ETs and GPPs of societal and ecological systems, and societal system area ratio and surface water diversion in the MDB from 1900 to 2010 (Fig. 6). With the combined use of Fig. 6a–d, a ratio of sustainable land allocation and a ratio of sustainable water diversion between the societal system and ecological system in water catchments could be determined by the water catchment managers for integrated catchment management, and the effectiveness of re-allocation of water and land could also be estimated by comparing their GPPs for the societal and ecological systems. The sustainable ratios of water and land allocations can largely support the rebalance of the societal and ecological systems.

5 Conclusions

This paper was aimed to recast water balance for allocating water between human society and the environment to support sustainable water and land management in water catchments. It shifted the catchment water balance from between human water demand and water supply to between human water use and ecological water use. The recast water balance offers an innovative and practical approach to understand the dynamical interactions of water, land and GPP between societal and ecological systems in catchments. It builds direct linkage between water and land management in water catchments and their influence on both human societal system and natural ecological system. Thus, the recast water balance could serve as the theoretical foundation for keeping the dynamic balance between the societal and ecological systems within a basin. It provided a new approach to advance the new discipline of "socio-hydrology".

In the long term perspective, this analysis could lead to a tool for the integrated land and water management in catchments, and improve the precision of catchment management decisions on land and water for sustainable catchment management.

By recasting the catchment water balance and estimating GPP of the societal system and ecological system in the MDB, this paper provided new understandings of the water and land dynamics between societal system and ecological system in the MDB in the past over more than 100 years, and it highlighted the experiences and lessons of catchment water management in the MDB in history. This approach could be applied to other water catchments, 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 the similar challenges with the MDB. Through comparative analysis of the ratio of sustainable land allocation and the ratio of sustainable water diversion between societal system and ecological system at different water catchments, the recast water balance would add the knowledge base on sustainable catchment management from both a normative and an analytical perspective.

Finally, we have been aware that, if data are available, the impact of water allocation on societal system can also be measured using other indicators, such as agricultural output and gross value of agricultural commodities which are more directly related to the water production value in the societal system.

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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	$\mathrm{GPP_1} = -9.1027 \times 10^{-4} \cdot \frac{\mathrm{ET_1^2}}{\mathrm{AR_1}} + 1.8423\mathrm{ET_1}$	0.96	8.16
Grass	$\mathrm{GPP_2} = -10.5274 \times 10^{-4} \cdot \frac{\mathrm{ET_2^2}}{\mathrm{AR_2}} + 1.8951\mathrm{ET_2}$	0.95	23.88
Native vegetation	$\mathrm{GPP_3} = -9.7125 \times 10^{-4} \cdot \frac{\mathrm{ET_3^2}}{\mathrm{AR_3}} + 1.8620\mathrm{ET_3}$	0.94	19.55
Total	$\mathrm{GPP_{total}} = \mathrm{GPP_1} + \mathrm{GPP_2} + \mathrm{GPP_3}$	0.97	13.99

