

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

3 **S. Zhou^{1, 2}, Y. Huang¹, Y. Wei² and G. Wang¹**

4 [1]{State Key Laboratory of Hydrosience and Engineering, Department of Hydraulic
5 Engineering, Tsinghua University, Beijing 100084, China}

6 [2]{Australia-China Joint Research Centre on River Basin Management, the University of
7 Melbourne, Parkville, Victoria, 3010, Australia}

8 Correspondence to: Y. Wei (ywei@unimelb.edu.au)

1 **Abstract**

2 Rebalancing water allocation between human consumptive uses and the environment in water
3 catchments is a global challenge. This paper proposes a socio-hydrological water balance
4 framework by partitioning catchment total ET into ET for society and ET for natural ecological
5 systems, and establishing the linkage between the changes of water balance and its social
6 drivers and resulting environmental consequences in the Murray-Darling Basin (MDB),
7 Australia, over the period 1900-2010. The results show that the more than 100-year period of
8 water management in the MDB could be divided into four periods corresponding to major
9 changes in basin management within the socio-hydrological water balance framework: period
10 1 (1900-1956) expansion of water and land use for the societal system, period 2 (1956-1978)
11 maximization of water and land use for the societal system, period 3 (1978-2002) maximization
12 of water use for the societal system from water diversion, and period 4 (2002-present)
13 rebalancing of water and land use between the societal and ecological systems. Most of
14 management changes in the MDB were passive and responsive. A precautionary approach to
15 water allocation between societal and ecological systems should be developed. The socio-
16 hydrological water balance framework could serve as a theoretical foundation for water
17 allocation to evaluate the dynamic balance between the societal and ecological systems in
18 catchments.

1 **1 Introduction**

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

8 In recent centuries catchment water management has sought optimization of catchment water
9 balance to secure water supplies for human consumptive demands and to meet the increasing
10 needs of human socio-economic development. This catchment water management paradigm
11 has been supported by hydrological science which has improved the understanding of the
12 partitioning of precipitation into evapotranspiration and surface runoff, based on the framework
13 of water balance (Beven, 2011; Yang et al., 2008; Zhang et al., 2004). This water balance,
14 derived from the principle of conservation of mass, is the most fundamental aspect of global
15 and regional hydrological cycles (Oki and Musiake, 1995). It has been a useful tool for water
16 planners and managers to maximize human water uses under the constraints of water extraction
17 capacity. However, it gives little attention to the water demand for catchment ecosystems and
18 to water sharing between the societal and ecological systems of water catchments. The water
19 balance approach worked well when humankind's water development capacity was very limited
20 and human water consumption volumes took up small percentages of the total available water
21 of catchments. However, when human water uses increase dramatically, and exceed a certain
22 level at which catchment ecosystems are increasingly degraded, the conventional water balance
23 approach is unable to support emerging water management issues such as allocating water
24 between the society and the environment (Alcamo et al., 2007; Kiguchi et al., 2014; Turner et
25 al., 2007; Zhou et al., 2014a).

26 There have been several attempts at exploring human-water systems with the co-evolutionary
27 approach (Geels, 2005; Kallis, 2011; Pataki et al. 2011). All these studies used 'thick
28 description' rather than explanatory approaches and therefore are unable to provide quantitative
29 bases for water allocation between the society and environment. Socio-hydrology is emerging
30 as a new discipline aimed at understanding the co-evolutionary dynamics of human-water
31 systems to underpin sustainable water management (Sivapalan et al., 2012). From its very
32 beginning it was argued that socio-hydrology must be a quantitative science. Since 2012

1 increasing numbers of studies in socio-hydrology have been reported in several case study areas,
2 such as the Tarim River Basin and Heihe River Basin in western China and the Murrumbidgee
3 River Basin in eastern Australia (Di Baldassarre et al. 2013; Srinivasan, 2013; Elshafei et al.,
4 2014; van Emmerik et al., 2014; Kandasamy et al., 2014; Liu et al., 2014; Lu et al 2015).
5 Kandasamy et al. (2014) traced the history of the Murrumbidgee catchment, an agricultural
6 water catchment in the Murray Darling River Basin, Australia, and found a swing phenomenon
7 of water sharing between agricultural water use and riverine environments. Elshafei et al. (2014)
8 in the same catchment developed a prototype framework for socio-hydrological modelling to
9 identify key feedback loops between the human-water relationship by specifying six key
10 functional components including catchment hydrology, population, economics, environment,
11 socioeconomic sensitivity and collective response. This framework combined the strengths of
12 previous attempts with rich descriptions of the human-water coevolution and formal
13 hydrological modelling. However, the modelled results did not correlate well with observed
14 irrigation areas. In addition, although it was already a necessary simplification of an extremely
15 complex coupled system, this framework is still too complex for water catchment managers to
16 use. Lu et al. (2015) quantitatively analyzed the evolution of human–water relationships in the
17 Heihe River Basin of northern China over the past 2000 years by reconstructing the historical
18 catchment water balance by partitioning precipitation into evapotranspiration and runoff. Their
19 study analyzed the impacts of societies on hydrological systems but did not explicitly link the
20 water balance to its drivers. While these studies have made great contributions to observing,
21 understanding and predicting human-water cycle dynamics in catchments there are still no clear
22 analytical or empirical frameworks for water allocation between human use and the
23 environment.

24 We argue that determination of water allocation between human societies and catchment
25 environmental uses is the first basic task of socio-hydrology as it is the critical linkage between
26 economic development and ecological sustainability of catchments. The aim of this paper is to
27 propose a simple socio-hydrological water balance framework for allocating water between the
28 human society and catchment ecological systems in which precipitation is partitioned into water
29 use for societal and ecological systems. Water management in the Murray-Darling Basin over
30 the past one hundred years is taken as a case study. It is expected that this study will provide an
31 empirical case for understanding historical human-water relationships and supporting
32 sustainable catchment management under changing climate and socio-economy conditions in
33 the future.

1 **2 A simple conceptual framework for socio-hydrological water balance**

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

7 We will follow the principle “as simple as possible but no simpler” (in Einstein’s words) to
8 minimize the numbers of variables and parameters to develop a framework, and apply it to a
9 timescale of more than one hundred years. We focus on an agricultural water catchment where
10 water is limiting agricultural production, and where on-going agricultural development of land
11 and water resources catchments has led to increased human use of water, significant
12 modification of catchment vegetation conditions, and a strong human imprint on the water cycle.

