

We thank the three reviewers for considering our manuscript “Recasting catchment water balance for water allocation between human and environmental purposes” (Submission Reference: hess-2014-558). On response (in red) to their comments (in black) are provided below. We have implemented most of the major changes suggested by the reviewers. In the few cases where we do not agree we explain our reasoning. We have also improved the quality of our manuscript during the revision. For details, please see the tracked version.

## **Responses to major comments of Reviewer #1**

**Comment 1:** General: This paper does not follow a socio-hydrology analysis as there are not feed- back loops. The analysis comprises of a regression of the data. Importantly there is no interaction between principal parameters ie no co-evolution.

We agree with the reviewer that the feedback loops provide a research pattern for socio-hydrology. Our manuscript aimed to develop the socio-hydrological water balance for allocating water between human society and catchment ecological systems. It partitions catchment total ET into ET for society and ET for natural ecological systems, and establishes the linkage between the changes of water balance and its social drivers and resulting environmental consequences in the Murray-Darling Basin (MDB). It provides an empirical case for understanding historical human-water relationships and supporting sustainable catchment management under changing climate and socio-economy conditions in the future. Therefore this study indeed reflected feedback between human and water use, both on a yearly basis and for over a hundred year period.

**Comment 2:** Detail: This paper explored the societal and ecological water use by recasting evapotranspiration. It is interesting to see how evapotranspiration is modified by humans. As whole the analysis depends on land use data with temporal resolution 10 years (11 points describing the period 1900-2005). All results and explanation hinge on this data.

We agree with the reviewer that the land use data are very important for the analysis. Our study period was from 1900 to 2010. It was based on annual water balance and the temporal resolution was yearly. However, we could not find yearly land use datasets from 1900 to 2010, and the HYDE 3.1 spatially-explicit database of land-use change with a temporal resolution 10 years provided the best available datasets, and which have been widely used. As annual land use change was normally small, annual land use data were obtained through linear interpolation, and this is reasonable for the purposes of this study.

**Comment 3:** The authors explained 4 periods based on the results, how are these periods identified? This is questionable as societal land use increase even after 1985. According to ABS, 84% of the land in the MDB is owned by businesses engaged in Agriculture. Modelling by the Bureau of Rural Sciences (BRS) has identified that 67% of the land is used for growing crops and pasture in 2001-2005. This is higher value than the presented in the paper and land use change continues to ~2000 as explained in Kandasamy et. Al (2014) for Murrumbidgee River. Actual rebalancing of water between ecology and human use started in 1997 as shown in figure 5 or figure 3(d).

The basis for division of the MDB land and water management into 4 periods was to reflect the evolution of human and water relationship with the change of the relative percentage of water use between societal systems and ecological system, land use change and water diversion

change, which are three key interacting factors for integrated catchment management. Specifically, Period 1 (1900–1956) corresponded with expansion of water and land use by the societal system, and at the end of this period the water used for societal system increased up to the amount used for the ecological systems. Period 2 (1956–1978) was a time of maximization of water and land use by the societal system, and Period 3 (1978–2002) was maximization of water diversion for the societal system, and Period 4 (2002–present) was when there was a rebalancing of water and land use between the societal and ecological systems.

The land use data were obtained from HYDE 3.1, which provided long-term estimates of croplands and grasslands. The uncertainty was roughly estimated as 5% in AD 2000 and 10% in AD 1900 (Klein et al., 2011). According to HYDE 3.1, the sum of croplands and grasslands was about 61% in the early 21<sup>st</sup> century, and this ratio was close to the modelled data of the BRS. In the last paragraph of the Discussion section, we discussed the limitations, i.e., the uncertainties of the data and methods used in this study.

*Klein Goldewijk, K., Beusen, A., Van Drecht, G., and De Vos, M.: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, Global Ecol. Biogeogr., 20, 73–86, doi:10.1111/j.1466-8238.2010.00587.x, 2011.*

**Comment 4:** there are is no observed validation for runoff/discharge. Is there any better estimation of runoff due to the inclusion of human dynamics compared to AWAP method? There are is no observed validation for runoff/discharge. Is there any better estimation of runoff due to the inclusion of human dynamics compared to AWAP method?

The AWAP data included a long-term historical monthly water balance (1900 to 2010) which were developed with model-data fusion methods in combination with measurements and are the most robust datasets for the MDB. They have been widely used for research and management practices (Briggs, et al., 2009). The impact of human dynamics has been included in the catchment water balance model through inclusion of diversion and changes of ET and runoff.

*Briggs, P. R., Haverd, V., King, E. A., Paget, M., and Trudinger, C. M.: Australian water availability project (AWAP): CSIRO marine and atmospheric research component: final report for phase 3, Bureau of Meteorology and CSIRO, 2009.*

**Comment 5:** When the land transformed from native to crop or grass, it changes the crop factors. How do crop factors come in to the analysis? According to this paper, ET is portioned based on the crop area ratio in each grid only. In figure 3 (a,b) native vegetation area remains the same from 1970, but why does ET ratio shows increasing trend later part of 2000. Any explanation? Even after reduced water allocation to irrigation, crop cultivation show increasing trend. How is that?

We did not consider crop factors changes in the manuscript because this research was based on modelled data rather than field investigations. As ET and GPP data for the three vegetation types over this period were not available, we used the land use datasets HYDE 3.1 to estimate ET and GPP for each vegetation type by assuming that the three vegetation types shared the ET and GPP by area ratio in each grid. We have discussed the limitations of this study in the Discussion section.

As we have shown in Section 2.1, ecological system evapotranspiration (ET<sub>e</sub>) includes evapotranspiration from precipitation, surface runoff, and groundwater in native vegetation

areas, and societal system evapotranspiration ( $ET_s$ ) comprises evapotranspiration in croplands and grasslands originating from precipitation and irrigation, and water consumed by society. The ET of the societal system from surface water diversion reached a maximum in 2002 and declined after that (Fig. 4 d), and more runoff was left for native vegetation, which contributed to the increasing trend of ET ratio for native vegetation.

**Comment 6:** This modelling does not have any feedback loops. It cannot show how population changes with trends in water use. Many not parameters are not considered in the analysis eg technology development.

Our study aimed to develop the socio-hydrological catchment water balance for allocating water between human society and catchment ecological systems. It described the feedback between human and water both on a yearly basis, and for over a hundred year period.

We agreed that population increase and technology development are two major drivers for the transition of societal systems, which have been widely used in social sciences. We have included these two factors, i.e., population and technological developments as the social drivers in our framework. The analysis and discussion on them were reflected in the whole revised manuscript.

**Comment 7:** Reference: <http://www.abs.gov.au/ausstats/abs@.nsf/mf/4610.0.55.007>  
Kandasamy, J. et al., 2014. Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences*, 18(3), pp.1027–1041.

Thanks. We have referred this paper in our manuscript.

## Responses to major comments of Reviewer #2

**Summary of the paper:** The authors argue that while previous studies have focused on partitioning catchment water balances between ET and runoff – few studies have tried to further partition ET between the component that is beneficial to humans and that which is purely for natural ecosystems. They want to do this for the MDB over a 100 year period. The authors have three pieces of data: 1) Conventional catchment balances from 1900-2010 which give them P, ET, and Runoff. Since non-agricultural water uses are small – they only need to concentrate on Crop ET. 2) They have estimates of GPP (in  $gC/m^2/year$ ) at a coarser scale from 2000-2010 from satellite data. 3) They have area ratios of cropland, grassland and land under native vegetation from 1900-2010. Since historical ET by land use type is not directly observable, but GPP is observable for recent periods, the authors make some assumptions about ET/unit area (I think) for each land use type and then use the relationship between GPP and ET to check if the modelled GPP estimates match those obtained from satellite imagery.

**Comment 1:** The objective of this paper seems to be to partition ET into human and ecological ET. The authors conclude that humans have been capturing a greater and greater share of ET over time until recently, when this trend has begun to reverse. Questions about whether humans are capturing too much have been raised by many previous scholars – particularly ecologists who asked what fraction of primary production was being captured by humans (see work by Stuart Pimm, Peter Vitousek in the 1990s). In the ecologists' case they were concerned by how much was left for other species and the implications for the earth's carrying capacity. In this paper, my concern is that it's not clear to me why this analysis is interesting and what the

analysis contributes beyond what we already know from the land ratios. Initially, I thought that perhaps the ET ratios would turn out to be wildly different from the land ratios (which would be interesting). But Figure 3 and Figure 4 suggest that both the ET and GPP more or less follow the land area ratios.

