RESPONSE TO REVIEWERS

Changes made in response to reviewer comment appears in yellow highlight in the revised manuscript.

<u>Reviewer #1 Yongping Wei</u>

1) Reviewer Comment:

I enjoy reading this manuscript. A landscape at water catchment is a holistic system in which nature and culture co-evolve. This begs the question: to what degree did the cultural construct influence the water catchment hydrology, and vice versa? However, the cultural construct (societal values) has not been adequately studied in existing hydrological models, except those studies mentioned in the manuscript. Therefore, this review is important by bringing this knowledge gap to the hydrology community (HESS). I would like to recommend this manuscript to be accepted, subject to responses to the comments as follows:

Authors response: We thank for Yongping Wei for her positive review. We firmly agree that the degree to which cultural constructs influence catchment hydrology and vice versa remains to be explored in depth.

2) Reviewer Comment:

Culture is a notoriously slippery concept, has no agreed-upon definition across social science fields. There are more 170 definitions of 'culture' in the literature. Culture is often perceived to be opposed to nature, becomes synonymous with civilization. Culture is defined operationally as a set of common values, norms and attitudes shared by the majority of a region population, which is arguably the most important mediating mechanism that links us not only with other human beings, but also with the rest of nature of which we are part and within which we live (Keesing 1974). To talk about cultural change is one thing. To measure them precisely is quite another. The study of cultural evolution has traditionally been the purview of anthropology and sociology.

Past attempts to explain cultural evolution used the 'thick description' rather than explanatory approach which would not distinguish between explanandum and explanans. It is known that they have poor predictability. This is why culture (societal value) has not been nicely integrated in the hydrological models. However, these disciplinary studies provide the fundamental basis for any attempts of quantifying the societal value. So, I would like to this manuscript to include a more thorough review of measurement and explanation of societal value in these disciplines.

Authors response: We agree that culture can be a nebulous concept and that there are numerous definitions. There are challenges in incorporating culture into socio-hydrological modeling. This is why we explicitly selected the VBN framework, which allows us to identify culture as a property that emerges from the feedbacks between values, norms, and the hydrological system. This is one of the first steps to integrate social science theories linked with values and norms in context of socio-hydrology. Please note that this is an opinion paper on values and norms in socio-hydrological models, which we agree should build upon strong knowledge of the subject matter. For this reason, we have provided a review of VBN theory, which we believe is very well aligned with the current state of the art in socio-hydrological modeling. With further progress in socio-hydrology, we should be able to define the components of culture (i.e., value, beliefs, norms) related to water management and seek the data sources to be exploited. Nonetheless, in the revised paper, we provided an additional review on the measurement and explanation of different values of society in Section 4.1 while keeping to the scope of the paper. Please see lines 442-450 in the revised manuscript.

3) Reviewer Comment: VBN is one of many theoretical frameworks in sociology which explains the impact of the value-belief-norm on individual or societal decision-making and practice. However, I do not think it is practical in the context of socio-hydrology, in particular when we aim to simulate and reconstruct the historical societal value. Given the limited documents (data) sources, how can you obtain data on value, belief and norms?
Authors Response: Please see our response to the reviewer comment 2. The VBN framework provides us a fundamental basis not only to quantify values but also to quantify the interlinkages between values and norms via beliefs (see Figure 2), norms and human actions via behavior, and human actions and norms via beliefs. Indeed we agree that the complexity of system concepts needs to sacrificed in favor or simpler ones (while maintaining theoretical integrity), such as only piggybacking on feedbacks between values, behavior and hydrological response, according to data availability on values, beliefs and norms (see e.g. Roobavannan et al, 2017). The data challenges are discussed in Sections 4.1 and 4.2.

4) Reviewer Comment: You make detailed difference between value, belief and norms in Figure 2, but you did not make clear difference between these three concepts in text. So I suggest to combine 3.1 and 3.2 and use a general concept to explain the feedbacks between value and behaviour.
Authors Response: We have provided more detailed discussions of these concepts, provided more detailed definitions and adapted our text to highlight this point of the referee further.

Please also see our response to the previous reviewer comment 2 and 3. We agree that there is a greater emphasis on values and behavior than beliefs and norms but this emphasis is no greater than the overall case for VBN theory. Section 3.1, however defines all the terms and even illustrates the role of beliefs and norms in how values influences behavior. Further, we also emphasize the role of beliefs in changing norms and hence water use behavior, when beliefs update as a result of environmental degradation from past water use behavior.

We respect the desire of the referee to use a general concept of the feedbacks between value and behavior and given the paucity of data, VBN theory provides us with a fundamental framework to do that exactly. Section 3.1 explains the VBN theory and defines its components, while Section 3.2 deals with data paucity and to what extent such a theory has been (or can be) implemented in socio-hydrological models. Section 3.1 describes briefly some key differences between values, beliefs, and norms. Please see the lines 240-256 in the revised manuscript.

5) Reviewer Comment: You did not give a full explanation of Figure 2, and you did not use main info in Figure 2 in your manuscript either, so I would suggest you delete it.
Authors Response: Please see our response to the previous reviewer comment 2-4. The illustration of a Murrumbidgee farmer is in context of Figure 2 (we have now made reference to this in the revised manuscript) while Section 3.2 (Figure 2 now also referenced here) confronts data availability with socio-hydrological models that embed the concepts from VBN theory. So we would like to keep Figure 2, if this is acceptable to the reviewer and editor.

6) Reviewer Comment: There is a bit repetition between Section 1, Section 2 and Section 4. Besides our findings in Australia (Wei et al., 2017) which you cited and used the data from, we had published similar findings in China (Xiong et al., 2016). I list it here for your information. Yonglan Xiong, Zhiqiang Zhang, and Yongping Wei. 2016. Evolution of China's water issue framed in Chinese mainstream media. AMBIO 45 (2): 241- 251DOI: 10.1007/s13280-015-0716-y.

Authors response: We have minimized the repetition, especially in terms of socio-hydro modeling studies cited. For completeness we also cited the work in China by Xiong et al. (2016). Thank you for bringing this to our notice.

Reviewer # 2 Xi Chen

1) Reviewer Comment: This paper did a review of socio-hydrology (SH) modeling with a focus on several place based studies. Based on the review, the Authors pointed out the importance of social norms and values in SH models. At the end, the paper proposed potential future pathways of SH models and discussed the challenges to generalize SH models. I have the following comments that I hope the authors could address in the revision.

Authors response: We thank Xi Chen for his review. We address all the specific comments below.

Specific comments:

2) Reviewer Comment: The paper explains the review case studies in multiple sessions with too much details. The focus of the paper should be the knowledge generated from those case studies. Maybe the authors can find a way to generalize the information provided by these studies.

Authors response: We follow the reviewer's advice and add a conceptual figure (Figure 6), and a one paragraph synthesis along with it, towards the end of section 4 to generalize the information presented in the section. Please note however that section 4 itself was designed to be a synthesis. Please see lines 393-410 in the revised manuscript.

3) Reviewer Comment: In section 2.2, maybe the authors should add the following reference, since this study is also using the idea of community sensitivity to do SH modeling.

Chen, X., D. Wang, F. Tian, and M. Sivapalan (2016), From channelization to restoration: Socio hydrologic modeling with changing community preferences in the Kissimmee River Basin, Florida, Water Resour. Res., 52, doi:10.1002/2015WR018194.

Authors response: This was an oversight. We have now added the reference. Please see the lines 182-186 in the revised manuscript

4) Reviewer Comment: Section 2.3: Roobavannan et al. (2017) is still in review, so it is hard to assess the review materials in this manuscript.

Authors response: Roobavannan et al. (2017) is now published and is accessible via http://www.doi.org/10.1002/2017WR020671. We have also updated the citation in the reference list in the revised manuscript.

5) Reviewer Comment: Line 288-294: The paper suggested that environment awareness and community sensitivity are both following the general logic of the VBN theory. So maybe the authors can unify the norm/value parameters to one and provide a clear definition based on the VBN theory.

Authors response: The purpose of community sensitivity and environmental awareness variable is to capture the society's changing value and norms and follow principles of VBN theory. It should be noted these variables include the values, beliefs and norms together. We have revised the paper to unify the relevant terms and use variables. We agree that we need to further differentiate the variables as we begin to reliably observe them. Please see lines 393-430 in the revised manuscript.