13 **2.1 Describing the socio-hydrological water balance**

14 The conventional water balance, derived from the principle of conservation of mass, provides
15 an effective framework for studying hydrological cycles and evaluating the hydrological
16 response of a catchment to climate and land use changes (Oki and Musiak, 1995; Zhang et al.,
17 2001, 2004). It is described by the equation:

$$18 \quad P = ET + R + G + dS/dt \quad (1)$$

19 where, P , ET , R , G and dS/dt are precipitation, evapotranspiration, surface runoff, recharge to
20 groundwater, and the change in soil water storage, respectively. They are the basic elements of
21 a catchment water balance.

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

1 $P = ET_s + ET_e + R_{out} + dG/dt + dS/dt$ (2)

2 $ET_e = ET_{eP} + ET_{eR} + ET_{eG}$ (3)

3 $ET_s = ET_{aP} + ET_{aI} + ET_H + ET_{oth}$ (4)

4 $D_R + D_G = ET_{aI} + ET_H + ET_{oth}$ (5)

5 where, P is precipitation, ET_s and ET_e are the evapotranspiration from the societal and
6 ecological systems, respectively, R_{out} is the outflow into sea, dG/dt is the change in groundwater
7 storage, and dS/dt is the change in soil and surface (reservoir) water storage. Partitioning of ET
8 into societal and ecological systems is mainly defined by land use. The native vegetation areas
9 which maintain ecological function are considered as the ecological system. Ecological system
10 evapotranspiration (ET_e) includes evapotranspiration from precipitation, surface runoff, and
11 groundwater in native vegetation areas, expressed as ET_{eP} , ET_{eR} and ET_{eG} , respectively. Societal
12 system evapotranspiration (ET_s) comprises evapotranspiration in croplands and grasslands
13 arising from precipitation (ET_{aP}) and irrigation (ET_{aI}), and water directly consumed by society,
14 namely water use for households (ET_H) and other industries (ET_{oth}). Water diversions from
15 surface runoff (D_R) and groundwater (D_G) supply irrigation water to croplands and grasslands
16 as well as water for use by households and industries. The remaining surface runoff is used for
17 ecological purposes, i.e., the environmental flows in the ecological systems (ET_{eR}) and outflows
18 to the sea (R_{out}).

19 **2.2 Estimating the impact of changes in socio-hydrological water balance on** 20 **societal-ecological systems**

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

3 Application of the socio-hydrological water balance framework in the 2 Murray-Darling Basin

3 3.1 Study area

4 The Murray-Darling Basin (MDB), located in southeast Australia, is the largest river system in
5 Australia. It is about 1 million km², covering three-quarters of New South Wales, more than
6 half of Victoria, all of the Australian Capital Territory, and significant portions of Queensland
7 and South Australia (Fig. 1). As one of the largest and driest catchments in the world the
8 climatic conditions and natural landscapes of the MDB are very diverse, from the rainforests of
9 the cool eastern uplands, temperate mallee country (dryland dominated by multiple-stemmed
10 eucalyptus species) of the south-east, inland sub-tropical areas of the north, to the hot, dry semi-
11 arid and arid lands of the western plains (MDBA, 2010). The MDB has held meaning for
12 Indigenous Australians for over 50,000 years and for European settlers for over two hundred
13 years. It directly supports around 10% of the Australian population (more than 2 million people)
14 who live in the basin, and more than 1.3 million people who live outside the basin also depend
15 on its water resources. The basin has around 65% of Australia's irrigated land and accounts for
16 about 39% (AUD 15 billion per year) of Australia's gross value of agricultural commodities
17 (MDBA, 2010).

18 Two centuries of European settlement, starting with grand dreams of taming the rivers, greening
19 the desert and making land productive, has transformed Australian water catchments.
20 Approximately 50% of native forests and 65% of native woodlands have been cleared or
21 extensively modified in the MDB (Fig. 1). The surface water flows of the Murray-Darling rivers
22 have decreased markedly and water volumes discharged into the Murray's estuary decreased
23 from 29,000 GL/year in the 1890s to 4,700 GL/year at present. The dramatic development of
24 land and water resources has led to unprecedented growth of agricultural production, but with
25 increased human use of water resources, and there has been significant modification of
26 landscapes and a strong human imprint on water cycle dynamics. The MDB has been changed
27 into a highly human impacted and managed river system, and the MDB's water resources and
28 associated ecosystems are in a state of crisis, characterised by highly degraded natural systems,
29 compromised ecological functions, and intense conflict and competition between users of
30 scarce supplies (Wei et al., 2011).

1 **3.2 Data sources and processing**

2 We use a one-hundred year timeframe (1900-2010) that represents a period over which dramatic
3 changes in climate, population, water and land use, ecological conditions, economic reform,
4 management regulation and technological innovation have occurred in the MDB. The annual
5 water balance components (in mm yr⁻¹) of the MDB from 1900 to 2010, including precipitation,
6 evapotranspiration, surface runoff, deep drainage and changes in soil water storage were
7 obtained from the water balance results produced by the Australian Water Availability Project
8 (AWAP). AWAP developed a simple and robust water balance model to simulate the terrestrial
9 water balance of the Australian continent by model-data fusion methods that combined
10 measurements and model predictions (Briggs et al., 2009). The AWAP results include a long-
11 term historical monthly time series (dataset “Run 26j”, 1900 to 2010) of the conventional water
12 balance components at a spatial resolution of 0.05°. This dataset has been widely used in
13 research and for management of water catchments in Australia.

14 The annual GPP in g C m² yr⁻¹ of the MDB from 2000 to 2010 were summed from the monthly
15 GPP data provided by the Numerical Terradynamic Simulation Group, University of Montana.
16 This group processed the Gross Primary Production (GPP) product “MOD17A2” (2000-2010)
17 from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 8-day intervals, with 1
18 km spatial resolution and a monthly time series of GPP at a resolution of 0.05°. These data were
19 considered as the observed GPP in this study.