This study aims to develop a simple socio-hydrological water balance framework for allocating water between human society and the environment to support sustainable water management of catchments. In this framework, water use is partitioned into use for societal systems and use for ecological systems, instead of conventional catchment water balance in which precipitation is partitioned into runoff and ET. The framework shifts the understanding of catchment water balance from between human water demand and water supply to between human water use and ecological water use. Furthermore, it establishes linkages between the drivers causing changes in socio-hydrological water balance and the resulting consequences for catchment societal-ecological systems. The proposed socio-hydrological water balance could serve as the theoretical foundation for maintaining dynamic balance between the societal and ecological systems within a catchment.

Yes, both ET and GPP more or less follow the land area ratios. This happens because the MDB lies in the semi-arid region where about 95% of precipitation was consumed as evapotranspiration. The irrigated area only accounts for 2% of the total land area and the crop pattern is relatively uniform. However, it would be different in the cases where there are diverse crop patterns.

**Comment 2:** The authors argue in several places that there is some kind of an “ideal” ET ratio. I find this unconvincing. Most decisions about how much water to leave for environmental uses are made with the objective of sustaining either biodiversity or ecosystem services. To justify this analysis – the authors would need to make the case that the ET ratio is a magical number that is not perfectly correlated with simpler, easily available indices like land area ratio AND yet it is also correlated to something societies care about. The paper does not make the case for an ET-ratio being relevant well.

Thanks for this comment. What we meant in our manuscript was that it is hoped that an ideal ratio of ET between societal and ecological systems should be determined for each river basin which would be extremely useful to provide the basis for integrated land and water management at river basins in a sustainable way, for example, to support decisions with the objective of sustaining either biodiversity or ecosystem services. But we agree that this is not a realistic goal. We have deleted the discussion of the “ideal ratio” and Figure 6 to avoid confusion.

**Comment 3:** In the particular case of MDB, as I understand it, the ecological concerns that drove the buybacks of irrigation water rights, were over freshwater ecological flows (the blue water or runoff component which the paper does not address) and not diminishing area under native vegetation (the green water component this paper does discuss). So an interesting insight that could come out of this analysis – for MDB at least – is the opposite of what the authors are arguing. It seems to me from the analysis presented, converting the land from cropland to native vegetation may not generate much additional stream flow at all because natural vegetation transpires up as much as cropland. This contradicts what I understood from other papers on the MDB, that stream flow has in fact slightly increased a bit after restoration efforts. So native vegetation must be transpiring less water than irrigated cropland. However, this doesn't emerge from this analysis because the ET ratios track the land ratios so closely. But perhaps the authors are finding that land conversions to natural vegetation result in less streamflow than expected because their ET has not been accounted for? This cannot be discerned from the paper as such

- but this seems worth exploring further. Would have been good to see just the three ET values for cropland, grassland and native vegetation - but this was never clearly presented anywhere. It cannot be read off Figure 2, as effects of the restoration phase comes at the very end of the time-series. Figure 3 only displays the ratios and not the absolute numbers.

We considered the whole MDB as the study area. In the socio-hydrological water balance, R was the outflow into the sea rather than runoff in the conventional water balance, and the environmental flows was considered as ET transformed from runoff in the ecological system, so was water diversion in the societal system. So the blue water, i.e., runoff within the catchment has been considered as environmental flows and water diversion which was finally transformed into ET, and the remaining runoff was outflow into the sea.

We agree that land use and hydrology are inextricably entwined in water catchments. A number of catchment deforestation studies indicate that catchment runoff is obviously increased after deforestation (e.g. Piao et al., 2007; Gallant and Gergis, 2011). Increasing cropping areas in the MDB since 1900 may has increased catchment runoff as a result of reducing native vegetative systems. The increased runoff, through water diversion, was then used for increasing irrigated cropping areas. Therefore, deforestation and water diversion have aggregated negative impacts on catchment ecosystems. We could not explain the interaction between them in a detailed way, but we argue in our Discussion section that while the research on the impact of these two interactive human activities on the catchment water cycle should be strengthened, without any doubts, more research should focus on their interactions.

We also discussed about implications of current policy of buybacks of irrigation water rights in the Discussion section according to our research findings. They are *“Increasing concern for the ecological quality of the MDB has brought about a series of initiatives of purchasing water from irrigators for environmental purposed. For example, the target for surface water recovery for the environment under the Basin Plan is 2750 gicalitres, of which 1500 gicalitres was planned to be obtained through surface water buybacks. These water volumes correspond with less than of the whole catchment ET and may improve the riverine ecological systems to some extent, but they have very little influence on catchment native vegetation systems. Therefore only integrated land and water management could address ecological degradation at both riverine and catchment levels. The socio-hydrological water balance framework developed in this study provides new understandings of the water and land dynamics at catchments”*.

Thanks for these extremely valuable comments which greatly help us to improve the quality of our manuscript. Since we could not obtain observed ET data for the three vegetation types for over a hundred year period in the MDB, the modelled water balance and interpolated land use data were used to partition ET based on the assumption that these three vegetation types shared the ET in each grid according to their area ratios. This method led to the results that the ET ratios followed the land ratios closely. The limitations of the data and methods of this study were discussed in the Discussion section.

In the original manuscript, we used the ET values in Figure 2, and used the ET ratio in Figure 3 because the ratio can better express the large inter-annual change of rainfall in the MDB. We have included another sub-figure, i.e., Figure 3(a) about the ET values for the three vegetation types in the revised manuscript.

*Piao, S., P. Friedlingstein, P. Ciais, N. de Noblet-Ducoudré, D. Labat, and S. Zaehle (2007), Changes in climate and land use have a larger direct impact than rising CO<sub>2</sub> on global river runoff trends, Proc. Natl. Acad. Sci. U. S. A., 104(39), 15242-15247.*

*Grantham T. E. , Mezzatesta M. , Newburn D. A., M. A. M.: Evaluating tradeoffs between environmental flow protections and agricultural water security, River Res. Appl., 30(3), 315–328, doi:10.1002/rra, 2014.*

**Comment 4:** I also had a lot of difficulty understanding the paper. The data used come in after the methods – so it’s not easy to infer that the methods are driven by the particular data sets available. As I understand it, the whole GPP thing was only brought in because that GPP is the only variable for which data are available to cross-check ET estimates. But unfortunately – this is never made clear in the paper and it took me a while to understand that the “optimization” was just a calibration of some sort. I am not familiar with this GPP dataset – so I did not delve into the technicalities and uncertainties of this analysis and cannot comment if the results are driven by the peculiarities of that dataset and the GPP-ET function chosen.

Thanks for this comment. We have rearranged the manuscript considering this comment and the comment 8 from the third reviewer. The socio-hydrological water balance framework was proposed in Section 2, followed by Section 3: Application of the socio-hydrological water balance framework in the Murray-Darling Basin in which the study area, data and methods are included.

The MODIS GPP (2000-2010) was considered as the observed GPP to validate the estimated GPP (1900-2010) using the optimization method, and the estimated GPP were used to analyze the impacts of water allocation on the societal system and ecological system at water catchments.

**Comment 5:** The authors seem to hint at an ideal ratio of ET for humans versus ET for ecosystems – e.g. Line 17 of Section 1 “there are no clearly defined theoretical guide- lines for water allocation between humans and the environment”. As I said earlier, I am not sure why there should be theoretical guidelines at the basin scale. E.g. It may be perfectly OK to have millions of acres of corn fields in Iowa, if biodiversity rich hotspots are protected in the Amazon – why should every basin aim for a specific mix of natural vegetation and cropland?

We agree. What we meant in our manuscript was that it is hoped that an ideal ratio of ET between societal systems and ecological systems should be determined for each river basin which would be extremely useful to provide the basis for integrated land and water management at river basins in a sustainable way, for example, to support decisions with the objective of sustaining either biodiversity or ecosystem services. But we agree that this is not a realistic goal. We have deleted the discussion of the “ideal ratio” and Figure 6 to avoid confusion.