6)Reviewer Comment: Line 448-453: van Emmerik et al. (2014) uses environment awareness, not community sensitivity.
Authors response: This has been corrected in the revised manuscript.

7) Reviewer Comment: Line 511-513: For the three listed river basins, please add the countries they are located in.
Authors response: The country of respective river basins are added in the revised manuscript.

8) Reviewer Comment: Line 521: Typo: "Elshafiei". These three references have been repetitively mentioned in this manuscript over 10 times. I think the focus of the paper should be the scientific knowledge that can push SH modeling forward, not the three case studies.
Authors response: The typo has been corrected. We agree with the reviewer that this section may give the impression that we are just repeating three different case studies. Our intention was really to connect them to VBN theory. We have minimized the apparent repetitions in the revisions.
Indeed, the focus of this section was to highlight the need to include changing values and norms of society in order to predict future projections. Through this review we explain that recent SH model studies have moved closer toward integration with key social science theories of perception and behavior, and have taken steps toward endogenizing values and norms. We intended to show that these models are internally consistent with patterns observed with proxy data of environmental awareness and water policy change, such as the newpaper article-based proxies of Wei et al. (2017). However, such proxy-reliant models are only the beginning of the way towards generalized models and their use in predictions for sustainable water management.

9) Reviewer Comment: Figure 5: The paper spends a fair amount of paragraphs to talk about the parameter "community sensitivity", but the analysis provided by the study is using "environment awareness", which I believe is a different parameter. Following my previous comment, maybe the authors should add explanations about the differences between these two parameters and try to generalize the parameters, which would be a part of the SH generalization process.
Authors response: Community sensitivity and environmental awareness are variables defined to capture the changing values and norms in different socio-hydrological models. Community sensitivity is an advance over the previously defined environmental awareness. We agree that they are different in the way they are defined, yet both are intended to capture the same concept of changing values and norms for use in socio-hydrological models. We however have added text on the difference between their definitions as the referee suggests, that community sensitivity is a more complex description of environment awareness. Both are modeled as memory variables. But while in the case of latter the time scale of the memory of past environmental disaster is kept constant, in the case of the former (i.e. community sensitivity) the time scale is dynamic and depends on community norms in context of its water environment. Please see lines 201-209.

NORMS AND VALUES IN SOCIO-HYDROLOGICAL MODELS

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ABSTRACT

Sustainable water resources management relies on understanding how societies and water systems co-evolve. Many place-based socio-hydrology (SH) modelling studies use proxies, such as environmental degradation, to capture key elements of the social component of system dynamics. Parameters of assumed relationships between environmental degradation and the human response to it are usually obtained through calibration. Since these relationships are not yet underpinned by social science theories, confidence in the predictive power of such place-based socio-hydrologic models remains low. The generalisability of SH models therefore requires major advances in incorporating more realistic relationships, underpinned by appropriate hydrological and social science data, and theories. The latter is a critical input, since human culture – especially values and norms arising from it - influences behaviour and the consequences of behaviours. This paper reviews a key social science theory that links cultural factors to environmental decision-making, assesses how to better incorporate social science insights to enhance SH models, and raises important questions to be addressed in moving forward. This is done in the context of recent progress in socio-hydrological studies and the gaps that remain to be filled. The paper concludes with a discussion of challenges and opportunities in terms of generalisation of SH models and the use of available data to allow future prediction and model transfer to ungauged basins.

KEYWORDS: Socio-hydrology; culture; values and norms; modeling; content analysis.

1. INTRODUCTION

The concept of sustainable development has received much attention among researchers, policy makers and stakeholders. Water is at the core of many of the sustainability challenges that human societies face (Bai et al., 2016; Falkenmark and Rockström, 2004; Rijsberman, 2006). Sustainable water resource management is key to production of food and energy to satisfy human needs, including poverty alleviation and healthy humans. As indiscriminate development threatens critical ecosystem services and biodiversity, the need to account for the environment has emerged as an important consideration in sustainable water management (Millennium Ecosystem Assessment, 2005). Enabling society to address sustainability challenges, and develop appropriate solutions, requires an ability to provide reliable predictions of changes to freshwater resources, their distribution, circulation, and quality under natural and human-induced changes from local to global scales, including changes that are part of water management (Srinivasan et al., 2017).

We cannot understand, let alone make future predictions of, water resource system dynamics, without understanding how the issues of economic gain, environmental degradation, and social inequities play out in society, and how social perceptions of these issues impact management decisions relating to water consumption, allocation and pricing, human settlements, infrastructure development, and environmental protection (Blair and Buytaert, 2016; Srinivasan et al., 2016). Such understanding will remain incomplete until we fully grapple with issues arising from human culture, including how components of culture – values, beliefs, and norms relate to water uses, livelihood, and the environment (Sivapalan and Blöschl, 2015). It is increasingly recognized that cultural factors are likely to influence changes in water management decisions and outcomes (Caldas et al., 2015), raising questions about what have become 'conventional' assumptions about humans as rational, utility maximisers who make decisions based upon complete information. Although economic models of altruism and impure altruism (i.e., "warm glow" effect: caring about others or the next generation not just out of altruism but because they get pleasure out of it themselves) have been successful in predicting the effect of prevailing values and norms on human behaviour and actions (Andreoni, 1989; Banerjee and Newman, 1993), they remain limited in accounting for the consequences of the human actions on societal values and norms in return.

The inter-disciplinary field of socio-hydrology was launched with the aim of studying the dynamic, two-way feedbacks between water and people in coupled human-water systems. In particular, socio-hydrology (SH) seeks to understand and interpret patterns and phenomena that emerge from two-way feedbacks in coupled human-water systems as a consequence of water management decisions and actions. Indeed, the subject matter of socio-hydrology are the many diverse phenomena that emerge from these two-way feedbacks and manifest as puzzles and paradoxes, exhibiting differences but also similarities between places, and reflecting distinct hydro-climatic, eco-environmental, and socioeconomic backgrounds (Sivapalan et al., 2014). Examples include the agrarian crisis in booming emerging economies such as India (Pande and Savenije, 2016), increasing levee heights in urban environments in spite of increased flood risk (Di Baldassarre et al., 2013) and the peaking in water resource availability in agricultural basins as they undergo development (Kandasamy et al., 2014; Liu et al., 2014).

Several place-based socio-hydrology studies in basins dominated by agricultural development, such as the Tarim (China, Liu et al., 2014), Murrumbidgee (Australia, Elshafei et al., 2014; van Emmerik et al., 2014), and Lake Toolbin (Australia, Elshafei et al., 2015) basins, have highlighted a shift in water use behavior from an initial focus on agricultural production to an increasing emphasis on environmental conservation, a shift that has been called the pendulum swing (Kandasamy et al., 2014). Similarly Chen et al., (2016) showed a shift in water management from flood mitgation to wetland protection at Kissimee river, USA. Socio-hydrology models developed to reproduce these observed dynamics attributed the shift to changing human values and norms, which were tracked indirectly through proxies (e.g., environmental degradation). For example, van Emmerik et al. (2014) modeled the human decision to allocate more or less water to agriculture or to the environment on the strength of a dynamic 'social' state variable called environmental awareness, which reflected societal perceptions of the environmental degradation within the prevailing value systems or culture (see also Di Baldassarre et al. (2013) for awareness of floods in the context of coupled human-flood systems, and Garcia et al., (2016) for awareness of shortage for town water supply in the context of coupled human-town water supply systems). In the socio-hydrological model of van Emmerik et al. (2014) the human response to changing environmental awareness is captured through an appropriate constitutive relationship, chosen in a somewhat intuitive way. Hence, the parameters governing the constitutive relationship could only be obtained through calibration of the overall model and would always be challenged unless they are verified to be right for the right reasons. Prediction-wise, both in time and space, confidence in such place-based models will be low so long as the constitutive relationship cannot be independently validated or theoretically justified.