20 The land use data are very important for the analysis in this study. As ET and GPP data for each
21 of the three vegetation types over the last century were not available, we used the land use
22 datasets, i.e., the History Database of the Global Environment (HYDE 3.1 version) to estimate
23 ET and GPP for each vegetation type. HYDE 3.1 provides long-term estimates of global human
24 population and built-up areas (croplands and grasslands used for livestock) at a spatial
25 resolution of 5' since the Holocene (10000BC to AD 2000) (Klein Goldewijk et al., 2011). The
26 database of population, croplands and grasslands area is available every 10 years from 1900 to
27 2000, and for 2005. The annual changes in land use were normally small so the annual datasets
28 at a resolution of 0.05 °of the population and the area ratios of croplands, grasslands and native
29 vegetation areas in the MDB from 1900 to 2010 were obtained from HYDE version 3.1 with
30 resampling and linear interpolation in ArcGIS. This is reasonable for the purposes of this study.
31 We did not consider crop factors changes because this research is based on modelled data rather
32 than field investigations.

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

5 **3.3 Describing the socio-hydrological water balance in the MDB**

6 The socio-hydrological water balance was estimated according to Eqs. (2) ~ (5), i.e.,
7 partitioning ET into societal and ecological systems, including ET from the precipitation and
8 that from runoff. The annual ET from precipitation for the croplands, grasslands and native
9 vegetation areas were partitioned into three parts by multiplying the average ET by the area
10 ratios of the three land use types for each grid, and then aggregating the separated ET of all the
11 grids in the MDB, respectively using the annual water balance datasets from the AWAP and
12 the annual datasets produced for each of the three area ratios by HYDE 3.1. This method was
13 performed with the assumption that the three vegetation types shared the ET in each grid
14 according to the ratios of their areas.

15 The annual ET from runoff referred to water diversion in the societal system and environmental
16 flows in the ecological systems. The data for water diversions were divided into four parts,
17 including ET from irrigation in croplands and grasslands, for households and industries. Water
18 use by households and other industries were assumed to be proportional to population, and the
19 ratios were set to be 0.078 and 0.153, respectively, according to the water account data (ABS,
20 2014a). The remaining water diversion was ascribed to irrigation, with a ratio of 4:1 between
21 croplands and grasslands, according to water use data of Australian farms (ABS, 2014b). The
22 environmental flows were calculated as the water remaining after surface runoff was subtracted
23 from surface water diversion and outflows into the sea.

24 In the MDB groundwater diversion and evapotranspiration from groundwater for native
25 vegetation are generally small compared to other elements and were not considered. Therefore,
26 groundwater recharge and changes in soil water storage were the same as those in the
27 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 gross primary productivity (GPP) to measure the impacts of water allocation on them. Water use efficiency (WUE), defined here as the ratio of carbon gain to water loss in terrestrial ecosystems, was 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 to 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 the origin (0, 0). The relationship between annual GPP and ET is given in Eq. (7).

$$WUE_t = a \cdot ET_t + b \quad (6)$$

$$GPP_t = WUE_t \cdot ET_t = a \cdot ET_t^2 + bET_t \quad (7)$$

where ET_t is the total ET per unit area in mm yr^{-1} , GPP_t is the total GPP in $\text{g C m}^{-2} \text{yr}^{-1}$, and WUE_t is the water use efficiency in g C/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:

$$GPP_t = -9.9455 \times 10^{-4} \cdot ET_t^2 + 1.8718ET_t \quad (8)$$

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:

$$F = \min \sqrt{\frac{\sum_{n=1900}^{2010} (GPP_{tn} - \sum_{i=1}^3 GPP_{in})^2}{111}} \quad (9)$$

1 where

$$2 \quad WUE_{in} = a_i \cdot \frac{ET_{in}}{AR_{in}} + b_i \quad (10)$$

$$3 \quad GPP_{in} = WUE_{in} \cdot ET_{in} = a_i \cdot \frac{ET_{in}^2}{AR_{in}} + b_i ET_{in} \quad (11)$$

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

1 4 Results

2 4.1 The socio-hydrological water balance in the MDB

3 The changes in the components of the conventional and socio-hydrological water balances in
4 the MDB from 1900 to 2010 are shown in Figs. 2 (a) and (b). The results for the conventional
5 water balance showed that on average about 95% of precipitation was consumed as
6 evapotranspiration. The evapotranspiration almost equalled, or even exceeded, precipitation
7 during drought periods, such as during the Federation Drought (1885-1902), the World War II
8 Drought (1937-1945) and the Millennium Drought (1997-2009), resulting in decreases in
9 surface runoff and soil water storage (Fig. 2 (a)). The conventional water balance reveals the
10 pattern of partitioning precipitation into evapotranspiration and runoff over the years. The
11 socio-hydrological water balance shows a different perspective (Fig. 2 (b)). It can be clearly
12 seen that evapotranspiration from societal use increased and surpassed that from ecological
13 systems after the 1950s. After that time human water use plays a more and more dominant role.
14 The socio-hydrological water balance indicates the co-evolutionary dynamics of water
15 allocation between the societal and ecological systems in the MDB for this one hundred-year
16 period.

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

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 GPP and ET (Figs. 3 (b) 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 g C m² yr⁻¹ in 1900 to 133 and 298 g C m² 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. 3 (b)). In the following two decades, the GPP ratios of the societal and ecological systems were maintained at about 0.6 and 0.4, respectively (Fig. 3 (c)). 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 the 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. 3 (c)). 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 pattern were relatively uniform. The impact of water allocation on societal and ecological systems.

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 reflected in changes in water allocation, land use, and the resulting GPP. In view of the socio-hydrological catchment water balance, the co-evolutionary history of the socio-ecological systems in the MDB can be divided into four stages (Fig. 4).

(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 the 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 period (Fig. 4 (b)). 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. 4 (a)). 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 at the same year (Fig. 4 (a)). The growth of population and expansion of agricultural land were the major reasons of the expansion of water use by the societal system, accompanied by the construction of small dams and irrigated infrastructure (Fig. 4 (c)). Therefore, 1956 should be considered to be the first critical period when land and water use for the societal system exceeded that for the ecological system for the first time.