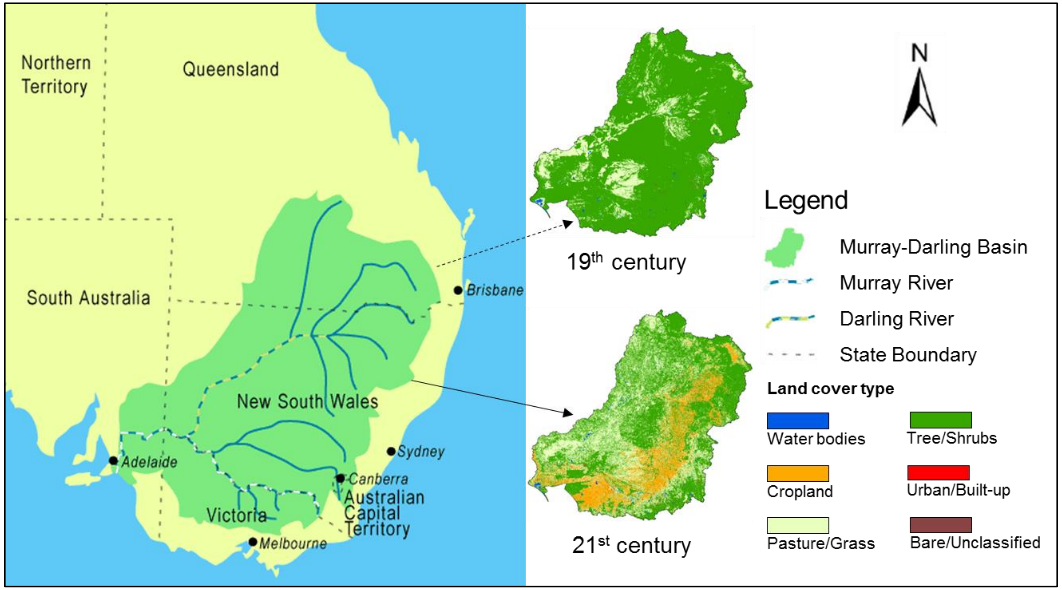

Figure 1. Location map and land cover changes of the Murray–Darling Basin.

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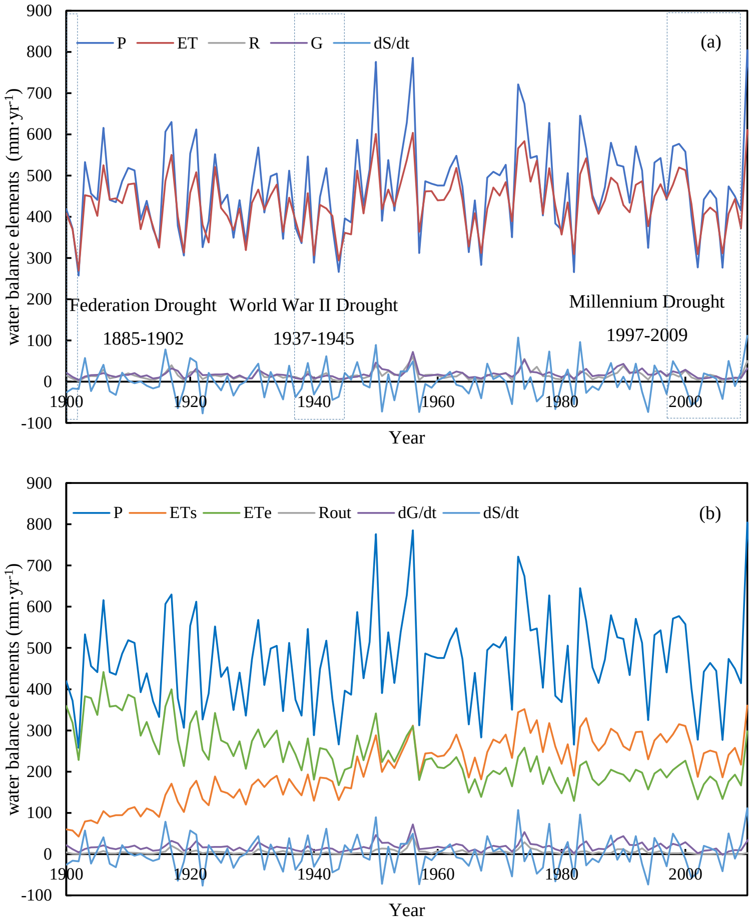

Figure 2. Water balance elements changes in the MDB from 1900 to 2010 in the conventional water balance **(a)** and in the recast water balance **(b)**.