Going forward, there is a need to generalize SH models both for predicting future socio-hydrological outcomes in one location and/or to apply them at other locations. Case studies have demonstrated an inherently dynamic quality to changing values and norms in relation to water use or environmental behaviour, but how to measure or "value" values and norms directly and independently of models remains as yet unresolved. Even if they can be measured in specific places, we need a broad theoretical framework that encapsulates the many physical and social controls that govern changing values and norms in order to synthesize data or measurements from many places across the globe and develop broad generalizations. These remain major challenges to the progress of socio-hydrology as the science underpinning sustainable water management (Pande and Sivapalan, 2016) and thus provide the motivation for this paper. Our aim is to position the progress made by SH models to date towards incorporating changing values and norms in the context of extant social science theories, and in doing so, to articulate possible ways forward to make major advances in the future.

This paper begins with a review of recent place-based, socio-hydrological modelling studies (van Emmerik et al., 2014; Elshafei et al., 2014, 2015; Chen et al., 2016, Roobavannan et al., 2017) that have incorporated changing values and norms by connecting them to measures of the states of basin economy and/or environmental health via assumed functional relationships. Next, we draw connections between extant social theory and recent SH studies that indicate how values and norms influence social behaviour towards the environment. The paper then outlines challenges and opportunities for generalising SH models, especially in respect of changing values and norms, so that more reliable predictions can be made across time and space. This includes a re-calibration exercise to demonstrate the value of new kinds of social data. This also includes exciting new avenues such as virtual social experiments or data mined from novel sources such as social surveys and media. It concludes with the possibility of generalising relationships between changing values and norms and human behavior in respect of the environment, benefiting from more place based studies. In this way, it underscores the need for more comparative analyses across many such case studies so that generalised relationships can be synthesised that are transferrable to ungauged locations.

2. VALUES AND NORMS IN SOCIO-HYDROLOGY MODELS

Following Wescoat (2013), the socio-hydrology literature has tended to define values and norms as the over-arching goals of individuals and of whole societies in respect of water use, conservation, and sustainability. Prior research in SH has allowed values and norms to undergo dynamic changes. Sivapalan et al. (2014) proposed a socio-hydrology framework which uses values and norms as drivers of the decision making that shapes society's goals and actions, and are in turn shaped by the outcomes for human wellbeing that result from past human decisions (Figure 1). In this way, values and norms are seen as endogenous to coupled human-water systems, co-evolving with the changing dynamics of water resource systems (Norton et al., 1998; Sivapalan and Blöschl, 2015). So far in SH research, values, beliefs and norms have been lumped together and represented by proxy variables. Next, we illustrate this through several examples.

2.1 Environmental awareness

van Emmerik et al. (2014) developed a SH model of the Murrumbidgee river basin (MRB) in eastern Australia to explain an observed "pendulum swing", i.e., a shift in water management focus away from economic development and towards ecosystem health. This shift was hypothesized to be the outcome of changes in values and norms in the community in respect of economic well being and ecosystem health. In the model, the dynamics of changing values and norms were represented by environmental awareness, a proxy state variable that reflected adverse changes to ecosystem health. A crucial aspect has been the inclusion of a sub-model to quantify environmental health. It was assumed that environmental degradation occurred when too much water was extracted for agricultural activities aimed at advancing economic wellbeing of the community. As a result, less water reached downstream wetlands. When wetland storage became lower than a specified threshold, ecosystem health suffered noticeably to be felt in the community, which was then reflected in the environmental awareness. Enhanced environmental awareness then triggered human action, in the form of reductions in water allocation to agriculture, leading to reductions in irrigated area, and increased water allocation to the environment. The situation would reverse itself upon a return of increased downstream environmental flows, restoration of wetland storage and improvement to ecosystem health.

The representation of environmental awareness in van Emmerik et al. (2014), although simple, represents a first attempt on the intuitive relationship between values and norms about perceived threats to ecosystem health and changes to water management actions. van Emmerik et al. (2014) was able to model the four eras described by Kandasamy et al. (2014), from an exclusive focus on agriculture, to environmental restoration. Note that other effects or characteristics of environmental degradation, such as changing water tables, or salinization of the soil, were not taken into account. Furthermore, regional or national policy, regional and national economy on changing perception is not taken into account in the formulation of environmental awareness. Finally, the functional form of the equation was calibrated using data on population, total irrigated area, agricuture water utilisation.

2.2 Community sensitivity

Elshafei et al. (2014) expanded further on the intuitive causality between changes to community values and norms in respect of ecosystem health, regional economy and consequent water management actions by humans. They elaborated on how agri-centric values conflicted with environmental values and influenced water use behavior and proposed a framework that modeled the competition between economic development and environmental awareness using 'community sensitivity', a new social state variable. They presented a feedback formulation where water use behavior is influenced by changing values and norms relating to the environment and economic well-being, as reflected in the community sensitivity. For the first time the authors brought in broader (e.g., regional) climatic, political and socio-economic contextual variables that may influence local values and norms in respect of water use, e.g., rapidly diversifying economic growth. Elshafei et al. (2015) explicitly demonstrated that environmental degradation impacted community sensisitivity and consequently water use behaviours. The foundation of their proposed framework was driven by the hypothesis that the coupled system dynamics are driven by the competition between a positive feedback loop (Economic-Population Loop) and a negative feedback loop (Community Sensitivity Loop).

Similarly, the community sensitivity concept was used to explain the shift in values and norms, and management emphasis from flood mitigation to environment protection in Kissimee river, Florida, USA (Chen et.al, 2016). They used wetland storage and flood intensity as proxy to measure changing value system. Their study showed that the value system was affected by the relative size of population in upstream and downstream portions of the catchment.

Economic diversification and institutions:

Roobavannan et al. (2017) presented a rigorous validation of the community sensitivity concept of Elshafei et al. (2014) and further extended it to account for the relative dependence of the basin economy on agriculture. Roobavannan et al. (2017) assumed that the tradeoff between economic wellbeing and environmental health at the community level depends also on contextual factors such as economic diversification. In this way the resulting SH model was able to explain the importance of economic diversification and sectoral transformation on the community sensitivity that then impacted human water management actions.

Roobavannan et al. (2017) also introduced a fish spices richness (FSR) index (Yoshika*wa et al*, 2014) as a separate proxy for ecosystem health. They also used time series of economic development (measured by total irrigated area and irrigation water utilisation) and diverse proxies for technology (i.e., patents) and water use behavior (e.g., environmental behavior based on fish species richness index) in validating the dynamic changes to community sensitivity.

Community sensitivity and environmental awareness are different in the way they are defined, yet both intend to capture the same concept of changing values and norms for use in socio-hydrological models. Environmental awareness accounts for society's perception of environment degradation while community sensitivity accounts for the balance of perception of environment degradation and economy growth of a region. Community sensitivity is a more complex assessment variable than environment awareness. Both are modeled as memory variables. But while in the case of latter the time scale of the memory of past environmental disaster is kept constant, in the case of the former (i.e. community sensitivity) the time scale is dynamic and depends on community norms in context of its water environment.

3. VALUES, BELIEFS AND NORMS AS DYNAMIC VARIABLES

So far in SH modelling research, aspects of human culture that drive human behaviour in respect of water management – i.e., values and norms – have been treated in a lumped way, represented by proxies, in a black-box manner. Moving SH forward requires opening the 'black box' of culture by questioning the assumptions behind and more clearly measuring and modelling cultural factors. For example, if values are conceptualized as over-arching goals of society (Wescoat, 2013), are they individual goals or collective goals associated with the emergent structure of a coupled human-water system, or both? Similarly, how malleable are values and norms as aspects of a coupled human-water system? Moreover, under what conditions should values and norms be expected to change, or remain stable? For that matter, what are the mechanisms through which values and norms might change, and the human behaviours and actions that result from them?

The ingredients for understanding the role of changing values and norms in coupled human-water systems can be summarized as (a) forward loop: theories of how individual values influence individual norms and behavior regarding water use, (b) backward loop: theories of why and how collective behavior can engender change in individual norms regarding the use of water for agriculture or the environment, (c) role of institutions in enabling changes in water policy that reflect collective behavior towards the water environment, (d) data that can provide information on proxy variables including environment related behavior and patterns and (e) models that use proxy data to conceptualize processes (a)-(c) in interpreting related patterns. Future work in SH will necessarily grapple with these types of questions that further elucidate the role of values and norms in coupled human-water systems.