(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. 4 (c)). 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. 4 (b)). The storage capacity reached 24,144 GL in 1970 from a starting point of near zero with the construction of dams, weirs, barrages and irrigation delivery canals (Fig. 4 (c)). Nearly 450 large dams and innumerable small farm dams were built, which gives

1 rise to some of the highest levels of water storage per capita in the world - more than 3 times
2 mean annual flow (Wei et al., 2011).

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

11 (3) Period 3 (1978-2002): Maximization of water use for the societal system from water
12 diversion

13 Water diversions increased and maintained nearly stable ratios of ET and GPP for society (Figs.
14 4 (a) and (c)). The Millennium Drought (1997-2009) occurred in this period and is regarded as
15 one of the worst droughts since European settlement (Murphy and Timbal, 2008). The
16 Millennium Drought dried out the MDB's major river systems, and the water-dependent
17 ecological assets such as the mid-Murrumbidgee Wetlands, and the Lowbidgee Floodplain
18 suffered significant degradation (Connor et al., 2013). The ET of the societal system from
19 surface water diversion reached a maximum in 2002 in order to maintain the maximized societal
20 system under severe drought, resulting in further exacerbation of ecosystem damage (Fig. 4 (d)).

21 (4) Period 4 (2002-present): Rebalance of water and land use between the societal and
22 ecological systems

23 This period saw a small decrease in the area of agricultural land, ET and GPP in the societal
24 system for the first time since the European settlement (Fig. 4 (a)). The water diversion to
25 society decreased. During wetter years, for example 2010, Australian governments took action
26 to purchase water entitlements for the environment and implement irrigation efficiency
27 programs to return water, about 2,750GL yr⁻¹, to the environment, and drive a transition to
28 Sustainable Diversion Limits after 2010. Within society, water trading and the introduction of
29 upgraded irrigation infrastructure and technology, such as efficient low-throw sprinkler and
30 drip/trickle irrigation methods, improved water productivity and facilitated the water
31 reallocation between the societal and ecological systems.

1 **5 Discussions and conclusions**

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

10 The management of water in the MDB over more than 100 years was divided into four periods
11 using the socio-hydrological water balance framework. They include: period 1 (1900-1956)
12 expansion of water and land use for the societal system, period 2 (1956-1978) maximization of
13 water and land use for the societal system, period 3 (1978-2002) maximization of water use for
14 the societal system from water diversion, and period 4 (2002-present) rebalancing of water and
15 land use between the societal and ecological systems. This recognition of distinct periods of
16 water management is very consistent with the results of Kandasamy et al (2014) in the
17 Murrumbidgee River Basin, a sub-catchment of MDB. The co-evolution of the human-water
18 relationship in the MDB is the result of the interactions of climatic and social drivers in the
19 Basin. Three droughts, particularly the “Millennium Drought”, population increases, and
20 improvement of water storage are major driving forces. The growth of population played the
21 overwhelming role in period 1 (1900-1956). Period 2 (1956-1978) was the result of a
22 combination of population growth and water storage increases. In period 3 (1978-2002) the
23 “Millennium Drought” acted as a trigger of the changes in the human-water relationship. Period
24 4 (2002-present) is a transitional period. Population increase was no longer a driver for the
25 increase of human water use. For the first time since 1900 water storage and water diversion
26 were redirected to environmental purposes. The environmental consequences of both the
27 Millennium Drought and social-economic development in the past were the major triggers for
28 management transition.

29 Two main lessons can be drawn from the analysis of co-evolutional processes of the human-
30 water relationship in the MDB. Over the long history of water management reforms in the MDB,
31 from the River Murray Waters Agreement in 1915, to the Murray-Darling Basin Agreement in
32 1987, attention was focused on water-sharing between the states of the Basin to develop their

1 economies. 1956 was the first critical period when water and land use for society for the first
2 time exceeded that for the ecological system. Unfortunately, it was not given attention by
3 catchment water and land managers at the time. When water and land use and GPP by society
4 were maximized in 1978 and some serious environmental issues appeared, the governments of
5 the Basin started to take some actions on water resources management to address the emerging
6 issues. In 1987 the Murray-Darling Basin Water Agreement was signed between the
7 Commonwealth, New South Wales, Victoria and South Australia governments to promote and
8 coordinate effective approaches to dealing with environmental problems, in particular salinity
9 and water quality (MDBA, 2010). The Millennium Drought aggravated the tension between the
10 societal and ecological systems, which resulted in water diversion for society to be maximized
11 in 2002, resulting in serious degradation of ecosystems. The Water Act of 2007 recognized the
12 importance of water allocation for environmental purposes. The Basin Plan, which aimed to
13 balance societal and economic effects of reduced consumptive water to make water available
14 for the environment, was proposed in 2010 and issued in 2012, and is the milestone of the
15 rebalance of the societal and ecological systems in the MDB. All these management changes in
16 MDB in history were passive, responsive and contingent. A precautionary approach to water
17 allocation between the societal and ecological systems should be developed based on the
18 analytical understanding of socio-hydrological catchment water balance.

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

29 Increasing concern for the ecological quality of the MDB has brought about a series of
30 initiatives of purchasing water from irrigators for environmental purposes. For example, the
31 target for surface water recovery for the environment under the Basin Plan is 2750 gigalitres,
32 of which 1500 gigalitres was planned to be obtained through surface water buybacks. These

1 water volumes correspond with less than 1% of the whole catchment ET and may improve the
2 riverine ecological systems to some extent, but they have very little influence on catchment
3 native vegetation systems. Therefore only integrated land and water management could address
4 ecological degradation at both riverine and catchment levels. The socio-hydrological water
5 balance framework developed in this study provides new understandings of the water and land
6 dynamics at catchments.

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

18 The proposed framework did not consider the change of societal values and norms as one of
19 social drivers for change of socio-hydrological water balance. We argue that changes in societal
20 values of water catchments, which define what we want water catchments to be, and changes
21 in available technologies which determine the means to identify needs for changes and
22 remediation practices, and their interactions, are key triggers for changes in socio-hydrological
23 water balance. Sivapalan et al. (2014) proposed incorporation of societal values into socio-
24 hydrological models. Elshafei et al. (2014) incorporated changing values and norms of a society
25 by introducing environmental awareness as a co-evolutionary variable of system dynamics. Wei
26 et al. (2015) empirically analyzed the evolution of newspaper reporting on water issues in
27 Australia since 1843. However, the metrics of societal values need be further researched before
28 they can be incorporated into the socio-hydrological modelling.