**Comment 6:** There seem to be inconsistencies between the text and the equations. The whole introduction of WUE into the equations seems strange to me, but perhaps it is just not explained well. On line 12 in Section 2.3, the authors say there is a “linear relationship between GPP and ET at a regional scale”. However, eq. 8 ultimately implies a non-linear relationship between GPP and ET.

Thanks. The WUE was defined as the ratio of GPP over ET, and the linear relationship between GPP and ET was assumed in order to estimate annual GPP using a constant WUE at a regional scale (Beer et al., 2007). However, a linear relationship is not the best expression which has been evaluated in many studies (Zhou et al., 2014). 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 is limited by other controlling factors, such as energy and nutrient. We have added several sentences to make this issue clearer in the revised manuscript.

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

*Zhou, S., Yu, B., Huang, Y., and Wang, G.: The effect of vapor pressure deficit on water use efficiency at the subdaily timescale, Geophys. Res. Lett., 41, 5005–5013, doi:10.1002/2014GL060741, 2014.*

**Comment 7:** I am not sure why the Area Ratio suddenly appears in the denominator in eq. 10.

Thanks for this comment. In the manuscript, “We supposed that WUE is negatively correlated to ET per unit area because of diminishing marginal WUE (Eq. 6)”. Since the unit for ET is  $\text{mm yr}^{-1}$  in the manuscript, ET per unit area is equal to ET ( $\text{mm yr}^{-1}$ ) per unit area ratio, and the area ratio is the same for the whole catchment, thus we omitted it directly. We have added some explanations to avoid confusion in the revised manuscript.

**Comment 8:** There were a few minor typos - Line 29 in Section 4 - pursuit should be pursuit.

Thanks. We have changed them in our revised manuscript.

### Responses to major comments of Reviewer #3

**General Comments:** Overall quality of the paper is moderate. The topic of water allocation for ecosystem services is highly relevant to the scope of HESS; the Murray-Darling basin an appropriate case study. The authors’ technique in modifying a tested hydrologic tool and applying it to evaluate ecosystem water needs is original and thought provoking. However, the authors place unbalanced focus on terrestrial portions of the river basin, neglecting water needs of the rivers themselves. Structuring of the water balance retains a fundamental flaw in human thinking about ecosystem needs for water. In the authors’ rendering of water accounting, all water needs are accounted for, leaving aquatic ecosystem requirements as a “whatever is left” term. This conceptualization supports outdated and disregarded ideas that water flowing in the river to the sea is ‘wasted’ or that human uses of water may continue unabated until all flows appropriated. The authors thus demonstrate little understanding of ecosystem services provided by aquatic ecosystems and the role of flow regime in aquatic ecosystem function, both of which should ideally be addressed in their framework. The partitioning of ET into agriculture, pasture, and native vegetation is interesting, however it is unclear what the analysis of ecological vs. societal ET/GPP provides that a land use analysis could not have provided. The key messages/contribution of the paper could be more effectively packaged by restructuring the paper slightly. The language and grammar are largely comprehensible, however, many errors in tense and syntax exist. Thorough copy-editing by a native speaker is necessary to eliminate all such errors.

We really appreciate this reviewer’s very valuable and constructive advice on our manuscript. It will greatly help us to improve the quality of our manuscript. As these general comments are reflected in the following specific comments, we will address them as follows:

**Comment 1:** Abstract must clarify that the four time periods of the MDB case study are obtained through the recast water balance and are an analytical outcome of the paper. As it reads now, it is understood that the authors divided time according to basin management and analyzed each period.

We agree. We have revised the sentence about the four time periods in our revised paragraph according to the reviewer's advice.

**Comment 2 :** Description of results and significance is lacking in abstract. For example, “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.” Specifically, which new understandings came from the analysis? What experiences and lessons were elucidated?

We fully agree. We have revised several sentences in the abstract to explain our new understanding of catchment water balance and the experiences and lessons for future catchment management that were obtained from our findings.

This study aims to develop a simple socio-hydrological water balance framework for allocating water between human society and the environment to support sustainable water management of catchments. In this framework, water use is partitioned into use for societal systems and use for ecological systems, instead of conventional catchment water balance in which precipitation is partitioned into runoff and ET. The framework shifts the understanding of catchment water balance from between human water demand and water supply to between human water use and ecological water use. Furthermore, it establishes linkages between the drivers causing changes in socio-hydrological water balance and the resulting consequences for catchment societal-ecological systems. The proposed socio-hydrological water balance could serve as the theoretical foundation for maintaining dynamic balance between the societal and ecological systems within a catchment.

**Comment 3:** Rather than repeatedly framing the technique as the “recast water balance”, it may be more effective to give the technique a more descriptive name. For instance the “socio-hydrology water balance” or the “human-ecosystems water balance”? Something that others could refer to in their future work. This new nomenclature should appear in the title.

Thanks for the reviewer's very valuable idea on improving our manuscript. We have used “socio-hydrological water balance” as a new nomenclature in our revised title.

**Comment 4:** Introduction needs more specific information about why the traditional water balance approach cannot support sharing of water between societal and ecosystem needs. What specifically are the shortcomings?

We had added more detailed description on why the traditional water balance approach cannot support water allocation between societal and ecosystem needs as suggested by the reviewer.

**Comment 5:** Needs mention of ecosystem services related to freshwater. How specifically is the traditional water-balance able/not able to support ecosystem services?

We agree. We have added a sentence about the lack of ecosystem services in conventional water balance in the introduction.

**Comment 6:** Discussion of IRBM needs updating. If there is a reason the authors choose to retain focus to IRBM it should be stated, with discussion of how IWRM and IRBM are compatible/different.

We agree. IRBM is IWRM at catchment (river basin) scale. Based on other comments, we have taken all discussion on IRBM or IWRM out of the revised manuscript.

**Comment 7:** Objective statement (lines C25822-23, pg. 914), specifically how will this study advance socio-hydrology?



This study aims to develop a simple socio-hydrological water balance framework for allocating water between human society and the environment to support sustainable water management of catchments. In this framework, water use is partitioned into use for societal systems and use for ecological systems, instead of conventional catchment water balance in which precipitation is partitioned into runoff and ET. The framework shifts the understanding of catchment water balance from between human water demand and water supply to between human water use and ecological water use. Furthermore, it establishes linkages between the drivers causing changes in socio-hydrological water balance and the resulting consequences for catchment societal-ecological systems. The proposed socio-hydrological water balance could serve as the theoretical foundation for maintaining dynamic balance between the societal and ecological systems within a catchment.

**Comment 8:** The paper could be more effective with a few simple restructures. I suggest describing theory first, followed by a case study example. First outline segregation of the water balance, moving description of the MDB to later in the paper.

We agree. We have restructured our manuscript as the reviewer suggested. Specifically, the socio-hydrological water balance framework was proposed in Section 2, followed by Section 3: application of the socio-hydrological water balance framework in the Murray-Darling Basin in which the study area, data and methods are included.

**Comment 9:** The authors' water balance does not account for reservoir storage.  $dS/dt$  is defined solely as soil water storage. This is valid in natural river basins, but as the authors' proposal is of the most utility in regulated basins, they should perhaps propose a term for surface storage, particularly to make their model more applicable to sub-annual analyses. Same comment could be made for storage in snowpack.

We agree. We have defined that  $dS/dt$  is the change in soil and surface (reservoir) water storage. The surface (reservoir) storage was used for water diversion and was consumed as societal system evapotranspiration by croplands and grasslands in this paper since this research was at the year scale. Thus, we neglected the change in reservoir storage in this study.

**Comment 10:** Some terms in classified as ET in the proposed water balance are not intuitive and need further explanation, for instance  $ET_H$ . Why is water used for households classified as ET?

We agree.  $ET_H$  and  $ET_{oth}$  referred to water consumed by society, namely water use for households and other industries, respectively. We name them as  $ET_H$  and  $ET_{oth}$  although not intuitive, for the consistent expression of all water use in the form of ET. In MDB,  $ET_H$  and  $ET_{oth}$  only take a very small percentage of total water use, thus they were not included in the major analysis. So these no intuitive terms will not hassle readers too much.