3.1 Values, Beliefs, and Norms: VBN theory

One line of conceptualization seems particularly promising for moving forward socio-hydrological research. The Values-Beliefs-Norms (VBN) theoretical framework (Stern et al., 1999; Ives and Kendal, 2014) is grounded firmly in social-psychological theory and has been empirically tested as a framework for understanding how cultural factors (i.e., values, beliefs and norms) shape environmental decision-making, and water use behaviour in particular, in a wide array of contexts. Figure 2 presents a stylized version of a VBN model linking values, beliefs, norms, and behaviours.

In the social sciences, "values" can have various meanings and definitions (Dietz, 2015). The social science literature on values is voluminous, but there is a large strand of research that employs the meaning of values from Schwartz (2001: 521), which defined values as "as desirable, trans-situational goals, varying in importance that serve as guiding principles in people's lives". Values in this sense are different from beliefs and norms. Beliefs are ideas about what is true (or not); beliefs can be held regardless of empirical evidence. Norms are rules, written/formal or unwritten/informal that prescribe behaviors. Norms specify how people should or should not act. Values – as guiding principles – motivate beliefs and norms, and influence whether people accept particular beliefs and norms. In this framework, behaviours are motivated by proximate norms, or obligations to act.

Norms themselves are shaped, or activated by beliefs, including a person's awareness of the consequences of their actions, how a person ascribes responsibility for their actions etc. More generally, norms are shaped by a person's ecological worldview, or how a person views humans vis-à-vis the natural environment (i.e., are humans *a part of* the natural environment, or *apart from* the natural environment). Ultimately, the VBN framework posits values-deeply-held, guiding principles about right and wrong – as the basis of water use behaviour in the context of socio-hydrology. Values are often assumed to be unchanging, relatively stable, and generally unquestioned principles that motivate water use behaviour and water policy actions indirectly through beliefs and norms.

The VBN framework is capable of being incorporated into SH models for the purposes of modelling dynamic feedbacks within the human component of the system or between the human and environmental components of the system (Caldas et al. 2015). Incorporating VBN into SH models requires addressing the questions raised above in greater detail, among others, but especially the question of where the feedbacks between values, beliefs, norms and behavior occur in the process of management and the competitive use of water resources.

To illustrate how values, beliefs and norms influence behavior (Figure 2), consider a simplified example of a farmer of English descent in the MRB who migrated into the basin in the early 1900s and farmed rice. The behaviour of this farmer towards wetlands is influenced by how the farmer and the farming community *believe* their water use affects what they hold dear or value. Implicitly, this means that their behaviour towards the environment depends on how they value water, or what they believe the water should be used for. These are questions of *values*, and values help navigate decisions that must be made about trade-offs between different valued end goals, or uses. Here, one key trade-off is between water for agricultural production (i.e., to support the viability of the farm operation and farmer's livelihood) and water for the environment (i.e., to support environmental flows, biodiversity, and ecosystem services). Humans can hold multiple values, and place different 'weights' or emphases on each of the values that affect a particular decision with regards to water use. The farmer may, for example, make a water use decision by drawing on a combination of self-interest/egoistic values (e.g., using water to support the economic well-being of their family, household, and farm), humanist-altruistic values (e.g., conserving water to preserve the long-term viability of the rural community), and biospheric-altruistic values (e.g., conserving water to preserve wildlife habitat and ecosystem services). A first step toward modelling this type of VBN process could be to assign weights for each value, allowing behaviours to change in correspondence to the weights that each value type exercises over time. Scaling up from the individual-level, value types can be identified from prevailing complexes of VBN processes in a basin so that SH dynamics in a basin are outcomes of generalised behaviours emerging from a distribution of basin residents laden with different value types and complexes. From this perspective, VBN elements at an aggregate level in a basin can become dynamic. For example, degrading ecosystem functioning, such as the drying of wetlands, can bring more uncertainty and risk over time to the things the farmer values (i.e., income, family, farming, community, the environment, etc.) and/or altering the farmer's beliefs (i.e., worldview, awareness of adverse conseqeunces, or perceived ability to reduce threats to things of value), shifting their behaviour away from a more egoistic, or agri-centric, orientation and towards wetland conservation and restoration. This is a very simplified example of a complex set of processes operating at multiple scales, but it illustrates how values, beliefs, norms, and behaviour might be seen to co-evolve and change through feedbacks in a coupled SH system.

There remain important gaps in how to identify the requisite components of VBN processes through measurement, how to scale up these processses from the individual level, and how to model feedbacks. However, as mentioned before, there has already been progress in this direction in the SH literature.

3.2 Validation of Modeled Changing Values and Norms

Place-based SH models have relied on proxy measures such as environmental degradation to capture changing values, beliefs, norms and behaviors (Figure 2) and their parameters were obtained by calibration. Despite the advantages of this approach, confidence in these models remains low, as the models struggle to be indepedently validated. To address the validation challenges faced to date in model-based socio-hydrology case studies, Elshafei et al. (2015) proposed that socio-centric approaches (such as newspaper content analysis) be employed to assess evolving community sentiment over long time periods.

Along these lines, Xiong et al., (2016) and Wei et al. (2017) recently analyzed the content of newspaper articles to measure and quantify the evolution of societal values and norms in relation to water management issues in China and Australia, respectively. The results of Wei et al. (2017) are especially informative to the growing body of socio-hydrology literature focused on Australian study sites, in particular the Murray Darling Basin (MDB). Their findings support the hypothesis that societal values shifted from an anthropo-centric to an enviro-centric focus over time.

The work of Wei et al. (2017) thus signals an important step forward for the socio-hydrology research community as its results demonstrate how an autonomous socio-centric analysis method may be employed to provide independent validation for conceptual theories and coupled modelling approaches carried out within the same broad geographical region. This more complete analysis of societal value and norms now enables us to go back and compare the results of this independent study against the predictions made by previous SH models. More specifically, Wei et al.'s (2017) results corroborate Kandasamy et al.'s (2014) proposed pendulum swing in societal sentiment in the Murrumbidgee Basin over a century timescale. As can be seen in Figure 3, observed (Figure 3a, Kandasamy et al., 2014) and modeled (Figure 3b, van Emmerik et al., 2014) time series of economic development (proxied by total irrigated area and irrigation water utilisation) correspond with the evolution of societal sentiment shown in the bottom panel of Wei et al.'s (2017) results (Figure 3c). Moreover, the narrative for each of the three phases described in Wei et al. (2017) repeats the timing and spirit of the phases depicted in Kandasamy et al. (2014), van Emmerik et al. (2014) and Elshafei et al. (2014, 2015) (Figure 3).

Another important implication of Wei et al.'s (2017) results is that they provide strong support for theories underpinning the use of the composite 'community sensitivity' variable put forward. Figure 4a,b illustrates that when societal values are initially focused on economic development the change in the community sensitivity variable (dV/dt) trends negative (i.e., society is predisposed towards anthropo-centric behaviours), whereas as societal values evolve towards environmental sustainability the change in community sensitivity variable trends positive (indicating a behavioural tendency towards conservation). Wei et al.'s (2017) findings thus provide strong validation for the non-linear dynamics observed in previously published coupled SH models that adopted alternate proxies for modelling the change in societal values and norms in relation to water resource management over time (i.e., composite community sensitivity and environmental awareness variables).

It is worth noting that Wei et al.'s (2017) results are not particular to a specific basin, but rather are intended to reflect a broader national or regional view. Validated SH models that endogenized water related beliefs and norms are distinct from regression based models that are not causal (e.g., Wei et al., 2017). The in-built non-linear dynamics allow possible 'extrapolation' of the coupled human-water dynamics across a gradient of hydro-climates, societies and economies, although this requires more work and testing. Similar to regionalisation techniques in hydrological modeling, socio-hydrological regionalisation will mean how the parameters of the coupled SH model, such as curvature parameter of the distribution function that trades off enviro-centric values with anthropo-centric values (Roobavannan et al., 2017), vary across different societies. Regression based models cannot be extrapolated to another place or time as there are no causal linkages provided to explain the transitional shifts in societal values observed therein. In other words, regression models that do not internalize coupled human water system dynamics can at best be used for 'interpolation' (i.e., can only explain the dynamics within the domain of the data) or data analysis. Nonetheless, verification of coupled models with data such as those presented in Wei et al. (2017) is important as it enables the discovery of fundamental principles of human behaviour through the validation of internal dynamics within the coupled models, and ultimately aids in the generalisation of socio-hydrologic system dynamics. The following shows how newspaper content analysis effectively plays the same informative role as Fish Species Richness, i.e., FSR (i.e., proxy for condition of ecology), in modelling water related endogenous behaviour.

