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Modelling socio-hydrological systems: a review of concepts, approaches and applications

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Abstract

Interactions between humans and the environment are occurring on a scale that has never previously been seen; one environmental facet that has seen particular co-evolution with society is water. The scale of human interaction with the water cycle, along with the coupling present between social and hydrological systems, means that decisions that impact water also impact people. Models are often used to assist in decision-making regarding hydrological systems, and so in order for effective decisions to be made regarding water resource management, these interactions and feedbacks should be accounted for in models used to analyse systems in which water and humans interact. This paper reviews literature surrounding aspects of socio-hydrological modelling. It begins with background information regarding the current state of socio-hydrology as a discipline, before covering reasons for modelling and potential applications. Some important concepts that underlie socio-hydrological modelling efforts are then discussed, including ways of viewing socio-hydrological systems, space and time in modelling, complexity, data and model conceptualisation. Several modelling approaches are described, the stages in their development detailed and their applicability to socio-hydrological cases discussed. Gaps in research are then highlighted to guide directions for future research. The review of literature suggests that the nature of socio-hydrological study, being interdisciplinary, focusing on complex interactions between human and natural systems, and dealing with long horizons, is such that modelling will always present a challenge; it is, however, the task of the modeller to use the wide range tools afforded to them to overcome these challenges as much as possible. The focus in socio-hydrology is on understanding the human–water system in a holistic sense, which differs from the problem solving focus of other water management fields, and as such models in socio-hydrology should be developed with a view to gaining new insight into these dynamics. There is an essential choice that socio-hydrological modellers face in deciding between representing individual system processes, or viewing the system from a more abstracted level and modelling it as such; using these different

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

approaches have implications for model development, applicability and the insight that they are capable of giving, and so the decision regarding how to model the system requires thorough consideration of, among other things, the nature of understanding that is sought.

1 Introduction

Land-use changes and water resource management efforts have altered hydrological regimes throughout history (Savenije et al., 2014), but the increase in the scale of human interference has led to an intensification in the effects that our interventions have upon the hydrology of landscapes around the world, as well as having significant impacts on societal development, via our co-evolution with water (Liu et al., 2014). Indeed the scale of human intervention that has taken place in meeting the requirements of a population that has expanded from 200 million to 7 billion over the last 2000 years has required such control that in many locations water now flows as man dictates, rather than as nature had previously determined (Postel, 2011). The pace and scale of change that anthropogenic activities are bringing to natural systems are such that hydroclimatic shifts may be brought about in the relatively short term (Destouni et al., 2012), as well as leading to a coupling between human and hydrologic systems (Wagener et al., 2010); this coupling means that both positive and negative social impacts may be brought about via decisions that impact the hydrological system. The growing awareness of the impacts humans are having on a global scale and associated stewardship practices (Steffen et al., 2007) will, therefore, have impacts beyond the ecological and hydrological spheres.

A number of terms have been coined in order to develop the way in which the relationship between mankind and nature, and in particular water, are thought about: “Hydrosociology” (Falkenmark, 1979; Sivakumar, 2012), the “Hydro-social” (Swyngedouw, 2009) and “Hydrocosmological” (Boelens, 2013) cycles and “Ecohydrosolidarity” (Falkenmark, 2009) to name a few. The concept of “The Anthropocene” (Crutzen

HESSD
12, 8761–8851, 2015

and Stoermer, 2000; Crutzen, 2002) to describe a new geological epoch in which we now exist, where mankind represents "a global geological force" (Steffen et al., 2007), rivalling the force of nature in the scale of impact on the earth system (Steffen et al., 2011), has been in circulation for some time, and the fact that man and water are linked through a "system of mutual interaction" (Falkenmark, 1977) has been recognised for many years. However, due to factors such as the implicit complexity and uncertainty involved in coupled human and natural systems, the feedbacks and interrelations between society and water are not commonly modelled when forecasting and developing policy. The relatively new field of "Socio-hydrology" (Sivapalan et al., 2012), however, seeks to change this by aiming to understand "the dynamics and co-evolution of coupled human–water systems".