29 Water allocation between the human society and catchment ecosystems is a real challenge for
30 the coming decades in many parts of the world. Despite of the uncertainty in long term datasets
31 and ignorance of change of societal values, the proposed socio-hydrological water balance
32 could be used to understand the history of water allocation between the societal and ecological

1 systems, i.e. how today's problems were created in the past, which may lead to more sustainable
2 catchment management in the future. As there are fundamental differences in the hydrology,
3 demography, societal values, levels of economic development and capacity of water
4 governance in areas such as the Yellow River Basin in China, the Colorado River Basin in the
5 United States and the Ebro River Basin in the Europe, which have the similar management
6 challenges with the MDB, application of the proposed water balance framework in these river
7 basins can enable exploration of common research problems, as well as highlight regional
8 differences and any unique responses. It will also enable the identification of important policy,
9 institutional and/or cultural differences for this globally significant issue, and point to lessons
10 that might not emerge from a single country study.

11 **Acknowledgements**

12 The water balance and land use data were supplied by the Australian Water Availability Project
13 (<http://www.eoc.csiro.au/awap/>) and the History Database of the Global Environment
14 (<http://www.pbl.nl/hyde/>), respectively. Figure 1 was developed by Mr Zelalem Tesemma and
15 Dr Yongping Wei. Professor Andrew Western from the University of Melbourne gave very
16 valuable comments on the revision of this manuscript. This paper is financially supported by
17 the National Natural Science Foundation of China (No. 91125018), the Australian Research
18 Council (ARC) (FT130100274), the National Key Science and Technology Project Fund from
19 the Ministry of Science and Technology (MOST) during the Twelfth Five-year Project (No.
20 2013BAB05B03), the Research and Development Special Fund for Public Welfare Industry of
21 the Ministry of Water Research in China (No. 201301081).

22 **References**

23 Australian Bureau of Statistics (ABS): Water Use on Australian Farms (2002-2010), available
24 at: <http://www.abs.gov.au/> (last access: May 2014), 2014a.

25 Australian Bureau of Statistics (ABS): Water Account, Australia (2008-2010), available at:
26 <http://www.abs.gov.au/> (last access: December 2014), 2014b.

27 Alcamo, J., Flörke, M. and Märker, M.: Future long-term changes in global water resources
28 driven by socio-economic and climatic changes, *Hydrol. Sci. J.*, 52(2), 247–275,
29 doi:10.1623/hysj.52.2.247, 2007.

30 Beer, C., Reichstein, M., Ciais, P., Farquhar, G. D. and Papale, D.: Mean annual GPP of Europe
31 derived from its water balance, *Geophys. Res. Lett.*, 34(5), L05401,
32 doi:10.1029/2006GL029006, 2007.

- 1 Beven, K. J.: Rainfall-Runoff Modelling: The Primer. [online] Available from:
2 <http://www.google.com.au/books?hl=zh-CN&lr=&id=eI-jjITirAC&pgis=1> (Accessed 17
3 November 2014), 2011.
- 4 Connor, J. D., Franklin, B., Loch, A., Kirby, M. and Wheeler, S. A.: Trading water to improve
5 environmental flow outcomes, *Water Resour. Res.*, 49(7), 4265–4276, doi:10.1002/wrcr.20323,
6 2013.
- 7 Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., and Blöschl, G.: Socio-
8 hydrology: conceptualising human- flood interactions, *Hydrol. Earth Syst. Sci.*, 17, 3295–3303,
9 doi:10.5194/hess-17-3295-2013, 2013.
- 10 Elshafei, Y., Sivapalan, M., Tonts, M. and Hipsey, M. R.: A prototype framework for models
11 of socio-hydrology: identification of key feedback loops and parameterisation approach, *Hydrol.*
12 *Earth Syst. Sci.*, 18(6), 2141–2166, doi:10.5194/hess-18-2141-2014, 2014.
- 13 Falkenmark, M.: Freshwater as shared between society and ecosystems: from divided
14 approaches to integrated challenges., *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, 358(1440),
15 2037–49, doi:10.1098/rstb.2003.1386, 2003.
- 16 F.W. Geels. Co-evolution of technology and society: The transition in water supply and
17 personal hygiene in the Netherlands (1850–1930)—a case study in multi-level
18 perspective. *Technology in Society* 27, no. 3(2005) : 363-397.
- 19 Gallant, A. J. E., and J. Gergis (2011), An experimental streamflow reconstruction for the River
20 Murray, Australia, 1783–1988, *Water Resour. Res.*, 47(12), W00G04.
21
- 22 Grantham T. E. , Mezzatesta M. , Newburn D. A., M. A. M.: Evaluating tradeoffs between
23 environmental flow protections and agricultural water security, *River Res. Appl.*, 30(3), 315–
24 328, doi:10.1002/rra, 2014.
- 25 Kandasamy, J., Sounthararajah, D., Sivabalan, P., Chanan, a., Vigneswaran, S. and Sivapalan,
26 M.: Socio-hydrologic drivers of the pendulum swing between agricultural development and
27 environmental health: a case study from Murrumbidgee River basin, Australia, *Hydrol. Earth*
28 *Syst. Sci.*, 18(3), 1027–1041, doi:10.5194/hess-18-1027-2014, 2014.
- 29 Kallis, G. 2011. Coevolution in water resource development the vicious cycle of water supply
30 and demand in Athens, Greece. *Ecological Economics* 69: 796-809.
- 31 Kiguchi, M., Shen, Y., Kanae, S. and Oki, T.: Reevaluation of future water stress due to socio-
32 economic and climate factors under a warming climate, *Hydrol. Sci. J.*, 140917054829006,
33 doi:10.1080/02626667.2014.888067, 2014.
- 34 Klein Goldewijk, K., Beusen, A., Van Dreht, G. and De Vos, M.: The HYDE 3.1 spatially
35 explicit database of human-induced global land-use change over the past 12,000 years, *Glob.*
36 *Ecol. Biogeogr.*, 20(1), 73–86, doi:10.1111/j.1466-8238.2010.00587.x, 2011.

