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Interactive Comment

Interactive comment on "Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River Basin, Australia" *by* T. H. M. van Emmerik et al.

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We would like to thank Referee 2 for the positive and constructive comments that will contribute to the improvement of our manuscript.

General comment

As we mentioned already in the paper, and as we reiterate here, the model that we present in our paper is not claimed to be the cardinal novelty of our research, i.e. model development is not the end in itself but is the means to an end. We do not claim that our model is generic and can be directly applied to other human-water coupled systems (see also Reply to Referee 3). The key goal of this paper is to show that socio-hydrologic modelling, abstracting human-water systems in terms of “stylized” models, can be used as a tool to explain or gain insights into the observed co-evolutionary dynamics of coupled human-water systems. In the case of the Murrumbidgee river basin (MRB), the modelling is used to reveal or bring out the interesting system feedbacks that brought about the “pendulum swing” observed in the MRB. We hypothesize that this understanding, when duplicated in other systems (see accompanying paper by Elshafei et al., 2013), can contribute towards the development of generic models that can be applied more universally. This is the long-term goal of our research. This was clearly stated in the manuscript, but in response to the reviewer’s comments, we will reinforce this message in a revised manuscript.

1. Some discussion on the analytical model including eleven ODEs can be interesting. It will be difficult to interpret the nonlinear dynamics of a system with such many nonlinear ODEs. The well-known Lorenz system, which is represented by only 3 nonlinear ODEs, shows chaotic behaviors. This then brings up some concerns about the stability of the solution of such complex systems that are characterized by nonlinear dynamics and feedback loops. Further studies that are to be based to the complex system theory can end with insights about the complex problems.

First of all a small correction: our model only has 5 coupled differential equations.

Yet, we agree with the concerns of the reviewer that even with 5 non-linear coupled equations, the system can show highly chaotic behaviour, and analysis of the stability of the model predictions is an important issue. However, such a stability analysis of the model predictions is beyond the scope of this paper and can be a subject for a study on its own.

Part of the reason for our response to the reviewer is that prediction of future behaviour of the system is not the aim of this paper. Rather, the aim is to generate explanation of the observed dynamics of the system in a quantitative manner was the main aim of this research. Therefore, we are more excited by the conceptual model structure (in the form of a competition between productive and restorative forces) that is presented in Figure 12, which was the outcome of the modelling study, than the actual model itself.

Nevertheless, in the revised manuscript we will highlight potential issues regarding chaotic behaviour of complex systems, as areas of future research, once generic models of coupled human-water systems are developed.

2. The parameters of the numerical model were obtained by calibration. However, more interesting results can be found from sensitivity analysis to those parameters. Which parameters are the system states most sensitive to? Which parameters can be major controlling ones? Which parameters can cause the instability of the sub-systems and the entire system? A related question is about the impact of the initial condition. The solution of a nonlinear system often depends on the initial state.

We share the referee's opinion on the interesting results a sensitivity analysis might yield. We believe the model consists of fundamentally sound relationships and the initial conditions are based on realistic pristine conditions. The parameters are calibrated using expert judgement to adjust the parameters. The sensitivity of parameters, threshold values and the initial conditions is an important topic in itself. In response to the reviewer's concerns, we will perform a sensitivity analysis on selected relationships. The main finding of our modelling exercise is the balance between the human productive force and natural restorative force. We will challenge our model, by testing how sensitive the relations are that led to this conclusion.

3. The results are interesting in terms of the sub-system coupling. Since this paper attempts to promote socio-hydrology, what are the insights, implications

(based on the results) and suggestions for future efforts to the hydrology side (processes and/or systems)? In other words, what is the take-home message derived from this study to current generation of hydrologists?

This was a question raised by Reviewer 3 as well.

Socio-hydrology is an emerging science that results from IAHS' Panta Rhei initiative. The new credo is to study hydrology in a changing environment. One of the aspects is to expand our study area from pristine catchments to areas which have experienced anthropogenic influence. The authors believe one of the important focus areas is to look at systems as a whole, instead of only the hydrologic part, while parameterizing the others. From our results one can see that hydrology fulfils a cardinal function in the system, since it is the driving force of agricultural development, migration, policy, storage increase, environmental degradation and awareness. On the other side the aforementioned have strong feedbacks with hydrology. What we show in our research is that if we want to understand the co-evolution of systems, understanding the historical behaviour of coupled human-water catchments and make predictions of the future, a framework as presented in this paper can contribute to the achievement of these goals.