This paper seeks to draw together relevant information and details of concepts pertaining to modelling of socio-hydrological systems, as well as reviewing reasons for modelling and potential future applications, before describing possible modelling techniques and their relevance to socio-hydrological situations, and so identifying in what circumstances different modelling techniques would be well used. This paper is not intended to be a comprehensive review of all modelling studies that could be deemed socio-hydrologic in nature, rather it should be seen as an amalgamation of knowledge surrounding socio-hydrological modelling, such that understanding why and how it could be undertaken is easily accessible. As can be seen in Fig. 1, the number of articles being published which relate to socio-hydrological modelling has increased dramatically over recent years, demonstrating interest in the subject (2015 is not included as this year is not complete, so its inclusion could cause confusion).

1.1 Socio-hydrology

The subject of socio-hydrology, first conceived by Sivapalan et al. (2012), seeks to understand the "dynamics and co-evolution of coupled human–water systems", including system behaviours such as tipping points and feedback mechanisms, some of which may be emergent (unexpected), caused by non-linear interactions between

HESSD
12, 8761–8851, 2015

processes occurring on different spatio-temporal scales. Such dynamics include "pendulum swings" that have been observed in areas such as the Murray–Darling Basin, where extensive agricultural development was followed by a realisation of the impacts this was having and subsequent implementation of environmental protections policies (Kandasamy et al., 2014; van Emmerik et al., 2014), the co-evolution of landscapes with irrigation practices and community dynamics (Parveen et al., 2015), as well as instances of catastrophe in which hydrological extremes have not been catastrophic in themselves, rather social processes that result in vulnerability have made extreme events catastrophic (Lane, 2014). There are also cases where social systems have not interacted with water in the way that was anticipated: examples include the virtual water efficiency and peak-water paradoxes discussed by Sivapalan et al. (2014), and yet others where the perception, rather than the actuality, that people have of a natural system determines the way it is shaped (Molle, 2007). Studying these systems requires not only an interdisciplinary approach, but also an appreciation of two potentially opposing ontological and epistemological views: the Newtonian view, whereby reductionism of seemingly complex systems leads to elicitation of fundamental processes, and the Darwinian view, in which patterns are sought, but complexity of system processes is maintained (Harte, 2002). Taking a dualistic worldview encompassing both of these perspectives, as well as the manner in which man and water are related (Falkenmark, 1979), allows for an appreciation of impacts that actions will have due to physical laws, as well as other impacts that will be brought about due to adaptations from either natural or human systems.

In understanding socio-hydrology as a subject, it may be useful to also briefly understand the history of terminology within hydrological thinking, and how this has led to the current understanding. Study of the hydrologic cycle began to "serve particular political ends" (Linton and Budds, 2013), whereby maximum utility was sought through modification of the cycle, and was viewed initially as fairly separate from human interactions: after several decades this led to a focus on water resources development in the 1970s, language clearly indicative of a utility-based approach. However, a change

HESSD
12, 8761–8851, 2015

in rhetoric occurred in the 1980s, when water resources management (WRM) became the focus, and from this followed integrated water resource management (IWRM) and adaptive water management (AWM) (Savenije et al., 2014), the shift from "development" to "management" showing a change in the framing of water, while the concepts of integrated analysis and adaptivity show a more holistic mindset being taken. The introduction of the hydrosocial cycle (Swyngedouw, 2009) shows another clear development in thought, which aimed to "avoid the pitfalls of reductionist ... water resource management analysis" (Mollinga, 2014) for the purpose of better water management. "A science, but one that is shaped by economic and policy frameworks" (Lane, 2014), socio-hydrology also represents another advancement in hydrological study, which requires further rethinking of how hydrological science is undertaken.