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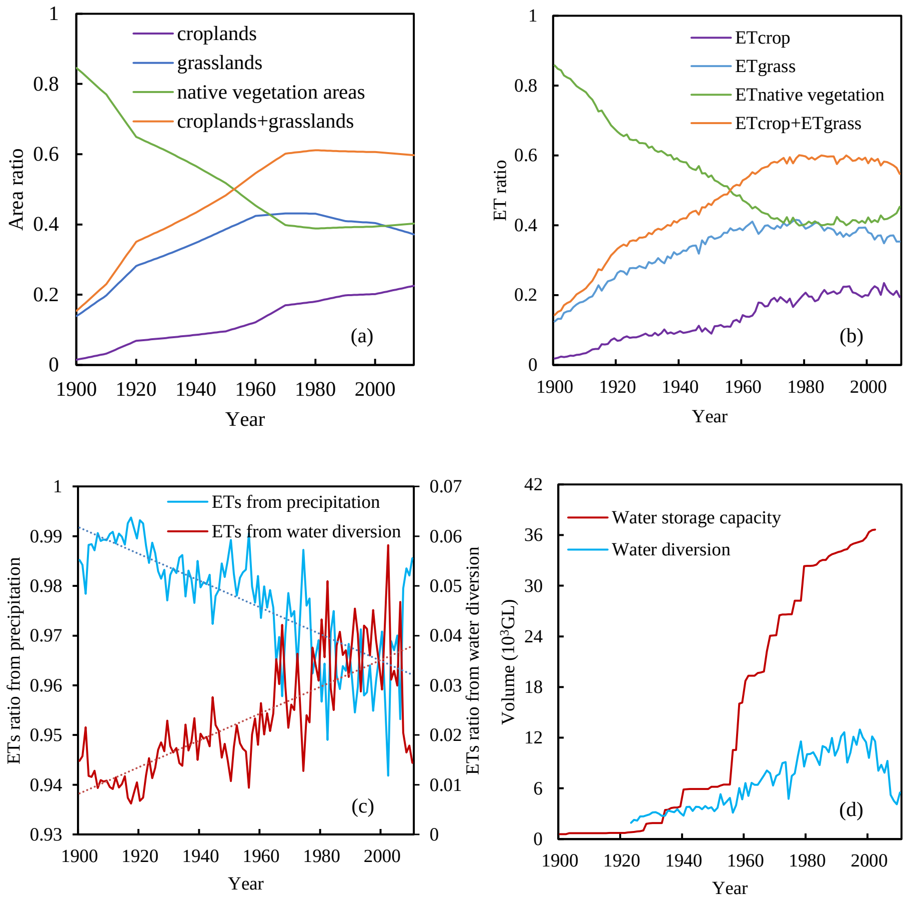

Figure 3. Time series of **(a)** area ratios of croplands, grasslands and native vegetation areas, **(b)** ET ratios of croplands, grasslands and native vegetation areas, **(c)** sources of ET in the societal system, and **(d)** water storage capacity and water diversion in the MDB from 1900 to 2010.

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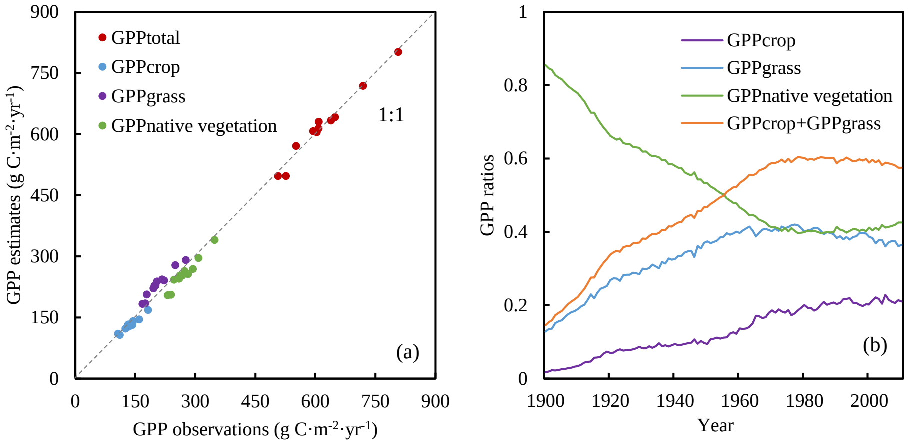

Figure 4. (a) Comparison of the estimated and observed GPPs for the whole MDB and croplands, grasslands and native vegetation areas, and **(b)** estimated GPP ratios of croplands, grasslands and native vegetation areas in the MDB from 1900 to 2010.