**Comment 11:** The authors claim their proposed water balance is an improved management tool to balance water needs of humans vs. ecosystem needs. However, their structuring of the water balance retains a fundamental flaw in human thinking about ecosystem needs for water. In the authors' rendering of water accounting, all water needs are accounted for, leaving aquatic ecosystem requirements as a "whatever is left" term. Page 917, line 11 ". . .the remaining surface runoff is retained for ecosystem purposes or flows into the sea." This conceptualization supports outdated and disregarded ideas that water flowing in the river to the sea is 'wasted' or that human uses of water may continue unabated until all flows are appropriated. The proposed places unbalanced emphasis on terrestrial water needs while ignoring aquatic needs. The authors thus demonstrate little understanding of ecosystem services provided by aquatic ecosystems and the role of flow regime in aquatic ecosystem function, both of which should ideally be addressed in their framework. To remedy, the authors could define  $R_{out}$  in Eq. 2 as

river runoff. The  $R_{out}$  term can then be unpacked as follows:  $R_{out} = R_e + R_{oth}$  Where  $R_e$  is a term for ecological river flows and  $R_{oth}$  is what remains after ecosystem needs and human needs have been accounted for. Rather than explaining  $R_e$  as runoff to the sea, suggesting it holds little or no benefit to the river basin, the authors may state that this quantity must be maintained at specified values through the water year to support ecosystem services in quantities determined through environmental flows assessment in accordance with the natural flow regime of the river basin.

Thanks for this very valuable critique. We fully agree that the role of flow regime in aquatic ecosystem function should be addressed in the framework. Due to the data limitations, in this proposed socio-hydrological water balance framework, ecological system evapotranspiration includes evapotranspiration from precipitation, surface runoff, and groundwater in native vegetation areas. Water consumed in aquatic ecosystems to support ecosystem services was considered a part of the evapotranspiration from surface runoff. However we have been aware that, in addition to GPP of native vegetation systems, the size and quality of inland wetlands and riverine ecosystems and aquatic ecosystems should be considered to assess the impacts of water allocation on catchment ecosystems. These limitations of this study have been explained in the Discussion section.

**Comment 12:** Figures 3a and b are redundant.

We agree. We have deleted Figures 3a and 3b in our revised manuscript.

**Comment 13:** Figure 3d- label reservoir storage to avoid confusion with soil storage. See comment 8 above.

Thanks for this comment. We have deleted Figure 3d and changed the label to “reservoir storage capacity” in Figure 4 as suggested by the reviewer in our revised manuscript.

**Comment 14:** What does the analysis of ecological vs. societal ET/GPP provide that a land use analysis could not have provided? What is the additional information provided in the water balance approach?

Thanks for these good questions that help us to sharpen our discussion in our revised manuscript. The analysis of ecological vs. societal ET/GPP which integrates the land and water analysis in the river basin can reveal the interactive impact of land and water use which neither land use analysis nor the water balance approach could provide. We have added Figures 3a and 3b to provide the trends of ET and GPP values from 1900 to 2010 in the revised manuscript.

**Comment 15:** The authors may strengthen their claim that the proposed water balance may be a tool for future sustainable water management in basins by suggesting how managers may approach determining acceptable thresholds/balance between ecological and societal water needs. This may be sourced from prior ecological study indicating thresholds or tipping points in land conversion or water abstraction and ecosystem quality.

Thanks for this valuable advice. According to other reviewers’ comments, we have restructured our manuscript and removed the discussion on “a tool for future sustainable water management in basins by suggesting how managers may approach determining acceptable thresholds/balance between ecological and societal water needs” from our revised manuscript.

**Comment 16:** There are many grammatical errors, in tense and syntax. Thorough copy-editing by a native speaker is necessary to eliminate all such errors.

We apologize for this. We have invited a land and water scientist who is a native English speaker to edit the revised manuscript.

**Comment 17:** Figure 2a and b: lines are difficult to distinguish, esp.  $R_{out}$ ,  $G$ , and  $dS/dt$ .

Moving the x-axis labels lower and using more distinct colors will help.

We agree. We have revised Figure 2 according to the reviewer's advice.

**Comment 18:** There is much redundant information in figures. Figure 5 summarizes much information from Figures 3 and 4.

We agree. We have revised Figures 3, 4 and 5 as suggested in our revised manuscript.

1 ~~Recasting catchment water balance for water allocation~~  
2 ~~between human and environmental purposes~~

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

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## 1 Abstract

2 Rebalancing water allocation between human consumptive uses and the environment in water  
3 catchments is a global challenge. ~~The conventional water balance approach which partitions~~  
4 ~~precipitation into evapotranspiration (ET) and surface runoff supports the optimization of water~~  
5 ~~allocations among different human water use sectors under the cap of water supply. However,~~  
6 ~~this approach is unable to support the emerging water management priority issue of allocating~~  
7 ~~water between societal and ecological systems. This paper proposes a socio-hydrological water~~  
8 ~~balance framework by partitioning catchment total ET into ET for society and ET for natural~~  
9 ~~ecological systems, and establishing the linkage between the changes of water balance and its~~  
10 ~~social drivers and resulting environmental consequences in the Murray-Darling Basin (MDB),~~  
11 ~~Australia, over the period 1900-2010, recast the catchment water balance by partitioning~~  
12 ~~catchment total ET into ET for the societal and ET for the natural ecological systems, and~~  
13 ~~estimated the impacts of water allocation on the two systems in terms of gross primary~~  
14 ~~productivity (GPP), in the Murray Darling Basin (MDB) of Australia over the period 1900-~~  
15 ~~2010. With the recast water balance, the more than 100-year water management in the MDB~~  
16 ~~was divided into four periods corresponding to major changes in basin management. The results~~  
17 ~~show that the more than 100-year period of water management in the MDB could be divided~~  
18 ~~into four periods corresponding to major changes in basin management within the socio-~~  
19 ~~hydrological water balance framework: period 1 (1900-1956) expansion of water and land use~~  
20 ~~for by the societal system, period 2 (1956-1978/1985) maximization of water and land use for by~~  
21 ~~the societal system, period 3 (1985/1978-2002) maximization of water use for the societal~~  
22 ~~system from water diversion for the societal system, and period 4 (2002-present) rebalancing~~  
23 ~~of water and land use between the societal and ecological systems. Most of management~~  
24 ~~changes in the MDB were passive and responsive. A precautionary approach to water allocation~~  
25 ~~between societal and ecological systems should be developed. The socio-hydrological water~~  
26 ~~balance framework could serve as a theoretical foundation for water allocation to evaluate the~~  
27 ~~dynamic balance between the societal and ecological systems in catchments. The recast water~~  
28 ~~balance provided new understandings of the water and land dynamics between societal and~~  
29 ~~ecological systems in the MDB, and it highlighted the experiences and lessons of catchment~~  
30 ~~water management in the MDB over the last more than 100 years. The recast water balance~~  
31 ~~could serve as the theoretical foundation for water allocation to keep a dynamic balance~~  
32 ~~between the societal and ecological systems within a basin for sustainable catchment~~  
33 ~~development. It provides a new approach to advance the discipline of socio-hydrology.~~

带格式的：定义网格后不调整右缩进，无孤行控制，不调整西文与中文之间的空格，不调整中文和数字之间的空格

## 1 Introduction

Human ~~overuse of water resources~~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 ~~for those subject to under~~ changing climate and socio-economic development (Falkenmark, 2003; Grantham et al., 2014). Future human wellbeing may be seriously compromised if we pass a critical threshold that tips catchment ecological systems from stable conditions.

~~In the past centuries, In recent centuries~~ catchment water management has sought the optimization of water balance for human consumptive demands and to secure water supplies ~~and~~to meet the increasing needs of human socio-economic development. This catchment water management paradigm has been supported by hydrological science which has ~~improved~~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 Musiak, 1995). It has been a useful tool for water planners and managers to ~~maximize human water uses under the constraints of water extraction capacity. However, it gives little attention to the water demand for catchment ecosystems and to water sharing between the societal and ecological systems of water catchments.~~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~~The water balance approach worked very well when humankind's water development capacity ~~was very limited and human water consumption volumes took up small percentages of the total available water of catchments, and water consumption volumes, were far smaller than the cap of the human water use.~~ However, when human water demand increases dramatically, ~~and exceed a certain level at which catchment ecosystems are increasingly degraded, the conventional water balance approach is unable to support emerging water management issues such as allocating water between the society and the environment 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).