- 1 Liu, Y., Tian, F., Hu, H. and Sivapalan, M.: Socio-hydrologic perspectives of the co-evolution
2 of humans and water in the Tarim River basin, Western China: the Taiji–Tire model, *Hydrol.*
3 *Earth Syst. Sci.*, 18(4), 1289–1303, doi:10.5194/hess-18-1289-2014, 2014.
- 4 Lu, Z., Wei, Y., Xiao, H., Zou, S., Xie, J., Ren, J., and Western, A.: Evolution of the human–
5 water relationships in the Heihe River basin in the past 2000 years, *Hydrol. Earth Syst. Sci.*, 19,
6 2261–2273, doi:10.5194/hess-19-2261-2015, 2015.
- 7 Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Zbigniew, W., Lettenmaier, D.
8 P. and Stouffer, R. J.: Stationarity Is Dead : Whither Water Management ?, , 319, 573–574,
9 2008.
- 10 Murphy, B. F. and Timbal, B.: A review of recent climate variability and climate change in
11 southeastern Australia, *Int. J. Climatol.*, 28(7), 859–879, doi:10.1002/joc.1627, 2008.
- 12 Oki, T. and Musiak, K.: Global atmospheric water balance and runoff from large river basins,
13 9(January 1994), 655–678, 1995.
- 14 Pataki, D. E., Carreiro M. M., Cherrier J., Grulke N. E., Jennings V., Pincetl S., et
15 al. (2011). Coupling biogeochemical cycles in urban environments: ecosystem services, green
16 solutions, and misconceptions. *Frontiers in Ecology and the Environment*. 9, 27-36.
- 17 Srinivasan, V.: Coevolution of water security in a developing city, *Hydrol. Earth Syst. Sci.*
18 *Discuss.*, 10, 13265–13291, doi:10.5194/hessd-10-13265-2013, 2013.
- 19 Piao, S., Friedlingstein, P., Ciais, N., de Noblet-Ducoudré D., Labat, and S. Zaehle (2007),
20 Changes in climate and land use have a larger direct impact than rising CO₂ on global river
21 runoff trends, *Proc. Natl. Acad. Sci. U. S. A.*, 104(39), 15242-15247.
- 22 Sivapalan, M., Savenije, H. H. G. and Blöschl, G.: Socio-hydrology: A new science of people
23 and water, *Hydrol. Process.*, 26(8), 1270–1276, doi:10.1002/hyp.8426, 2012.
- 24 Turner, B. L., Lambin, E. F. and Reenberg, A.: The emergence of land change science for global
25 environmental change and sustainability., *Proc. Natl. Acad. Sci. U. S. A.*, 104(52), 20666–71,
26 doi:10.1073/pnas.0704119104, 2007.
- 27 Van Emmerik, T. H. M., Li, Z., Sivapalan, M., Pande, S., Kandasamy, J., Savenije, H. H. G.,
28 Chanan, a. and Vigneswaran, S.: Socio-hydrologic modeling to understand and mediate the
29 competition for water between agriculture development and environmental health:
30 Murrumbidgee River basin, Australia, *Hydrol. Earth Syst. Sci.*, 18(10), 4239–4259,
31 doi:10.5194/hess-18-4239-2014, 2014.
- 32 Wei, J. Wei, Y., Western, A., Skinner, D., and Lyle., C.. 2015. Evolution of newspaper coverage
33 of water issues in Australia during 1843-2011. *AMBIO* 44:319-331.
- 34 Wei, Y., Langford, J., Willett, I. R., Barlow, S. and Lyle, C.: Is irrigated agriculture in the
35 Murray Darling Basin well prepared to deal with reductions in water availability?, *Glob.*
36 *Environ. Chang.*, 21(3), 906–916, doi:10.1016/j.gloenvcha.2011.04.004, 2011.

- 1 Yang, H., Yang, D., Lei, Z. and Sun, F.: New analytical derivation of the mean annual water-
2 energy balance equation, *Water Resour. Res.*, 44(3), n/a–n/a, doi:10.1029/2007WR006135,
3 2008.
- 4 Yang, Y., Long, D. and Shang, S.: Remote estimation of terrestrial evapotranspiration without
5 using meteorological data, *Geophys. Res. Lett.*, 40(12), 3026–3030, doi:10.1002/grl.50450,
6 2013.
- 7 Zhang, L., Dawes, W. R. and Walker, G. R.: Response of mean annual evapotranspiration to
8 vegetation changes at catchment scale, *Water Resour. Res.*, 37(3), 701–708,
9 doi:10.1029/2000WR900325, 2001.
- 10 Zhang, L., Hickel, K., Dawes, W. R., Chiew, F. H. S., Western, A. W. and Briggs, P. R.: A
11 rational function approach for estimating mean annual evapotranspiration, *Water Resour. Res.*,
12 40(2), n/a–n/a, doi:10.1029/2003WR002710, 2004.
- 13 Zhou, S., Huang, Y., Yu, B. and Wang, G.: Effects of human activities on the eco-environment
14 in the middle Heihe River Basin based on an extended environmental Kuznets curve model,
15 *Ecol. Eng.*, 76, 14–26, doi:10.1016/j.ecoleng.2014.04.020, 2014a.
- 16 Zhou, S., Yu, B., Huang, Y. and Wang, G.: The effect of vapor pressure deficit on water use
17 efficiency at the subdaily time scale, *Geophys. Res. Lett.*, 41(14), 5005–5013,
18 doi:10.1002/2014GL060741, 2014b.
- 19

1 **Figure captions**

2 **Fig. 1.** Location map and land cover changes of the Murray-Darling Basin.

3 **Fig. 2.** Water balance elements changes in the MDB from 1900 to 2010 in the conventional
4 water balance (a) and in the socio-hydrological water balance (b).