In order to illustrate how newspaper content analysis serves as a complementary source of information that can be used in socio-hydrological modelling, the Wei et al. (2017) data was used to re-calibrate the 'environment awareness' state variable of van Emmerik et al. (2014).

Instead of wetland storage which was used in van Emmerik et al. (2014), the Fish Species Richness (*r*) is now used as a proxy of environment health. The temporal dynamics of environment awareness (E) is assumed to be given by the following differential equation:

$$\frac{dE}{dt} = \varepsilon(r)$$

where $\varepsilon(r)$ is the rate of accumulation/depletion of environmental awareness, which is a function of *r*. The functional form of $\varepsilon(r)$ is assumed to be given by:

$$\varepsilon(r) = \begin{cases} \alpha\,[\exp(\beta r) - 1], & r < r_c \\ -\lambda, & r > r_c \end{cases}$$

where r_c is the critical Fish Species Richness below which environment awareness is expected to increase exponentially governed by parameters α and β and λ is dissipation rate of environmental awareness when the ecosystem is healthy, i.e., $r > r_c$. The Fish Species Index, *r*, (Yoshika*wa et al*, 2014) is estimated by the following power law function:

$$r = \beta_0 {Q_B}^{\beta_1}$$

where Q_B is the flow in the downstream streamflow (i.e., environmental flow) and β_0 and β_1 are parameters of the FSR index (Yoshikawa *et al.*, 2014).

Values of the parameters $\alpha, \beta, \lambda, r_c$ need to be calibrated. In the absence of social data to calibrate the model, van Emmerik et al. (2014) used other basin-wide hydrological data to calibrate the model. Here we use the Wei et al. (2017) data to calibrate the model parameters, through application of the GLUE method. Initial estimates for the parameters are obtained manually making sure essential dynamics are captured. After that, 100,000 random samples of parameters (uniform sampling) that lie within the range of 50% to 150% of the initial values are obtained.

Figure 5a shows the modeled environmental awareness by van Emmerik et al. (2014) and a comparison with that calibrated to the Wei et al. (2017) data (Figure 5b). The environmental awarness (E, Figure 5a) bears a remarkable similarity to that obtained by Wei et al. (2017) through newspaper content analysis. Even though van Emmerik et al. (2014) at that time was not privy to the Wei et al. (2017) data, the model already succeeded in capturing the change in community's values and norms regarding water resources. While naturally attracting criticism for the lack of direct calibration, in hindsight the validity of the approach may now be appreciated and that new social data such as Wei et al.'s (2017) can be used to validate predictions of changing values and norms. Figure 5b shows how with foresight and with availibity of complementary societal values data of Wei et al. (2017) (see dashed line), the FSR can robustly simulate E. In doing so it provides independent validation of the model results of van Emmerik et.al. (2014) and the approch that was adopted at the time.

4. FROM PLACE-BASED TO GENERALIZED MODELS: CHALLENGES AND OPPORTUNITIES

Community sensitivity and environmental awareness are defined to capture the changing values and norms in different socio-hydrological models. In van Emmerik et al. (2014) a simple memory function governed by wetland storage sufficed, whereas in Elshafei et al. (2014) more complex community sensitivity equations were introduced, both linking water use related values, beliefs, norms and behavior through two-way feedbacks. Roobavannan et al. (2017), advanced this a step further by representing community level belief about the environment, i.e., community sensitivity, as a consequence of the distribution of weights that individuals attach to enviro-centric versus anthropo-centric values. Such a distribution was made contextual, by making it dependent on economic diversification. The endogenous treatment of values and norms by these studies have implicitly followed the general logic of elements of the VBN theory presented above, even if this was originally unintended (see the feedback from actions to beliefs in Figure 2), and have therefore responded to the challenges of incorporating feedbacks from water use behavior to beliefs and water management norms, consistent with the notion of endogenous and dynamic culture (Caldas et al. 2015).

It should be noted that these variables include values, beliefs and norms together (Figure 6). Indeed there is a need to further distinguish and differentiate the variables as they become more reliably observed, which would be realized with progress in SH. A more generalized understanding of community sensitivity can then be developed.

The pathway to generalisation of SH models is an important goal that allows future prediction (extrapolation in time) and translation of SH models at other geographical locations (extrapolation in space). It provides an important means for the adoption of socio-hydrology in the practice of long-term or strategic water resource management. Generalisation needs to address both the proxies used in SH modelling and the data used to calibrate them, as recent SH modelling studies have highlighted.

Models provide languages or templates in terms of which the following three aspects can be interpreted: 1) how beliefs and norms depend on values, 2) how values and norms influence individual behavior towards the environment, e.g., the wetland health or releasing environment water for bio-diversity, and 3) how pro-environmental behaviour of some in the community (e.g., rallies by the Green Movement) can influence the beliefs of others in the basin and bring about a change in water management (i.e., the feedback). Such templates also enlighten us with variables that need to be measured, so that multiple concepts via the models can be tested and can improve our system understanding.

For example, the policy change in the 1990s in MRB led to increased environmental flow. To interpret this in terms of change in water management norms of the MRB, models need to link beliefs and norms to water use behaviour within the basin. This needs information on a range of relevant values such as altruistic values (i.e., healthy MRB for present and future generations, enough money for the next generation) and egoistic values (i.e., making money), along with information on beliefs, norms, and behaviours, such as how water is being used.

4.1 Measurement of changing norms and values

Direct measurement of social value is often very difficult, resulting in the use of indirect methods (or proxies). Studies have attempted to understand social values on pro-environmentalism (Bengston 1994; Ives and Kendal 2013) and could be differentiated based on the method of measurement. Assigned values can be expressed in either monetary or non-monetary terms, and are relevant to economic and psychology approaches. In a social science context, assigned values have been quantitatively measured using a variety of techniques, including survey and interview approaches with the help of psychometric scales used in psychology (Bengston, 1994), social experiments in behavioral economics (Janssen et al., 2014; Yu et al., 2016) and content analysis (Seymour et al., 2010; Bark et al. 2016a; Xu and Bengston 1997; Wei et al., 2017).

Schwartz's framework (Schwartz, 1992) specifies a set of ten distinct values across cultures, which suggests that these are universal motivations for attitudes and behaviors. Humans differ mainly in terms of the importance attached to the constellation or structure of these held values. Drawing on Schwartz's framework, values can be measured through survey instruments, which include items that assess the degree to which respondents feel each value is important for their life (Dietz et al., 2005). Following Stern et al. (1999), beliefs (general and specific) and norms – along with Schwartz's value types – have been measured using survey instruments in a wide array on spatio-temporal contexts. These survey-based measures provide cross-sectional indicators. Whether, and how, values, beliefs and norms are dynamic is an active area of incipient research.

Economic valuation offers another set of useful approaches to inform natural resource management (Farber et al., 2002; Pande et al., 2011; Loomis et al., 2000; Norton and Noonan, 2007; Wilson et al., 1999; Bark et al., 2016b). Economic valuation approaches to measuring values are quite distinct from the broader meanings and uses of 'values' described above. These approaches include non-market valuation (Smith, 1993), contingent valuation (Bateman et al., 2006) and other related techniques, which have been extensively used over the decades and enabled the exploration of how people 'trade-off' their values in decision-making (Freeman 1993). This enables (i) values to be measured for large and diverse groups of people, (ii) changes in values to be tracked across groups of people or across time, and (iii) models to be developed to predict values based on other factors (e.g., demographics, cultural background). One key limitation of these approaches is that to the extent that values are measured monetarily, these approaches may not accurately capture underlying values that are difficult to assign monetary value, but may be more fundamental for decision-making. More generally, there are still unresolved and important questions about value measurement that reflect conceptual and methodological divisions among social sciences and economics. Overcoming these divisions will be crucial for addressing problems in coupled human-water systems.