1 ~~Integrated river basin management (IRBM) has been widely promoted by both water academics~~  
2 ~~and practitioners since the 1980s and has become a mainstream water management strategy~~  
3 ~~(Downs et al., 1991; Mitchell, 1990; Pahl-Wostl and Hare, 2004; Zakaria, 2004). It is defined~~  
4 ~~as “the process of coordinating conservation, management and development of water, land and~~  
5 ~~related resources across sectors within a given river basin, in order to maximise the economic~~  
6 ~~and social benefits derived from water resources in an equitable manner while preserving and,~~  
7 ~~where necessary, restoring freshwater ecosystems” (GWP, 2000). Despite its popularity the~~  
8 ~~definition of IRBM continues to be broad and vague, and the theoretical framework~~  
9 ~~underpinning IRBM, e.g. how water and land should be integrated in catchments, is far from a~~  
10 ~~practical guide for its application (Biswas, 2004; Hering and Ingold, 2012).~~

11 There have been several attempts at exploring human-water systems with the co-evolutionary  
12 approach (Geels, 2005; Kallis, 2011; Pataki et al. 2011). All these studies used ‘thick  
13 description’ rather than explanatory approaches and therefore are unable to provide quantitative  
14 bases for water allocation between the society and environment. Socio-hydrology is emerging  
15 as a new discipline aimed at understanding the co-evolutionary dynamics of human-water  
16 systems to underpin sustainable water management (Sivapalan et al., 2012). From its very  
17 beginning it was argued that socio-hydrology must be a quantitative science. Since 2012  
18 increasing numbers of studies in social-hydrology have been reported in several case study  
19 areas, such as the Tarim River Basin and Heihe River Basin in western China and the  
20 Murrumbidgee River Basin in eastern Australia ( Di Baldassarre et al. 2013; Srinivasan, 2013;  
21 Elshafei et al., 2014; van Emmerik et al., 2014; Kandasamy et al., 2014; Liu et al., 2014; Lu et  
22 al 2015). Kandasamy et al. (2014) traced the history of the Murrumbidgee catchment, an  
23 agricultural water catchment in the Murray Darling River Basin, Australia, and found a swing  
24 phenomenon of water sharing between agricultural water use and riverine environments.  
25 Elshafei et al. (2014) in the same catchment developed a prototype framework for socio-  
26 hydrological modelling to identify key feedback loops between the human-water relationship  
27 by specifying six key functional components including catchment hydrology, population,  
28 economics, environment, socioeconomic sensitivity and collective response. This framework  
29 combined the strengths of previous attempts with rich descriptions of the human-water  
30 coevolution and formal hydrological modelling. However, the modelled results did not correlate  
31 well with observed irrigation areas. In addition, although it was already a necessary  
32 simplification of an extremely complex coupled system, this framework is still too complex for  
33 water catchment managers to use. Lu et al. (2015) quantitatively analyzed the evolution of

1 human–water relationships in the Heihe River Basin of northern China over the past 2000 years  
2 by reconstructing the historical catchment water balance by partitioning precipitation into  
3 evapotranspiration and runoff. Their study analyzed the impacts of societies on hydrological  
4 systems but did not explicitly link the water balance to its drivers. While these studies have  
5 made great contributions to observing, understanding and predicting human-water cycle  
6 dynamics in catchments there are still no clear analytical or empirical frameworks for water  
7 allocation between human use and the environment.

8 ~~While these studies have made great contributions to observing, understanding and predicting~~  
9 ~~water cycle dynamics in catchments, there are no clearly defined theoretical guidelines for water~~  
10 ~~allocation between human and the environment.~~

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

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

## 26 **2 A simple conceptual framework for socio-hydrological water balance**

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



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

## 7 **2.1 Describing the socio-hydrological water balance**

8 The conventional water balance, derived from the principle of conservation of mass, provides  
9 an effective framework for studying hydrological cycles and evaluating the hydrological  
10 response of a catchment to climate and land use changes (Oki and Musiake, 1995; Zhang et al.,  
11 2001, 2004). It is described by the equation:

$$12 \quad P = ET + R + G + dS/dt \quad (1)$$

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

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

$$25 \quad P = ET_s + ET_e + R_{out} + dG/dt + dS/dt \quad (2)$$

$$26 \quad ET_e = ET_{eP} + ET_{eR} + ET_{eG} \quad (3)$$

$$27 \quad ET_s = ET_{aP} + ET_{aI} + ET_H + ET_{oth} \quad (4)$$

$$28 \quad D_R + D_G = ET_{aI} + ET_H + ET_{oth} \quad (5)$$

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

## 15 **2.2 Estimating the impact of changes in socio-hydrological water balance on** 16 **societal-ecological systems**

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

## 28 **2.3 Interpreting the evolutionary processes of human–water relationships with** 29 **change of the socio-hydrological water balance, its drivers and resulting** 30 **consequences**

31 We interpret the evolutionary processes of the human–water relationships from the perspective

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

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

### 25 3 Application of the socio-hydrological water balance framework in the 26 Murray-Darling Basin

#### 27 ~~2 Materials and methods~~

##### 28 2.13.1 Study area

29 The Murray-Darling Basin (MDB), located in southeast Australia, is the largest river system in  
30 Australia. It is about 1 million km<sup>2</sup>, covering three-quarters of New South Wales, more than  
31 half of Victoria, all of the Australian Capital Territory, and significant portions of Queensland

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

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

## 25 **2.2—Recasting catchment water balance**

26 ~~The conventional water balance, derived from the principle of conservation of mass, provides~~  
27 ~~an effective framework for studying hydrological cycles and evaluating the hydrological~~  
28 ~~response of a catchment to climate and land use changes (Oki and Musiak, 1995; Zhang et al.,~~  
29 ~~2001, 2004). It is described by the equation~~

$$30 \quad P = ET + R + G + dS/dt \quad (1)$$

1 where,  $P$ ,  $ET$ ,  $R$ ,  $G$  and  $dS/dt$  are precipitation, evapotranspiration, surface runoff, recharge to  
 2 groundwater, and the change in soil water storage, respectively. They are the basic elements of  
 3 catchment water balance. Eq. (1) has been commonly applied in the partitioning of precipitation  
 4 into evapotranspiration and surface runoff in catchment water resources planning and  
 5 management for balancing water supply and water demand by society. However, it has not been  
 6 applied to partition precipitation into water use by societal and environmental purposes. Here,  
 7 we recast the conventional catchment water balance to seek the balance of water allocation  
 8 between societal and ecological systems within a water catchment. The new catchment water  
 9 balance is expressed as follows:

$$10 \quad P = ET_s + ET_e + R_{out} + dG/dt + dS/dt \quad (2)$$

$$11 \quad ET_e = ET_{ep} + ET_{er} + ET_{eg} \quad (3)$$

$$12 \quad ET_s = ET_{sp} + ET_{sr} + ET_{sh} + ET_{stn} \quad (4)$$

$$13 \quad D_R + D_G = ET_{sp} + ET_{sh} + ET_{stn} \quad (5)$$

14 where,  $P$  and  $dS/dt$  are the same as those in Eq. (1),  $ET_s$  and  $ET_e$  are the evapotranspiration from  
 15 the societal and ecological systems, respectively,  $R_{out}$  is the outflow into sea, and  $dG/dt$  is the  
 16 change in groundwater storage. Partitioning of ET into societal and ecological systems is mainly  
 17 determined by land use. The native vegetation areas which maintain ecological function are  
 18 considered as the ecological system. Ecological system evapotranspiration ( $ET_e$ ) includes  
 19 evapotranspiration from precipitation, surface runoff, and groundwater in native vegetation  
 20 areas, expressed as  $ET_{ep}$ ,  $ET_{er}$  and  $ET_{eg}$ , respectively. Societal system evapotranspiration ( $ET_s$ )  
 21 comprises evapotranspiration in croplands and grasslands coming from precipitation ( $ET_{sp}$ ) and  
 22 irrigation ( $ET_{sr}$ ), and water directly consumed by society, namely water use for households  
 23 ( $ET_{sh}$ ) and other industries ( $ET_{stn}$ ). Water diversions from surface runoff ( $D_R$ ) and groundwater  
 24 ( $D_G$ ) serve irrigation in croplands and grasslands and water use in society, the remaining surface  
 25 runoff is used for ecological purposes or flows into the sea ( $R_{out}$ ).