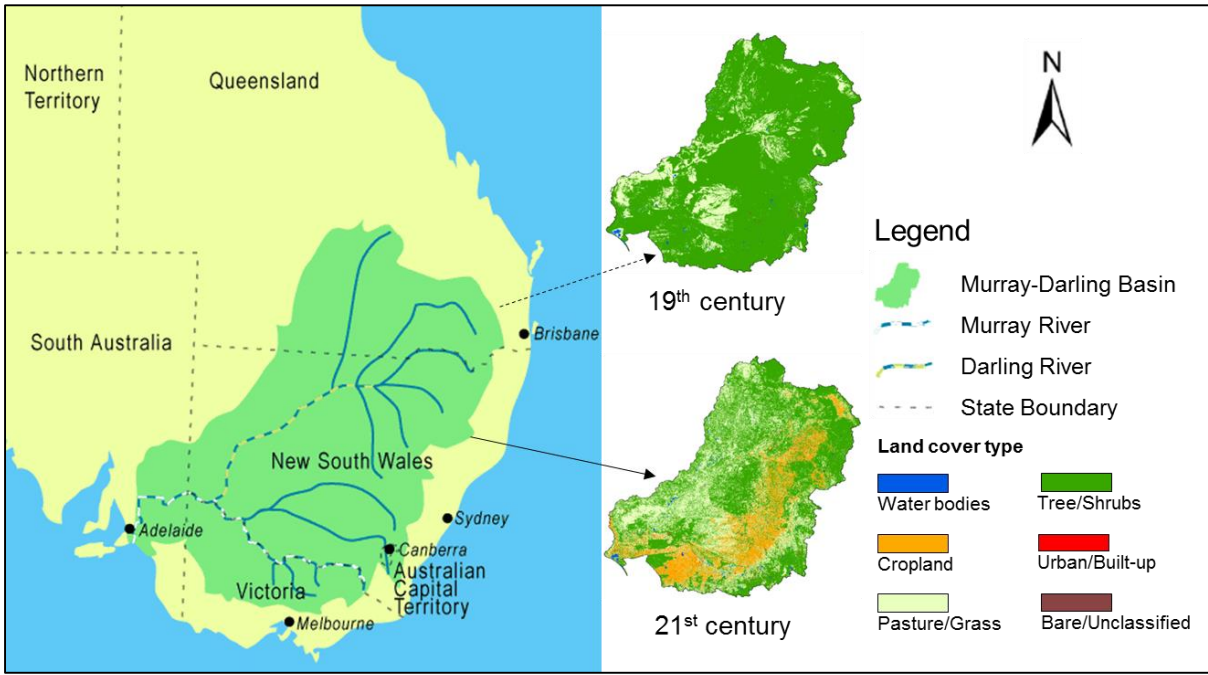
5 **Fig. 3.** Time series of (a) ET, (b) GPP and (c) ratios of ET, GPP and land area for croplands,
6 grasslands and native vegetation areas in the MDB from 1900 to 2010.

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

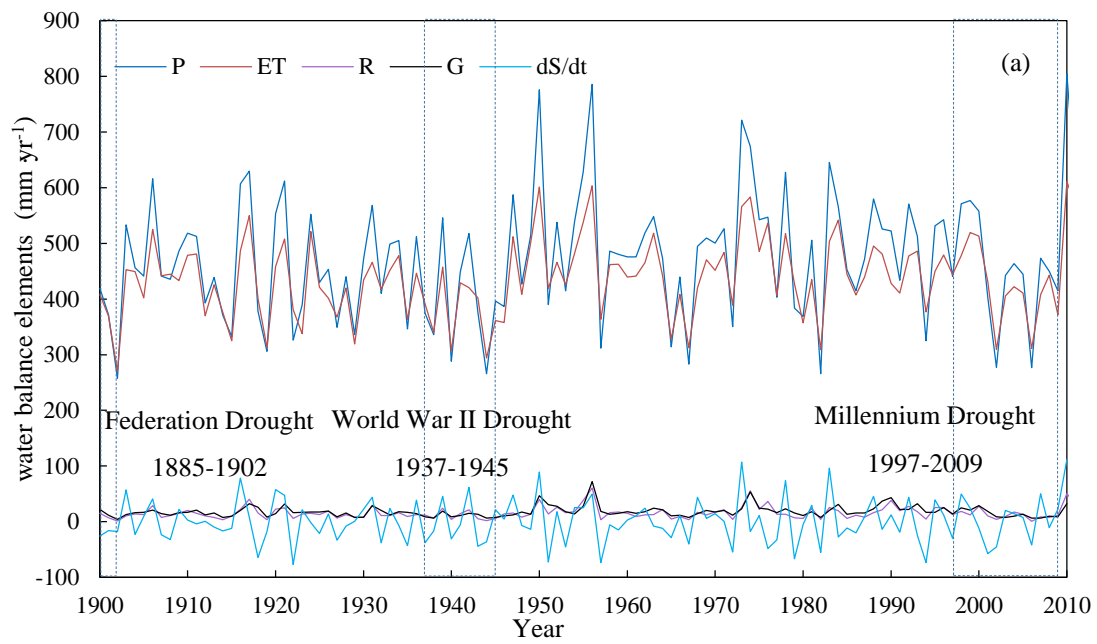
1 **Table 1.** The results and accuracy of GPP in the MDB obtained with the optimization method.

Vegetation type	GPP-ET function	R ²	RMSE (g C m ⁻² yr ⁻¹)
Crop	$GPP_1 = -9.1027 \times 10^{-4} \cdot \frac{ET_1^2}{AR_1} + 1.8423ET_1$	0.96	8.16
Grass	$GPP_2 = -10.5274 \times 10^{-4} \cdot \frac{ET_2^2}{AR_2} + 1.8951ET_2$	0.95	23.88
Native vegetation	$GPP_3 = -9.7125 \times 10^{-4} \cdot \frac{ET_3^2}{AR_3} + 1.8620ET_3$	0.94	19.55
Total	$GPP_{total} = GPP_1 + GPP_2 + GPP_3$	0.97	13.99