It is less challenging to observe contemporary water-related behaviour. However, as the time scale of analysis expands, the task of measuring behaviour becomes equally challenging. Paleoclimate proxies such as $\delta^{18}O$ or tree rings have been extensively used to interpret water availability as well as social organization in the past (Pande and Ertsen, 2014; Staubwasser et al., 2003). These observations can be supplemented by other forms of indirect measurement of water related behaviour such as newspaper content analysis, and records of memberships in activist organisations, strengthening proxy observations of pro-environmental behaviour in the near past.

4.2 Utilisation of new types of data

A challenge related to model transferability is generic data needs. If environment awareness and community sensitivity functions are able to assess some trade-off between enviro-centric and anthropo-centric values types, global socio-economic data sets such as the World Value Surveys (WVS, 2017) and UN demographic datasets (UN, 2017) might offer the possibilty of quantifying values, so that models can be transferred to unmonitored locations. Whether such data sources can be used to quantify such values remains a very important open question.

In the past, the use of soft data in hydrological modelling has been demonstrated to provide additional insights into the functioning of ungauged basins, and has in some cases been used to successfully assess the realism of a model (see e.g., van Emmerik et al., 2015). Similarly, socio-hydrological systems face similar problems of extrapolation to other places, as numerical data series do not always exist to calibrate or validate SH models. Wei et al.'s (2017) use of newspaper content data to compute a numerical expression of environmental sustainability and economic development demonstrates the benefits of further exploration of this type of new data sources since it can allow the calibration of SH models, as shown in Figure 5. Future efforts should therefore not only be limited to developing new SH modeling frameworks, but also entail finding new ways to access information and translate it into numerical expressions, e.g., indices such as FSR, that can be used for model validation, and model realism assessment.

A new era of data-driven science (Peters-Lidard et al., 2017) is dawning, with increased computational power, new proxies and alternative data sources. Smart distillation of information from alternative sources (e.g., web databases, social data, other types of Big Data) may provide the valuable auxiliary data required to take the next step in SH model development and provide an innovative way to find and quantify the social proxies which are currently difficult to justify. This will need to be combined with online data monitoring such as smart sensing and citizen science monitoring as well as field campaigns to validate model results as well as to obtain socio-hydrological data relating to e.g. environmental sentiment, local sociatel values, and fertility conditions. In the future, socio-hydrologists could exploit or mine data/information from such varied sources, leading to the inclusion of Big Data science in socio-hydrology. This new paradigm represents a clear set of opportunities for data-mining and data-driven modelling methods in socio-hydrology. These apply machine learning and 'computationally intelligent' algorithms to elicit, characterise, quantify and model the myriad, implicit structures and relationships embedded within complex, multivariate datasets. In so doing, they offer a pathway for formulating new understandings of the saliency and power of socio-hydrologic variables, and the inter-relationships and behaviours that exist between them (Mount et al., 2016).

4.3 Comparative socio-hydrology studies

Parameters are used to calibrate the proxies to fit local basin data. Comparative studies from several basins will enable better interpretation of what model parameters mean and their character. For example, Roobavannan et al. (2017)'s model of endogenous behaviour could be made more socio-hydrologically meaningful. Its attractiveness parameter relates migration to the difference in unemployment within and outside the basin. A more meaningful representation of this variable, for example in terms of the cost of migration, such as moving costs and the cost of obtaining new skills away from water based employment, will enable regionalisation of associated parameter values and the transfer of models from data intensive basins such as the MRB to data scarce basins such as the Aral Sea.

Comparative studies can also provide the data to develop regional relationships for SH model parameters. Similar to regionalisation techniques in hydrological modeling (Asong et al., 2015; Buytaert and Beven, 2009; Götzinger and Bárdossy, 2007; Merz and Blöschl, 2004; Yadav et al., 2007; Blöschl et al., 2013), socio-hydrological regionalisation will define how the parameters of the coupled SH model vary with different societies and basins. Once defined, regional curves may be used to interpolate parameters and hence models to ungauged locations. Initial efforts have already been attempted in Elshafei et al., (2016) but these need to be improved and validated through more independent comparative studies. Yet another possibility can be of investigating a Budyko type curve for coupled human-water systems with endogenous values and norms that will enable extrapolation of emergent behaviours in space and time. Comparative assessement will also put to test theories, such as those that propose values and norms as emergent properties of a coupled human-water system, such that all its biological constituents including humans and vegetation obey certain metabolic scaling laws (Fischer-Kowalski, 1998; Silva et al., 2006).

In this regard, a new working group on comparative socio-hydrology within Panta Rhei has been launched to serve this purpose (Fuqiang Tian, personal communication). It plans to obtain socio-hydrological data from diverse river basins such as Tarim in China, Murrumbidgee in Australia and Kissimmee in USA, including historical documentation of the evolution of coupled human-water system to develop a generalized understanding of coupled human-water behavior. This is being done through comparative analysis to identify and interpret diverse emergent behavior such as farmer suicides in less developed and developed countries such as India and Australia respectively, "pendulum swing" in basins in China, USA and Australia and the levee effect versus memory effect in flood plains across the globe. Such comparative analyses can prove to be very constructive in identifying general principles that govern dynamic changes in values and norms.

5. CONCLUSIONS

Recent socio-hydrological studies in Austrialia have moved closer toward integration with key social science theories of perception and behavior, and have taken a key step toward endogenizing values and norms. These models are internally consistent with patterns observed with proxy data of environmental awareness and water policy change, such as the newpaper articles based proxies of Wei et al. (2017). However, such theoretically and empirically consistent models are only the beginning of the way forward to generalizing models and its predictions for sustainable water management.

Human culture – comprised of values, beliefs, and norms – is key to understanding stability and change in coupled human-water systems. Often, such variables and related closure relationships within socio-hydrological models are latent and hard to observe. This poses challenges in testing and confirming the realism of assumed relationships. However, with the advent of the information intense era, diverse proxy data sources such as citizen science observatories, and social media can be harnessed and novel big data algorithms can be used to process them in a form that can be of use to socio-hydrological models.

Yet such opportunities can only build confidence in our place based understanding of a socio-hydrological phenomenon such as the pendulum swing observed in the Murrumbidgee River Basin. What we need are generalized relationships or principles underlying emergent phenomena if we are to stand up to the challenge of making predictions in ungauged locations in space and time. This clearly calls for more place based studies, both past and present and across spatio-temporal scales, that are backed up by novel socio-hydrological observations such as historical accounts and socio-centric data, and a comparative analysis of such studies where similar emergent phenomenon has been observed to help synthesize the underlying socio-hydrological principles.

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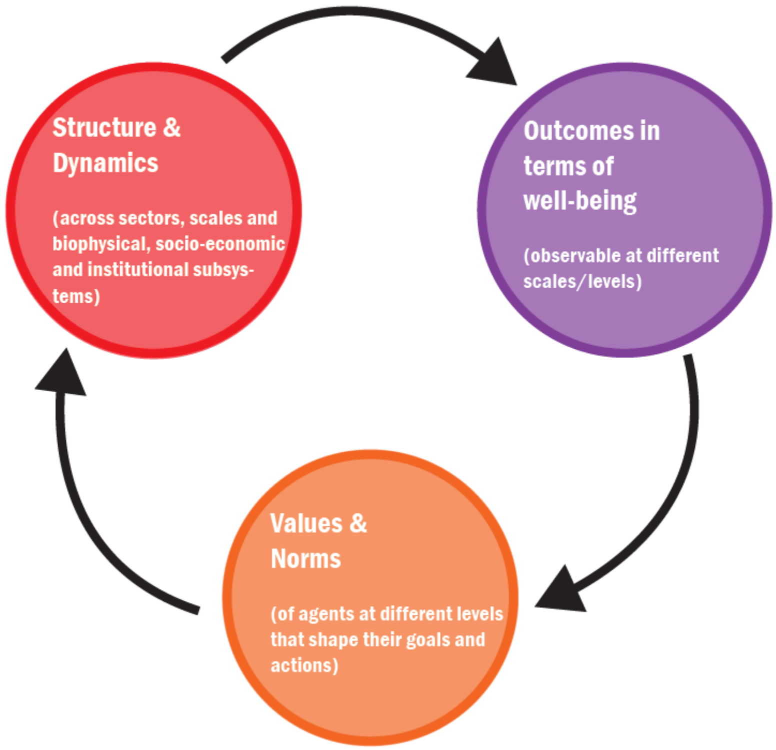