26 The annual ET from precipitation for the croplands, grasslands and native vegetation areas were  
 27 partitioned into three parts by multiplying the average ET by the area ratios of the three land  
 28 use types for each grid, and then aggregating the separated ET of all the grids in the MDB,  
 29 respectively, using the annual datasets of water balance and land use at a spatial resolution of  
 30  $0.05^\circ$  in the remote sensing images. The water diversion was divided into four parts, including  
 31 ET from irrigation in croplands and grasslands, for households and other industries. Water uses

1 ~~by the households and other industries were assumed to be proportional to population, and the~~  
2 ~~ratios were set to be 0.078 and 0.153, respectively, according to the water account data (ABS,~~  
3 ~~2014a). The remaining water diversion was used for irrigation, with a ratio of 4:1 between~~  
4 ~~croplands and grasslands, according to the water use data on Australian farms (ABS, 2014b).~~

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

### 9 **3.2 Data sources and processing**

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

22 The annual GPP in  $\text{g C m}^{-2} \text{yr}^{-1}$  of the MDB from 2000 to 2010 were summed from the monthly  
23 GPP data provided by the Numerical Terradynamic Simulation Group, University of Montana.  
24 This group processed the Gross Primary Production (GPP) product “MOD17A2” (2000-2010)  
25 from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 8-day intervals, with 1  
26 km spatial resolution and a monthly time series of GPP at a resolution of  $0.05^\circ$ . These data were  
27 considered as the observed GPP in this study.

28 The land use data are very important for the analysis in this study. As ET and GPP data for each  
29 of the three vegetation types over the last century were not available, we used the land use  
30 datasets, i.e., the History Database of the Global Environment (HYDE 3.1 version) to estimate  
31 ET and GPP for each vegetation type. HYDE 3.1 provides long-term estimates of global human

1 population and built-up areas (croplands and grasslands used for livestock) at a spatial  
2 resolution of 5' since the Holocene (10000BC to AD 2000) (Klein Goldewijk et al., 2011). The  
3 database of population, croplands and grasslands area is available every 10 years from 1900 to  
4 2000, and for 2005. The annual changes in land use were normally small so the annual datasets  
5 at a resolution of 0.05 °of the population and the area ratios of croplands, grasslands and native  
6 vegetation areas in the MDB from 1900 to 2010 were obtained from HYDE version 3.1 with  
7 resampling and linear interpolation in ArcGIS. This is reasonable for the purposes of this study.  
8 We did not consider crop factors changes because this research is based on modelled data rather  
9 than field investigations.

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

### 14 **3.3 Describing the socio-hydrological water balance in the MDB**

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

24 The annual ET from runoff referred to water diversion in the societal system and environmental  
25 flows in the ecological systems. The data for water diversions were divided into four parts,  
26 including ET from irrigation in croplands and grasslands, for households and industries. Water  
27 use by households and other industries were assumed to be proportional to population, and the  
28 ratios were set to be 0.078 and 0.153, respectively, according to the water account data (ABS,  
29 2014a). The remaining water diversion was ascribed to irrigation, with a ratio of 4:1 between  
30 croplands and grasslands, according to water use data of Australian farms (ABS, 2014b). The

1 environmental flows were calculated as the water remaining after surface runoff was subtracted  
2 from surface water diversion and outflows into the sea.  
3 In the MDB groundwater diversion and evapotranspiration from groundwater for native  
4 vegetation are generally small compared to other elements and were not considered. Therefore,  
5 groundwater recharge and changes in soil water storage were the same as those in the  
6 conventional water balance.

#### 7 **2.33.4 Estimating the impact of water allocation on the societal system and** 8 **ecological system in water catchments**

9 The impacted sectors of water allocation on the societal and ecological systems in the MDB  
10 include native vegetation system, croplands, grasslands, ~~the~~ households, and ~~other~~ industries.  
11 As the water consumption from the last two items was less than 1% of the total in the MDB,  
12 we focused on the impact of water allocation on native vegetation system, croplands and  
13 grasslands. We used the gross primary productivity (GPP), the total energy assimilated from  
14 these three systems, to measure the impacts of water allocation on them. Water use efficiency  
15 (WUE), defined here as the ratio of carbon gain to water loss in terrestrial ecosystems ~~was,~~  
16 ~~has~~ ~~been~~ used to estimate annual GPP because of the linear relationship between GPP and ET at a  
17 regional scale (Beer et al., 2007). However, a linear relationship between GPP and ET was not  
18 the best expression, as evaluated in many studies (Zhou et al., 2014b). In order to improve the  
19 estimation of GPP we assumed that WUE is negatively correlated to ET per unit area because  
20 of diminishing marginal WUE when GPP was limited by other controlling factors, such as solar  
21 radiation and nutrients (Eq. 6). ~~WUE was calculated as the ratio of GPP over ET, and was~~  
22 ~~assumed to be constant in a certain region (Yang et al., 2013). We supposed that WUE is~~  
23 ~~negatively correlated to ET per unit area because of diminishing marginal WUE (Eq. 6).~~ The  
24 relationship between GPP and ET could be expressed ~~with~~ ~~by~~ a quadratic function which passes  
25 the origin (0, 0). The relationship between annual GPP and ET is given in Eq. (7).

$$26 \quad WUE_t = a \cdot ET_t + b \quad (6)$$

$$27 \quad GPP_t = WUE_t \cdot ET_t = a \cdot ET_t^2 + bET_t \quad (7)$$

28 where  $ET_t$  is the total ET per unit area in  $\text{mm yr}^{-1}$  (~~short for  $\text{mm H}_2\text{O m}^{-2} \text{yr}^{-1}$~~ ) for croplands,  
29 ~~grasslands and native vegetation areas~~,  $GPP_t$  is the total GPP in  $\text{g C m}^{-2} \text{yr}^{-1}$ , and  $WUE_t$  is the  
30 water use efficiency in  $\text{g C/mm}$  water  $\text{H}_2\text{O}$  for all the vegetation types. The parameters  $a$  and  $b$ ,



1 were determined with the observed GPP from 2000 to 2010 when data were available, and the  
 2 result with a correlation coefficient of 0.99 was given as follows:

$$3 \quad GPP_t = -9.9455 \times 10^{-4} \cdot ET_t^2 + 1.8718ET_t \quad (8)$$

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

$$10 \quad F = \min \sqrt{\frac{\sum_{n=1900}^{2010} (GPP_{tn} - \sum_{i=1}^3 GPP_{in})^2}{111}} \quad (9)$$

11 where

$$12 \quad WUE_{in} = a_i \cdot \frac{ET_{in}}{AR_{in}} + b_i \quad (10)$$

$$13 \quad GPP_{in} = WUE_{in} \cdot ET_{in} = a_i \cdot \frac{ET_{in}^2}{AR_{in}} + b_i ET_{in} \quad (11)$$

14 where i refers to crop (i=1), grass (i=2) and native vegetation (i=3), respectively, and n is the  
 15 year from 1900 to 2010. Since the unit for ET is mm yr<sup>-1</sup> in this study, AR<sub>in</sub>, i.e., the area ratio  
 16 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  
 17 from Eq. (6) because it equals to 1 for the whole basin. AR<sub>in</sub> is the area ratio and  $\frac{ET_{in}}{AR_{in}}$  is the ET  
 18 per unit area of the vegetation i at the year n. The parameters a<sub>i</sub> and b<sub>i</sub>, were calibrated according  
 19 to Eq. (9) using the data from 1900 to 2010. The total GPP and the GPP of each vegetation type  
 20 were hence compared with observed data to verify the effectiveness of the parameters in Eq.  
 21 (11). The observed GPP of the three vegetation types were partitioned using the same method  
 22 as the partitioning of ET from precipitation.