We show that through the development of a parsimonious model as we have presented, key elements can be identified that control the dynamics and organizing principles of human-water coupled systems' dynamics. Therefore, we believe that the current generation of hydrologists can see that new approaches in hydrology may lead to new insights in the interactions between humans, hydrology and ecology. Furthermore, we have identified several important aspects that need further attention in future research. For example, regions which are not irrigation/surface water dependent (e.g. rain-fed agriculture, no agriculture, usage groundwater) might reveal different feedback mechanisms. However, we also believe that the maximization principle of people and agriculture are generic fundamental principles. We will improve the take-home message, especially for the current generation of hydrologists.

4. Page 3393, lines 9-10, some explanation on the "generic model framework" will be helpful, i.e., on the conceptualization, model formulation, and/or model solution?

Thank you for your comment.

In this paper we present an approach to conceptualize human-water coupled systems, connect the sub-systems, formulate and solve the equations. We acknowledge that it is unlikely that the exact model as presented will be able to mimic the co-evolution in other human-influenced systems, especially where other mechanisms are dominant. In the case of the Murrumbidgee River Basin, the system is a surface water and agriculture dominated one. Where groundwater and other human activities are dominant, the system dynamics and its drivers might be completely different. By applying our approach to other case studies (with similar governing processes and completely different governing processes), we aim to distil generic characteristics, processes, feedback mechanisms and/or ODEs that will lead to the formulation of a generic framework that can be used to study different types of coupled human-water systems.

We will include a more detailed explanation of our overall, long-term goals with regard to model development.

5. Page 3396, lines 20-25, Equation 1. In the economic literature, agricultural land change is driven by land value (USDA provides the estimate of land value by regions over years). Moreover, some justification/rationale on the impact of environment awareness on irrigated area based on literature will be helpful. For example, authors may look at the irrigated area change over years in the Republican River Basin, where irrigation development after 1990 has been indeed related to groundwater over withdrawal and stream flow depletion issues.

Thank you for this comment.

We will analyse the case of the Republican River Basin to find analogies with the MRB

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to support our assumptions and justify our equation for the change in agricultural area per capita.

6. The population dynamic equations need some justifications in terms of 1) the form of general demography models; 2) irrigation potential and environmental awareness as driving forces; 3) immigration limited within the boundary of a basin (three parts). Is there any history of population change with irrigation development, especially within the study basin?

Thank you for your comment.

Our population dynamics equation is conceptually similar to the migration model proposed by Fedotov et al. (2008). People migrate to maximize economic profit, which is based on microeconomic fundamentals. The MRB is an agriculture dominated area, where throughout the 20th century population change and agricultural development occurred side by side, see Kandasamy et al. (2014). Therefore, the assumption that the migration of people is determined by the irrigation potential (i.e., potential economic gains) and environmental awareness (economic losses) is reasonable one. The latter represents environmental measures at several levels, as our approach is lumped. This captures both individual cases where over-exploitation of farmland can make a single farmer move out and governmental policy imposed on larger areas. Population dynamics consists of internal and external migration, in that immigration is not limited within the boundaries of the basin. Within the model space, an attractiveness gradient causes people to migrate within the basin. In case of overall unfavourable conditions, people migrate to outside the MRB. A more realistic approach is to run similar models for regions adjacent to the MRB, but since this will make the model unnecessarily complex, it is chosen to not do so at this moment.

In terms of model structure, our model has many similarities with published stylized socio-hydrologic models by Di Baldassarre et al. (2013), Srivivasan (2013) and Elshafei et al. (2014). We will compare our approach to the above mentioned models in the revised manuscript. We will add more justification of the people dynamics along the lines of the comments posted by the reviewer. We will also include more available people and irrigation development data from Kandasamy et al. (2014) to support our assumptions. Expansion of the population dynamics in the sense of e.g. including attractiveness of areas outside this model lies outside the scope of this paper and is let to further research.