Figure 1: Framework proposed by Sivapalan et al., (2014). Socio-hydrology models use proxies for environment degradation and for economic well being

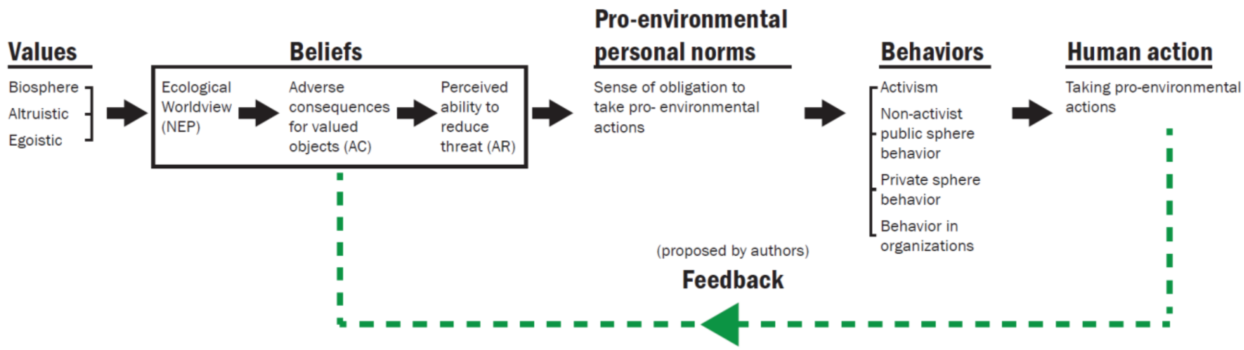
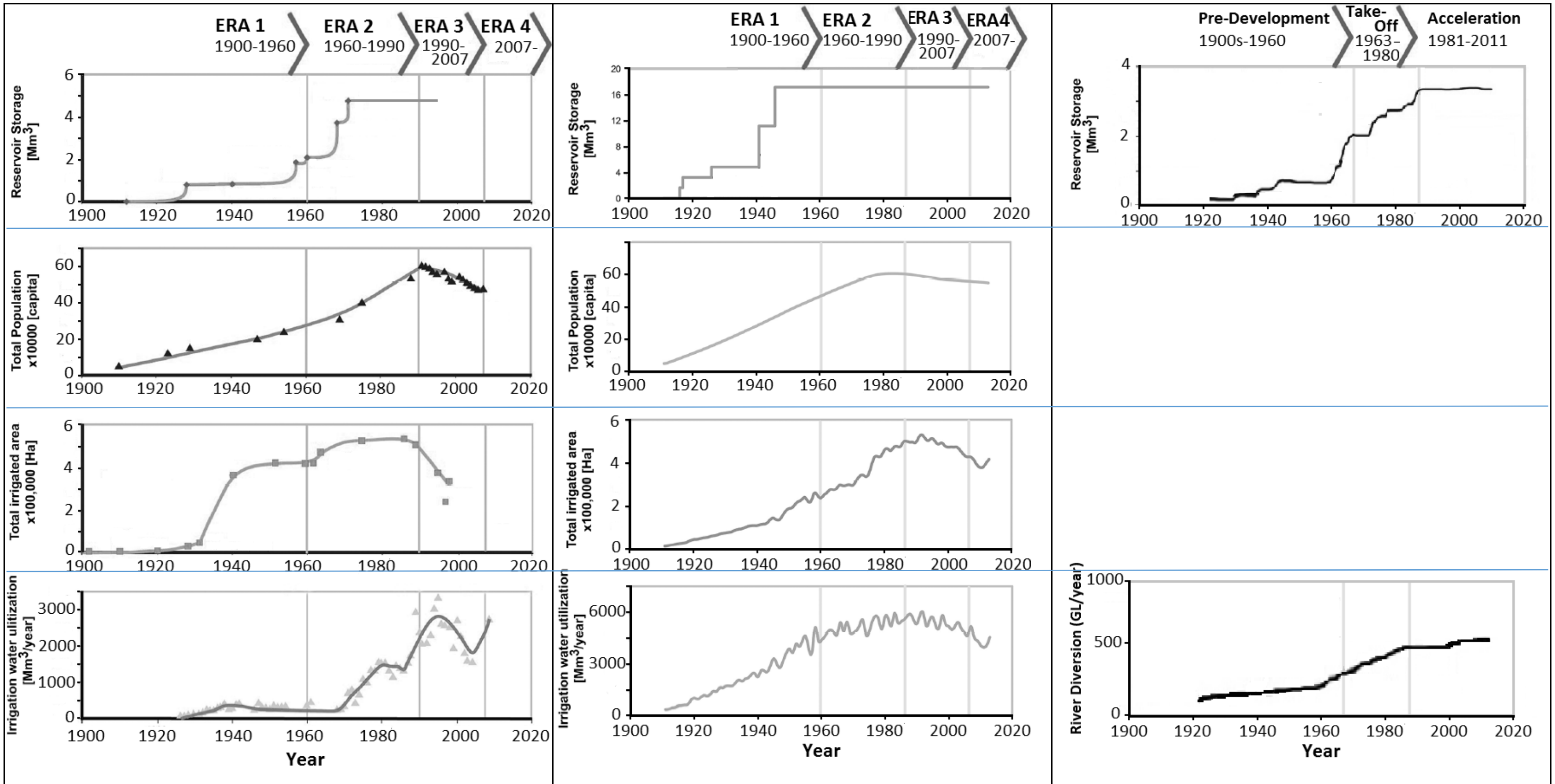


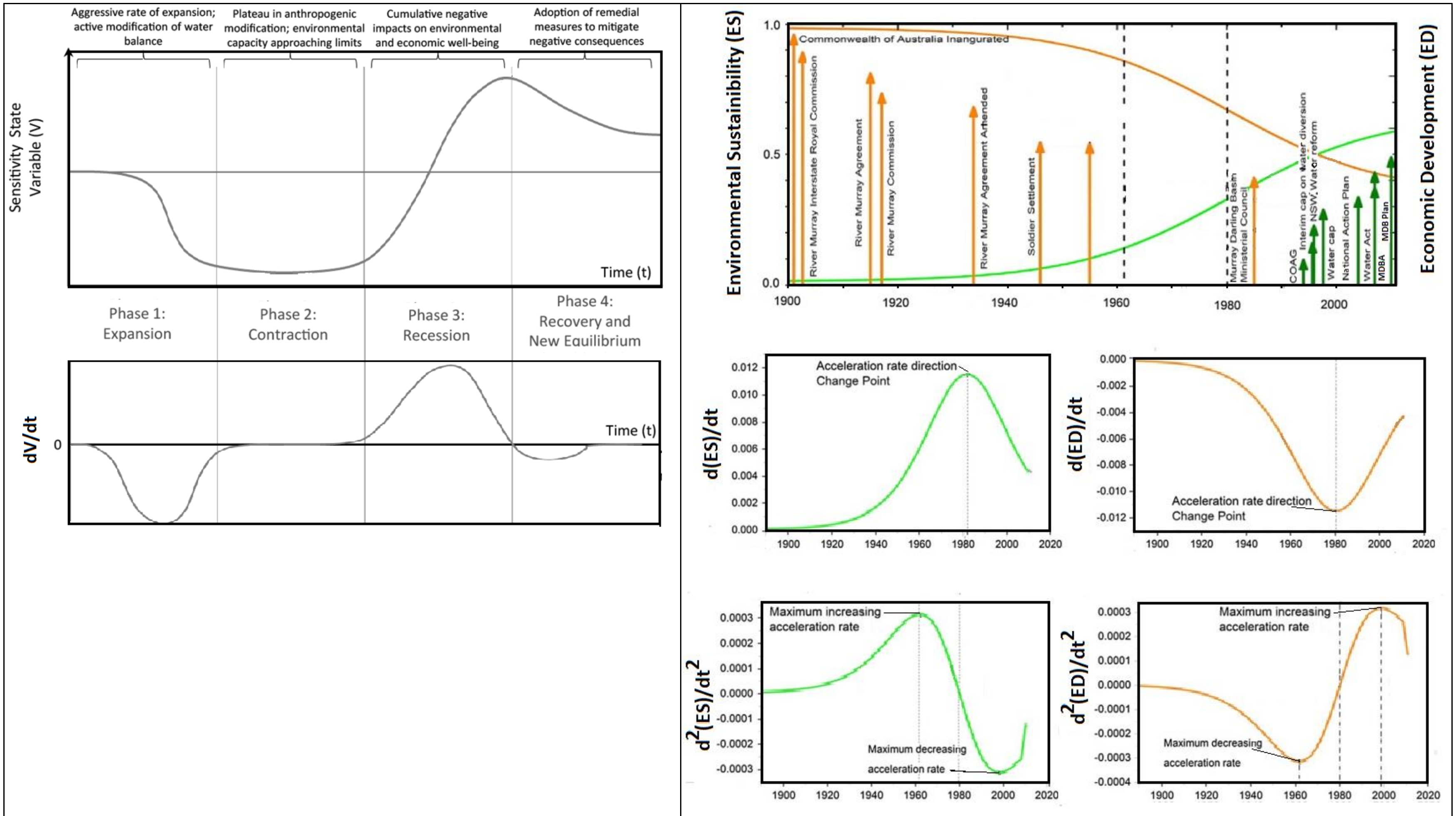
Figure 2: Value Belief Norm (VBN) theory. Adapted from (Ives and Kendal, 2014; Stern, 2000). The feedback (green arrow) from communal behavior to individual beliefs is introduced here by the authors to recognize that it has indeed been included in recent SH studies in preliminary ways and (van Emmerik et al, 2014; Elshafei et al, 2014; Roobavaanan et al, 2017) needs to be formalized in future studies.