Understanding of water (perceived or otherwise), as well as intervention following this understanding, has lead to large changes in landscapes, which have then altered the hydrological processes that were initially being studied (Savenije et al., 2014), and as such the goals of study in hydrology are subject to regular modification and refinement. Troy et al. (2015a) point out that, as a subject still in its infancy, socio-hydrology is still learning the questions to ask. However, Sivapalan et al. (2014) sets out the main goals of socio-hydrologic study:

- Analysis of patterns and dynamics on various spatio-temporal scales for discernment of underlying features of biophysical and human systems, and interactions thereof

- Explanation and interpretation of socio-hydrological system responses, such that possible future system movements may be forecast (current water management approaches often result in unsustainable management practices due to current inabilities in prediction)

- Furthering the understanding of water in a cultural, social, economic and political sense, while also accounting for its biophysical characteristics and recognising its necessity for existence

HESSD
12, 8761–8851, 2015

It is hoped that the achievement of these goals will lead to more sustainable water management and may, for example, lead to the ability to distinguish between human and natural influences on hydrological systems, which has thus far been difficult (Karoly, 2014). Achievement of these goals will involve study in several spheres, including in historical, comparative and process contexts (Sivapalan et al., 2012), as well as “across gradients of climate, socio-economic status, ecological degradation and human management” (Sivapalan et al., 2014). In accomplishing all of this, studies in socio-hydrology should strive to begin in the correct manner; as Lane (2014) states, “a socio-hydrological world will need a strong commitment to combined social-hydrological investigations that frame the way that prediction is undertaken, rather than leaving consideration of social and economic considerations as concerns to be bolted on to the end of a hydrological study”.

The importance of socio-hydrology has been recognised since its introduction: The International Association of Hydrological Sciences (IAHS) has designated the title of their “Scientific Decade” (2013–2022) as “Panta Rhei (Everything flows)” (Montanari et al., 2013), in which the aim “is to reach an improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems” (Montanari et al., 2013). In the IAHS’s assessment of hydrology at present (Montanari et al., 2013), it is recognised that current hydrological models are largely conditioned for analysis of pristine catchments and that societal interaction is generally included in separately developed models, so that interactions between the two are not well handled: socio-hydrological study is posited as a step towards deeper integration that has long been called for (Falkenmark, 1979). The recent series of “Debates” papers in *Water Resources Research* (Di Baldassarre et al., 2015; Sivapalan, 2015; Gober and Wheater, 2015; Loucks, 2015; Troy et al., 2015a) shows a real, continued commitment to the development of socio-hyrology as a subject; the unified conclusion of these papers is that the inclusion the interaction between society and water is necessary in modelling, though the authors varied in their views on how this should be conducted, the sphere within which socio-hydrology should operate, and

HESSD
12, 8761–8851, 2015

P. Blair and W. Buytaert

the value that socio-hydrological models may have. The continued commitment necessary to the subject is highlighted via the statement that "if we who have some expertise in hydrologic modelling do not some other discipline will [include nonhydrologic components in hydrologic models]" (Loucks, 2015).

In a world where the decisions that mankind makes have such influence, those who make those decisions should be well-informed as to the impacts their decisions may have. As such, those working in water resources should be well-versed in socio-hydrologic interaction, seeking to be "T-shaped professionals" (McClain et al., 2012) (technical skills being vertical, coupled with "horizontal" integrated resources management skills), and as such training should certainly reflect this, perhaps learning from the way that ecohydrology is now trained to hydrologists.

Socio-hydrology can learn many lessons from other, similarly interdisciplinary subjects. Ecohydrology is one such subject, whereby the interaction between ecology and hydrology is explicitly included. Rodriguez-Iturbe (2000) gives a number of the questions that ecohydrology attempts to answer, which may be very similar to the questions that socio-hydrology attempts to answer:

- "Is there emergence of global properties out of these [eco-hydrological] dynamics?"
- "Does it tend to any equilibrium values?"
- "Is there a spontaneous emergence ... associated with the temporal dynamics?"
- "Can we reproduce some of the observed ... patterns?"
- "Is there a hidden order in the space-time evolution which models could help to uncover?"
- "Does the system evolve naturally, for example, without being explicitly directed to do so?"