7. The storage equation. It seems that only surface water (from the river) is used for irrigation; while groundwater is the major source in many basins, where surface and ground water are often connected; deep groundwater is used in many cases (e.g., Northern China and Great Plain of the U.S.); inter-basin water transfer is another source. A bit more complex hydrologic relationships might make the analysis more realistic.

The model that we present is indeed a simplistic version of reality. However, irrigation in the MRB mainly relies on surface water, so is quite appropriate for this basin. For other situations where water usage is mainly groundwater or a combination of groundwater and surface water, a more complex hydrologic model will be needed. We would like to emphasize that we share these concerns if our modelling approach is to be applied to other case studies. For the sake of simplicity, which is the MRB also reflects reality best, we will not expand our model with a groundwater term.

8. Equation 6. Should "min" be "max"? Why only Q1 and why not Q2?

In equation 6, "min" indeed should be "max", leading to the following description: dW/dt = max(0, Q1out – mu) – kW. We thank the referee for noting this typo. In the model we used the correct formulation. It is only Q1out because the wetlands are only fed by the downstream outflow of the system. The measure of ecology in our model is the state of the Lowbidgee Wetlands, downstream of Area 1. Anthropogenic alteration of the system affects the flow regime, leading to a changed inflow of water to the wetlands. This is explained in Section 2.2.4 Ecology equation. The authors will extend and clarify this section to prevent further confusion.

9. Equation 7, should the epsilon function be an “S” function with a negative value when n is below a threshold and a positive value with diminishing marginal value when n is above a threshold? Can this function be related to environmental regulations over time, which however might cause step change of some of the sub-systems?

In table 3 the formulation of epsilon can be found. If n is equal to zero (below threshold) the function has a negative value. If n is larger than 0, the value is positive. From Fig. 11 it can be seen that at two moments in time, n>0 led to a steep increase in environmental awareness, at the end of the 1980s and at the beginning of the 2000s. This can be related to the start of the 3rd and 4th era in the MRB. In the 3rd era an increased environmental awareness led to a focus on consensus strategies to achieve sustainable management. In the 4th era the consensus model failed and led to the emergence of government intervention (Kandasamy et al., 2014). We address this clearly in the manuscript and relate the environmental awareness function and its result more directly to the results from Kandasamy et al. (2014).

10. Equation 8, crop yield changes by region (i) given different natural (e.g., soil and landscape) and technology conditions in different regions.

The referee raised an interesting point of attention. In the current model, soil and landscape variability are not taken into account. This would introduce more model complexity and the authors believe this will not lead to directly significant model improvement. Technology could be a function of the sub-basin state of wealth. However, this could lead to unrealistic scenarios, e.g. developing settlements with a low state of wealth will have a low level of technology. On the one hand this is true, given that the area is under development and farmers may not have the financial means to opt for state of the art technology. However, in the system the state of technology has improved and modern irrigation techniques or equipment is available on the market. A better description of

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technology is a very interesting topic and could be worth research on its own. For this paper the authors believe equation 8 and the formulation of technology are sound for its purpose.

11. Fig. 6 and Fig. 7 show interesting correlations among multiple sub-systems. Can these be related to policy/regulation change over the historical time?

The authors thank the referee's comment. Fig. 6 and 7 can indeed be related to policy and regulation changes over time, as found and described by Kandasamy et al. (2014), see the reply to comment 9. We will describe the correlation between the model results and the historical events as presented by Kandsamy et al. (2014) more clearly, in order to put our results in a more realistic context and relate it to historical events.

12. The time period includes near future time (2014-2020). So the segments during the future period predict the plausible near future states. This should be interested to basin managers and stakeholders. Additional discussion will be interesting.

The model was run for the period 1910 – 2013. Therefore no predictions of future states are made. Our intention is to explain the past and not to predict the future. We will emphasize this in the manuscript to prevent confusion. Our goal in this paper is to show that with our socio-hydrological framework we are able to mimic the historical dynamics of the MRB and identify the key drivers of the system's co-evolution. We agree with the referee that potential predictions of this framework are very interesting, from both the perspective of basin managers and stakeholders as from a modelling point of view. This is left for future research.

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