(a) Observed data (Kandasamy et al., 2014) and modelled pendulum swing in the MRB.	(b) Modelled pendulum swing in the MRB (van Emmerik, 2014)	(c) Murray-Darling data (which includes the MRB) depicted in Wei et al. (2017).

Figure 3. Observed and modelled pendulum swing in the MRB during the period 1910–2013. Era 1 (1900-1980) Expansion of agriculture and associated infrastructure, Era 2 (1960-1990) Onset of environmental degradation, Era 3 (1990-2007) Establishment of

widespread environmental degradation, Era 4 (207-2014) Remediation and emergence of environmental customer. The eras correspond to phases in Elshafei et al (2015): Expansion (1911-1960), aggressive rate of expansion and active modification of water balance; Contraction (1960s), plateau in anthropogenic modification; Recession (1970-2002), cumulative negative impacts on economic and environmental well-being; Recovery and new equilibrium (2002-present), Adoption of remedial measures; and in Wei et al. (2017): Pre-development (1900s-1960s) Societal values dominated by economic development; Take-off (1963-1980) Societal values reflected increasing environmental awareness due to outbreak of pollution events; Acceleration (1981-2011) Growing shift in societal values towards environmental sustainability.



(a) An idealised sketch showing a hypothetical trajectory over time for (top) the Sensitivity state variable, and (bottom) the change in Sensitivity (dV/dt) in the case of an example catchment (Elshafei et al., 2014).

b) Regression curves of societal value of economic development and environmental sustainability, and major turning points and development stages of each societal value (Wei et al., 2017).

Figure 4. Defining shifts and turning points of stages of societal values

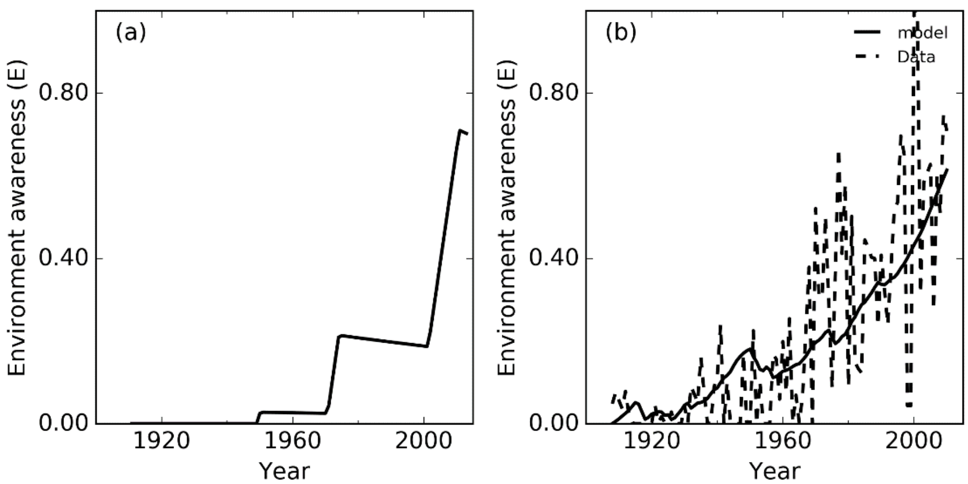


Figure 5. (a) Variation of modelled environment awareness by van Emmerik et.al, (2014) using calibrated model with hydrological and population data (b) variation of modelled environment awareness using calibrated model (solid line) with societal value data (data from Wei et al. (2017), dashed line) of water resources for environment stability.

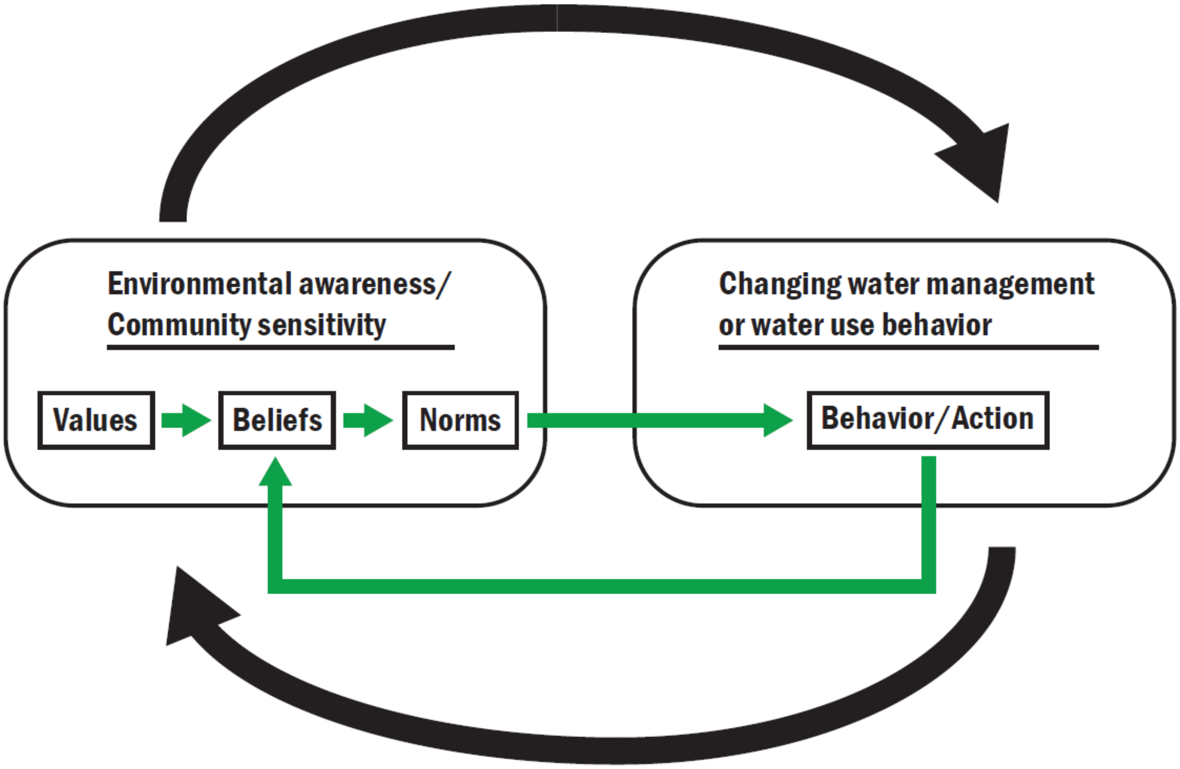


Figure 6. A conceptual diagram of relationships between variables studied in SH modelling and VBN theory. Black arrows show the feedback loops captured in SH modelling and green arrows show relationships that need to be studied in context of water management.