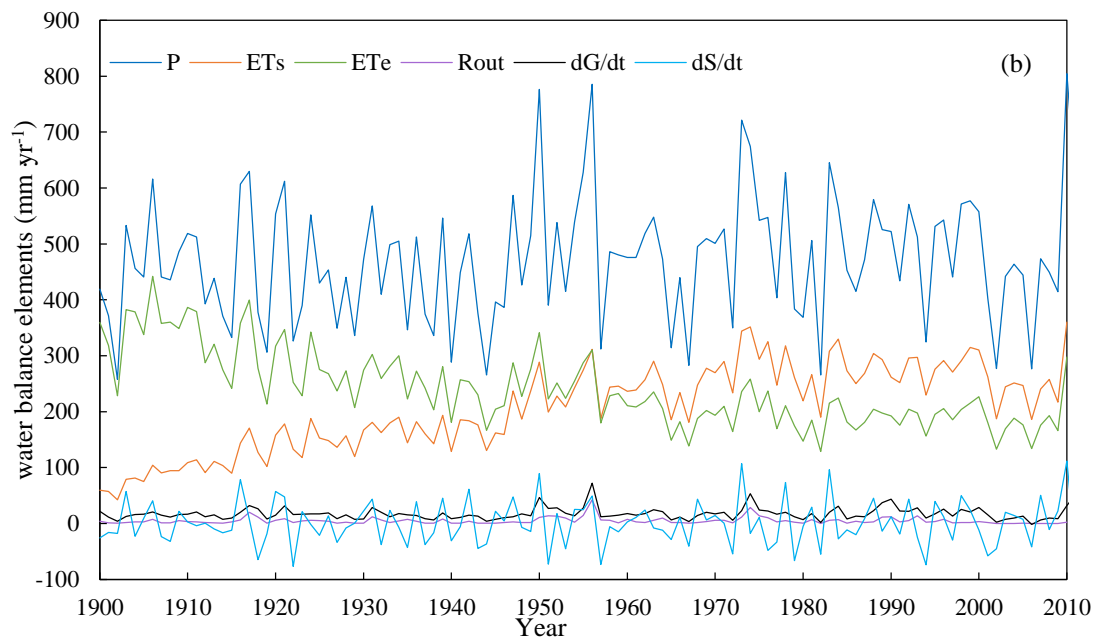
2



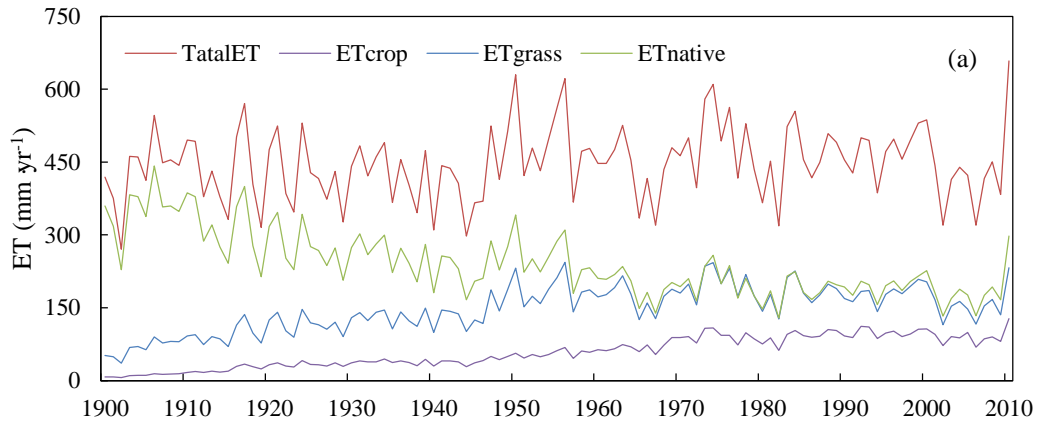
1



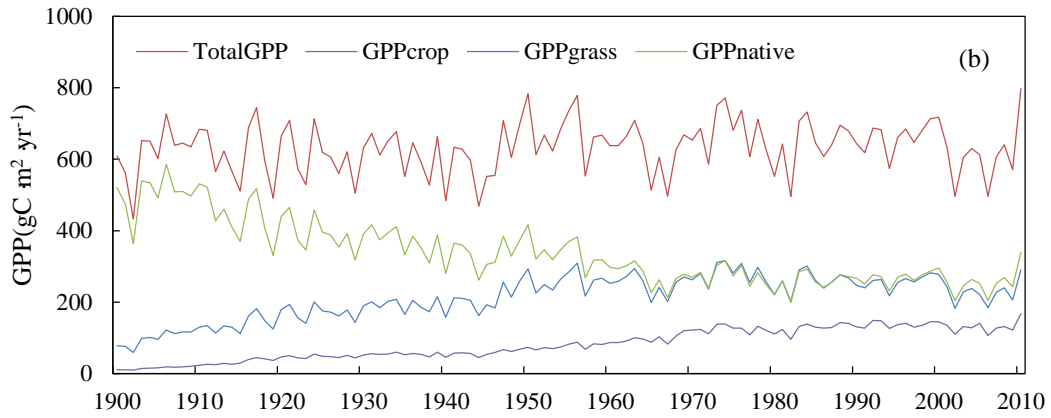
1



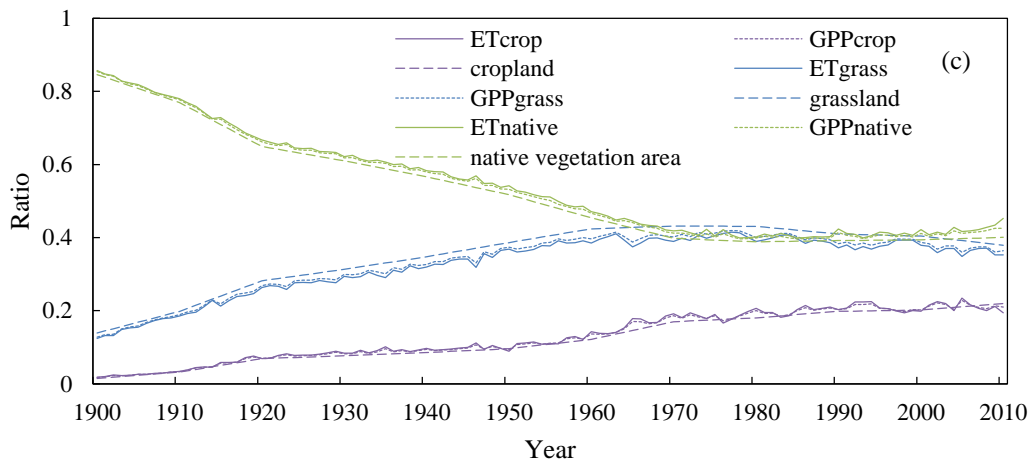
2



1



2



3