## 23 **2.4—Data sources and processing**

24 ~~The annual water balance elements in mm yr<sup>-1</sup> of the MDB from 1900 to 2010 including~~  
 25 ~~precipitation, evapotranspiration, surface runoff, deep drainage and change in soil water storage~~  
 26 ~~were obtained from the water balance dataset "Run 26j", which was produced by the Australian~~  
 27 ~~Water Availability Project (AWAP). In the AWAP a simple and robust water balance model~~

1 was developed to simulate the terrestrial water balance of the Australian continent with model-  
2 data fusion methods to combine measurements and model predictions (Briggs et al., 2009). The  
3 AWAP achievements include a long-term historical monthly time series of dataset “Run 26j”  
4 (1900 to 2010) of the conventional water balance elements at a spatial resolution of 0.05°.

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

11 The annual datasets at a resolution of 0.05° of the population and the area ratios of croplands,  
12 grasslands and native vegetation areas in the MDB from 1900 to 2010 were obtained from the  
13 History Database of the Global Environment (HYDE 3.1 version) with resampling and linear  
14 interpolation in ArcGIS. HYDE 3.1 provides long-term estimates of global human population  
15 and built-up areas (croplands and grasslands used for livestock) at a spatial resolution of 5' since  
16 the Holocene (10000BC to AD 2000) (Klein Goldewijk et al., 2011). The database of  
17 population, croplands and grasslands area is available every 10 years from 1900 to 2000, and  
18 2005.

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

## 23 **3.4 Results**

### 24 **3.4.1 The recast water balance in the MDB**

25 The changes in the components of elements in the conventional and socio-hydrological recast  
26 water balances in the MDB from 1900 to 2010 are shown in Figs. 2 (a) and (b). The results for  
27 can be seen from the conventional water balance that on average about 95% of precipitation  
28 was consumed as evapotranspiration. The evapotranspiration almost equalled, or even exceeded,  
29 precipitation in drought periods, such as during the Federation Drought (1885-1902), the World  
30 War II Drought (1937-1945) and the Millennium Drought (1997-2009) years, resulting  
31 decreases in surface runoff and soil water storage (Fig. 2 (a)). The conventional water balance

1 ~~reveals the pattern of partitioning precipitation into evapotranspiration and runoff over the years.~~

2 ~~The socio-hydrological~~The ~~recast~~ water balance shows a different perspective (Fig. 2 (b)). It  
3 can be clearly seen that evapotranspiration from societal use ~~increased~~~~kept on increasing~~ and  
4 surpassed that from ecological system after the 1950s. ~~After that time human water use plays a~~  
5 ~~more and more dominant role. The socio-hydrological water balance indicates the co-~~  
6 ~~evolutionary dynamics of water allocation between the societal and ecological systems in the~~  
7 ~~MDB for this one hundred-year period., showing a stark historical trend of the co-evolutionary~~  
8 ~~dynamics between the societal and ecological systems during the history of the MDB for an~~  
9 ~~over one hundred year period. The conventional water balance reveals the pattern of~~  
10 ~~partitioning precipitation into evapotranspiration and runoff over the years, and the recast water~~  
11 ~~balance indicates the dynamics of water allocation between the societal and ecological systems.~~

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

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

### 3.24.2 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. 4 (a). 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 ~~slight a little bit of~~ overestimation of GPP, ~~as shown in Fig. 4 (a).~~

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 (Figs. 3 (b) and (c)). ~~The GPPGPPs~~ 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 m<sup>2</sup> yr<sup>-1</sup> in 1900 to 133 and 298 g C m<sup>2</sup> yr<sup>-1</sup> 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 21<sup>st</sup> 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. 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 (Fig. 3 (b), Fig. 4 (b)). This clearly indicates that changes in water allocation between societal and ecological systems would ultimately 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.

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

1 the total land area and the crop pattern were relatively uniform. The impact of water allocation  
2 on societal and ecological systems.

### 3 4.3 Revisiting water catchment management in the MDB during 1900-2010 with 4 the results from the socio-hydrological water balance

## 5 **4—Discussions**

### 6 ~~4.1—Revisiting catchment water management in the MDB during 1900-2010 with~~ 7 ~~the results from the recast water balance~~

8 The relationship between human and the environment in the MDB has been changing over time,  
9 ~~as which is~~ reflected in changes in water allocation, land use, ~~water allocation~~, and resulting  
10 ~~GPP between societal and ecological systems~~. In view of the socio-hydrological recast  
11 catchment water balance, the co-evolutionary history of the socio-ecological systems in the  
12 MDB could be divided into four stages (Fig. 54).

13 (1) Period 1 (1900-1956): Expansion of water and land use for the societal system

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

19 There was rapid expansion of the development in the MDB represented by the substantial  
20 growth of agriculture land, and the population increased gradually during this period (Fig. 4  
21 (b)).-(Fig. 3 (a)). The area ratio of the societal system increased considerably starting from 0.15  
22 in 1900 to 0.52 in 1956, and the area of the ecological system declined to less than that of the  
23 societal system in the mid-1950s (Fig. 4 (a)5). The ET from the societal system superseded that  
24 from the ecological system in 1956, and the GPP from the societal system also exceeded that  
25 from the ecological system at the same year (Fig. 4 (a)5). The growth of population and  
26 expansion of agriculture land ~~were~~ was the major reasons of expansion of the societal system,  
27 accompanied by the construction of a small size of dams and irrigated infrastructure (Fig. 4  
28 (c)5). Therefore, 1956 should considered to be the first critical period when land and water use  
29 for the societal system exceeded that for the ecological system for the first time. ~~Although we~~  
30 ~~do not know the ideal ratios of ET and GPP of the societal system to ecological system in the~~

1 ~~MDB, 1956 should be the first critical period when land and water use for the societal system~~  
2 ~~superseded that for the ecological system for the first time.~~

3 (2) Period 2 (1956-~~1985~~1978): Maximization of water and land use for the societal system

4 Agricultural expansion went on during this period, especially irrigated agriculture, supported  
5 by water diversion (Fig. ~~4 (c)3 (a)~~). The vast investment in irrigation infrastructure supported  
6 the dramatic growth of agriculture and associated industries and the population of the MDB  
7 rapidly grew after 1956 (Fig. 4 (b))~~the agricultural industries~~. The storage capacity reached  
8 24,144 GL in 1970 from a starting point of nearly zero with the construction of dams, weirs,  
9 barrages and irrigation delivery canals (Fig. ~~4 (c)5~~). Nearly 450 large dams and innumerable  
10 small farm dams were built, which gives rise to some of the highest levels of water storage per  
11 capita in the world - more than 3 times mean annual flow (Wei et al., 2011).

12 ~~1985 was the year when ET and GPP of the societal system reached maxima. ET and GPP ratios~~  
13 of the societal system reached maxima in 1978 (Fig. 4 (a)). The construction of a large scale of  
14 dam and irrigated infrastructure and expansion of agriculture land were the major reasons of  
15 water use expansion of the societal system during this period (Fig. ~~4 (c)5~~).

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

24 (3) Period 3 (~~1985~~1978-2002): Maximization of water ~~diversion~~use for the societal system  
25 from water diversion

26 Water diversion increased as much as possible for maintaining and maintained nearly stable  
27 ratios of ET and GPP a nearly stable GPP for society (Fig. ~~Figs. 4 (a) and (c)5~~). The millennium  
28 drought (1997-2009) occurred in this period and is regarded as one of the worst since European  
29 settlement (Murphy and Timbal, 2008). The millennium drought dried out the MDB's major  
30 river systems, and the water-dependent ecological assets such as the mid-Murrumbidgee  
31 Wetlands, and the Lowbidgee Floodplain suffered significant degradation (Connor et al., 2013).

1 The ET of the societal system from surface water diversion reached a maximum in 2002 in  
2 order to maintain the maximized societal system under severe drought, resulting in further  
3 exacerbated ecosystem damage (Fig. 4 (d)5).