HESSD
12, 8761–8851, 2015
Modelling socio-hydrological systems
P. Blair and W. Buytaert

Ecohydrology would also necessarily be a constituent part of socio-hydrological models, since anthropogenic influences such as land cover have ecological impacts, which will themselves create feedbacks with social and hydrological systems. Another subject that socio-hydrology may learn a great deal from is socio-ecology, a subject studying the interrelations between ecological and social systems.

1.2 Socio-ecology

The study of socio-ecological systems (SESs) and coupled human and natural systems (CHANS), involves many aspects similar to that of socio-hydrology: feedbacks (Runyan et al., 2012), non-linear dynamics (Garmestani, 2013), co-evolution (Hadfield and Seaton, 1999), adaptation (Lorenzoni et al., 2000), resilience (Folke et al., 2010), vulnerability (Simelton et al., 2009), issues of complexity (Liu et al., 2007a), governance (Janssen and Ostrom, 2006), policy (Ostrom, 2009) and modelling (Kelly (Letcher) et al., 2013; An, 2012) are all involved in thinking around, and analysis of, SESs. As such, there is much that socio-hydrology can learn from this fairly established (Crook, 1970) discipline, and so in this paper a proportion of the literature presented comes from the field of socio-ecology due to its relevance. Learning from the approaches taken in socio-ecological studies would be prudent for future socio-hydrologists, and so much can be learnt from the manner in which characteristics such as feedback loops, thresholds, time-lags, emergence and heterogeneity, many of which are included in a great number of socio-ecological studies (Liu et al., 2007a) are dealt with. Many key concepts are also applicable to both subject areas, including the organisational, temporal and spatial (potentially boundary-crossing) coupling of systems bringing about behaviour “not belonging to either human or natural systems separately, but emerging from the interactions between them” (Liu et al., 2007b), and the required nesting of systems on various spatio-temporal scales within one another.

Socio-hydrology may, in some ways, be thought of as a sub-discipline of socio-ecology (Troy et al., 2015a), and indeed some studies that have been carried out under the banner of socio-ecology could well be termed socio-hydrologic studies (e.g.

Roberts et al., 2002; Schlüter and Pahl-Wostl, 2007; Marshall and Smith, 2010; Molle, 2007), and Welsh et al. (2013) terms rivers "complicated socio-ecological systems that provide resources for a range of water needs". There are however, important differences between socio-ecology and socio-hydrology which should be kept in mind when transferring thinking between the two disciplines, for example infrastructure developments such as dams introduce system intervention on a scale rarely seen outside this sphere (Elshafei et al., 2014), and the speed at which some hydrologic processes occur at means that processes on vastly different temporal scales must be accounted for (Blöschl and Sivapalan, 1995). There are also unique challenges in hydrologic data collection, for example impracticably long timescales are often being required to capture hydrologic extremes and regime changes (Elshafei et al., 2014).

In a study comparable to this, though related to socio-ecological systems, Schlüter (2012) gives research issues in socio-ecological modelling; these issues are also likely to be pertinent in socio-hydrological modelling:

- "Implications of complex social and ecological structure for the management of SESs
- The need to address the uncertainty of ecological and social dynamics in decision making
- The role of coevolutionary processes for the management of SESs
- Understanding the macroscale effects of microscale drivers of human behaviour"

Along with studying similarly defined systems and the usage of similar techniques, socio-ecology has suffered problems that could also potentially afflict socio-hydrology. For example, different contributors have often approached problems posed in socio-ecological systems with a bias towards their own field of study, and prior to great efforts to ensure good disciplinary integration social scientists may have "neglected environmental context" (Liu et al., 2007b) and ecologists "focused on pristine environments in which humans are external" (Liu et al., 2007b). Even after a coherent SES framework