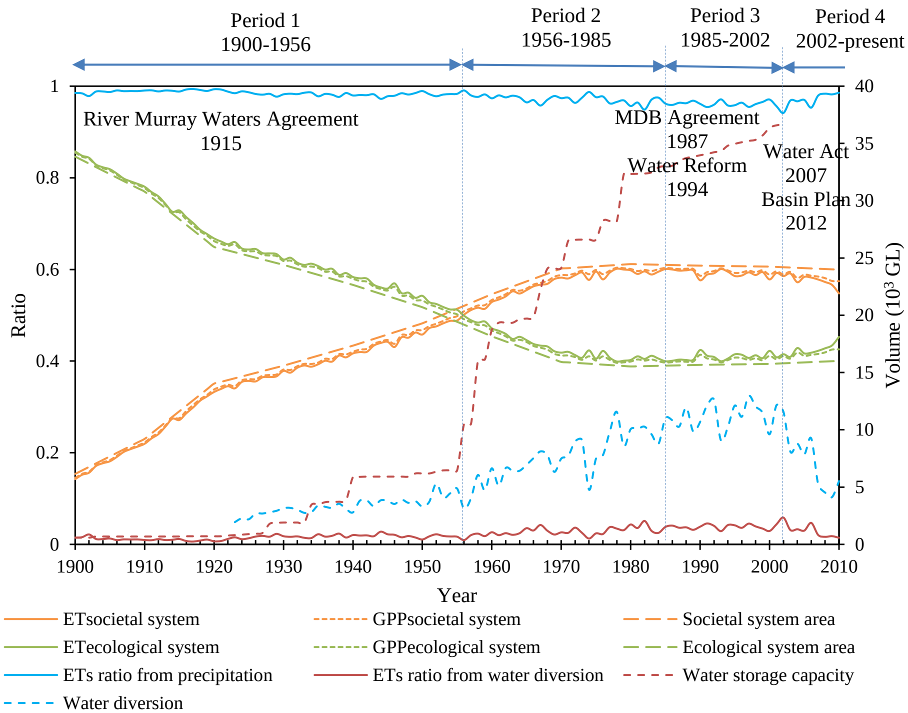

Figure 5. Development stages of the societal and ecological systems in the MDB since 1900, including period 1 (1900–1956) expansion of the societal system, period 2 (1956–1985) maximization of the societal system, period 3 (1985–2002) maximization of water diversion for the societal system and period 4 (2002–present) rebalance of the societal and ecological systems.

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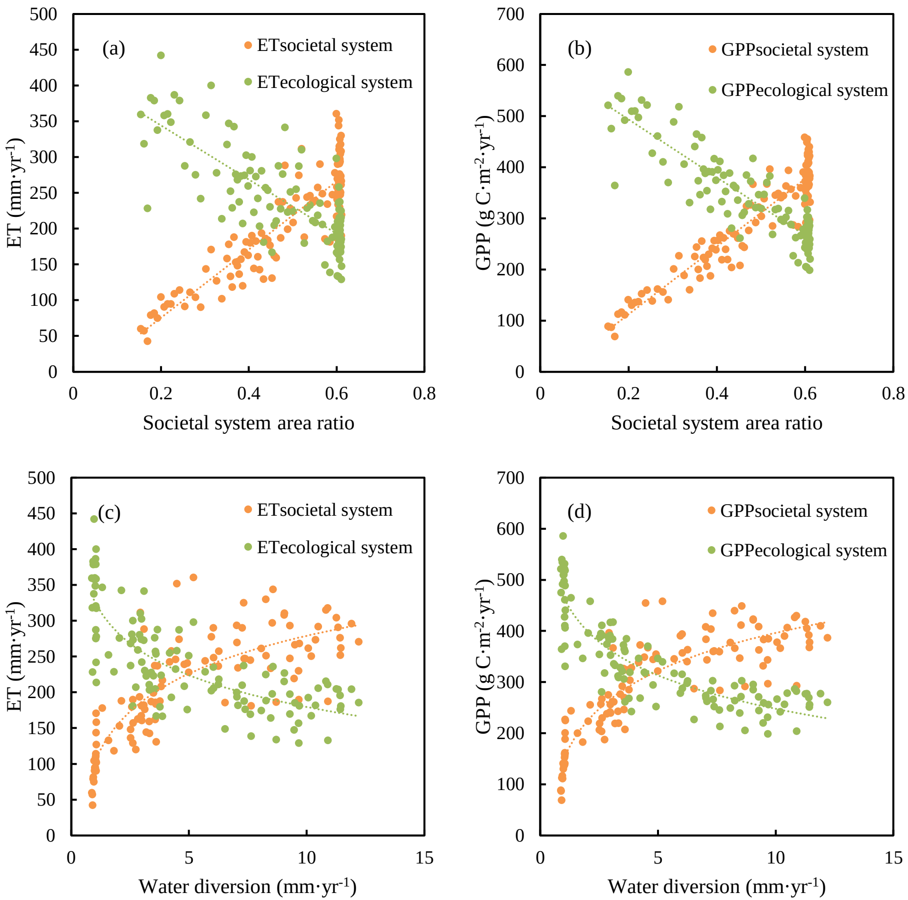

Figure 6. Relationships between **(a)** ET and societal system area ratio, **(b)** GPP and societal system area ratio, **(c)** ET and surface water diversion, **(d)** GPP and surface water diversion in the MDB from 1900 to 2010.

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