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

6 This period saw a small decrease of agricultural land, ET and GPP in societal system for the  
7 first time since the European settlement (Fig. 4 (a)5). The water diversion to society largely  
8 decreased. ~~When During~~ wetter years, for example 2010 ~~explained part of these decreases, the~~  
9 Australian Government took action to purchase water entitlements for the environment and  
10 implement irrigation efficiency programs to return water, about 2,750GL yr<sup>-1</sup>, to the  
11 environment, and drive a transition to the Sustainable Diversion Limits ~~since after~~ 2010. Within  
12 ~~the~~ society, water trading and the introduction of upgraded irrigation infrastructure and  
13 technology, such as efficient low-throw sprinkler and drip/trickle irrigation methods, improved  
14 water productivity and facilitated the water reallocation between the societal and ecological  
15 systems.

16 ~~Over the long history of water management reforms in the MDB from the River Murray Waters~~  
17 ~~Agreement in 1915 to Murray Darling Basin Agreement in 1987, attention was focused on~~  
18 ~~water sharing between the basin states to develop their economies. Although so far no research~~  
19 ~~findings have indicated the sustainable ratios of ET and GPP of the societal to ecological~~  
20 ~~systems in the MDB, 1956 should be the first critical period when water and land use for society~~  
21 ~~for the first time superseded that for the ecological system. Unfortunately it was not given~~  
22 ~~enough attention by catchment water and land managers. When water and land use and GPP in~~  
23 ~~the society was maximized in 1985 and some serious environmental issues appeared, the Basin~~  
24 ~~governments started to take some actions on water resources management to address these~~  
25 ~~emerging issues. Two years later, the Murray Darling Basin Water Agreement was signed~~  
26 ~~between the Commonwealth, New South Wales, Victoria and South Australia governments to~~  
27 ~~promote and coordinate effective approaches to dealing with environmental problems, in~~  
28 ~~particular salinity and water quality (MDBA, 2010). The millennium drought aggravated the~~  
29 ~~tension between the societal and ecological systems, which resulted in water diversion for~~  
30 ~~society to be maximized in 2002, resulting in serious degradation of ecosystems. The Water~~  
31 ~~Act in 2007 recognized the importance of environmental water. The Basin Plan, aimed to~~  
32 ~~balance societal and economic effects of reduced consumptive water as required for the~~

1 environment, was proposed in 2010 and issued in 2012, and is the milestone of the rebalance  
2 of the societal and ecological systems in the MDB. Therefore, the recast water balance approach  
3 is very useful to understand the co-evolution of the societal and ecological system in the MDB  
4 and highlight the experiences and lessons of catchment water management in history.

#### 5 **4.2— Implication of the recast water balance approach for integrated land and** 6 **water management in catchments**

7 The water balance and GPP changed considerably in the societal and ecological systems in the  
8 MDB during the period 1900–2010 as a result of land use and water use changes. GPP, closely  
9 related to water allocation, is absolutely the consequences of the land and water development  
10 of over the more than 100 years in the MDB. Therefore, GPP could be used as the outcome or  
11 objective of water and land management in water catchments. The pursuit of growing GPP in  
12 society resulted in maxima of the societal system and water diversion for society and degraded  
13 ecosystems. The history of the MDB revealed the relationships of societal development and the  
14 consumption of water and land resources. With the knowledge of these relationships, water and  
15 land would be better managed, and the balance between the societal and ecological systems in  
16 the MDB could be kept in a better status.

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

### 26 **5 Discussions and conclusions**

27 This paper proposes a simple socio-hydrological water balance framework for allocating water  
28 between human society and the environment to support sustainable water management of  
29 catchments. The framework shifts the understanding of catchment water balance from between  
30 human water demand and water supply to between human water use and ecological water use.  
31 It described changes in socio-hydrological water balance and established linkages between the



1 drivers causing changes and the resulting consequences for catchment societal-ecological  
2 systems. The socio-hydrological water balance could serve as the theoretical foundation for  
3 maintaining dynamic balance between the societal and ecological systems within a catchment.

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

23 Two main lessons can be drawn from the analysis of co-evolutional processes of the human-  
24 water relationship in the MDB. Over the long history of water management reforms in the MDB,  
25 from the River Murray Waters Agreement in 1915, to the Murray-Darling Basin Agreement in  
26 1987, attention was focused on water-sharing between the states of the Basin to develop their  
27 economies. 1956 was the first critical period when water and land use for society for the first  
28 time exceeded that for the ecological system. Unfortunately, it was not given attention by  
29 catchment water and land managers at the time. When water and land use and GPP by society  
30 were maximized in 1978 and some serious environmental issues appeared, the governments of  
31 the Basin started to take some actions on water resources management to address the emerging  
32 issues. In 1987 the Murray-Darling Basin Water Agreement was signed between the

1 Commonwealth, New South Wales, Victoria and South Australia governments to promote and  
2 coordinate effective approaches to dealing with environmental problems, in particular salinity  
3 and water quality (MDBA, 2010). The Millennium Drought aggravated the tension between the  
4 societal and ecological systems, which resulted in water diversion for society to be maximized  
5 in 2002, resulting in serious degradation of ecosystems. The Water Act of 2007 recognized the  
6 importance of water allocation for environmental purposes. The Basin Plan, which aimed to  
7 balance societal and economic effects of reduced consumptive water to make water available  
8 for the environment, was proposed in 2010 and issued in 2012, and is the milestone of the  
9 rebalance of the societal and ecological systems in the MDB. All these management changes in  
10 MDB in history were passive, responsive and contingent. A precautionary approach to water  
11 allocation between the societal and ecological systems should be developed based on the  
12 analytical understanding of socio-hydrological catchment water balance.

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

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

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

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

23 Water allocation between the human society and catchment ecosystems is a real challenge for  
24 the coming decades in many parts of the world. Despite of the uncertainty in long term datasets  
25 and ignorance of change of societal values, the proposed socio-hydrological water balance  
26 could be used to understand the history of water allocation between the societal and ecological  
27 systems, i.e. how today's problems were created in the past, which may lead to more sustainable  
28 catchment management in the future. As there are fundamental differences in the hydrology,  
29 demography, societal values, levels of economic development and capacity of water  
30 governance in areas such as the Yellow River Basin in China, the Colorado River Basin in the  
31 United States and the Ebro River Basin in the Europe, which have the similar management  
32 challenges with the MDB, application of the proposed water balance framework in these river

1 basins can enable exploration of common research problems, as well as highlight regional  
2 differences and any unique responses. It will also enable the identification of important policy,  
3 institutional and/or cultural differences for this globally significant issue, and point to lessons  
4 that might not emerge from a single country study.

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

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

19 ~~By recasting the catchment water balance and estimating GPP of the societal system and~~  
20 ~~ecological system in the MDB, this paper provided new understandings of the water and land~~  
21 ~~dynamics between societal system and ecological system in the MDB in the past over more~~  
22 ~~than 100 years, and it highlighted the experiences and lessons of catchment water management~~  
23 ~~in the MDB in history. This approach could be applied to other water catchments, such as the~~  
24 ~~Yellow River Basin in China, the Colorado River Basin in the United States and the Ebro River~~  
25 ~~Basin in the Europe which have the similar challenges with the MDB. Through comparative~~  
26 ~~analysis of the ratio of sustainable land allocation and the ratio of sustainable water diversion~~  
27 ~~between societal system and ecological system at different water catchments, the recast water~~  
28 ~~balance would add the knowledge base on sustainable catchment management from both a~~  
29 ~~normative and an analytical perspective.~~

30 ~~Finally, we have been aware that, if data are available, the impact of water allocation on societal~~  
31 ~~system can also be measured using other indicators, such as agricultural output and gross value~~

1 ~~of agricultural commodities which are more directly related to the water production value in~~  
2 ~~the societal system.~~

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1 **Figure captions**

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

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

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

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

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

20 ~~**Figure 6.** Relationships between (a) ET and societal system area ratio, (b) GPP and societal~~  
21 ~~system area ratio, (c) ET and surface water diversion, (d) GPP and surface water diversion in~~  
22 ~~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 <sup>2</sup>	RMSE (g C m <sup>-2</sup> yr <sup>-1</sup> )
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