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

was introduced (Liu et al., 2007b), some perceived it to be “lacking on the ecological side” (Epstein and Vogt, 2013), and as such missing certain “ecological rules”. Since socio-hydrology has largely emerged via scholars with water resources backgrounds, inclusion of knowledge from the social sciences, and collaboration with those in this field, should therefore be high on the agenda of those working in socio-hydrology to avoid similar issues. Another issue that both socio-ecologists and socio-hydrologists face is the tension between simplicity and complexity: the complexity inherent in both types of coupled system renders the development of universal solutions to issues almost impossible, whereas decision-makers prefer solutions to be simple (Ostrom, 2007), and while the inclusion of complexities and interrelations in models is necessary, including a great deal of complexity can result in opacity for those not involved in model development, leading to a variety of issues. The complexity, feedbacks, uncertainties, and presence of natural variabilities in socio-ecological systems also introduce issues in learning from systems due to the obfuscation of system signals (Bohensky, 2014), and similar issues will also be prevalent in socio-hydrological systems.

2 The demand for socio-hydrological system models

There could be significant demand for socio-hydrological system models in several circumstances, however there are three main spheres in which such modelling could be used (Kelly (Letcher) et al., 2013):

- System Understanding
- Forecasting and Prediction
- Policy and Decision-making

The purpose of this section is to give an idea of why socio-hydrological modelling may be conducted, as the techniques used should be steered by what is required of their

HESSD
12, 8761–8851, 2015

outputs. This section is linked to, though separated from, current and future applications, since the applications will likely require study in all three of the mentioned spheres in the solution of complex problems (examples of applications will later be given in a further section). In this section, the significance of modelling in each of these areas will be introduced, the limitations that current techniques have investigated, and so the developments that socio-hydrological modelling could bring determined. The three typologies of socio-hydrological study that Sivapalan et al. (2012) presents (historical, comparative and process) could all be used in the different spheres. There are of course, significant difficulties in socio-hydrological modelling, which should not be forgotten, in particular due to the fact that "characteristics of human variables make them particularly difficult to handle in models" (Carey et al., 2014), as well as issues brought about by emergence, as models developed on current understanding may not be able to predict behaviours that have not previously been observed, or they may indeed predict emergent properties that do not materialise in real-world systems.

2.1 System understanding

"Perhaps a way to combat environmental problems is to understand the interrelations between ourselves and nature" (Norgaard, 1995). Understanding the mechanisms behind system behaviour can lead to a more complete picture of how a system will respond to perturbations, and so guide action to derive the best outcomes. For example, understanding the mechanisms that bring about droughts, which can have exceptionally severe impacts, can allow for better preparation as well as mitigative actions (Wanders and Wada, 2014). Creating models to investigate system behaviour can lead to understanding in many areas, for example Levin et al. (2012) gives the examples of socio-ecological models leading to understanding of how individual actions create system-level behaviours, as well as how system-level influences can change individual behaviours.

IWRM has been the method used to investigate human–water interactions in recent years, but the isolation in which social and hydrological systems are generally treated

HESSD
12, 8761–8851, 2015

in this framework leads to limitations in assimilating "the more informative co-evolving dynamics and interactions over long periods" (Elshafei et al., 2014) that are present. This isolation has also led to the understanding of mechanisms behind human–water feedback loops currently being poor, and so integration has become a priority (Montanari et al., 2013).

If models of the coupled human–water system could be developed, this could give great insight into the interactions that occur, the most important processes, parameters and patterns, and therefore how systems might be controlled (Kandasamy et al., 2014). Historical, comparative and process-based studies would all be useful in this regard, as understanding how systems have evolved (or indeed co-evolved Norgaard, 1981) through time, comparing how different locations have responded to change and investigating the linkages between different parameters are all valuable in the creation of overall system understanding. Improved system understanding would also lead to an improvement in the ability for interpretation of long-term impacts of events that have occurred (Kandasamy et al., 2014). It is important to note that, while this study focuses on modelling, system understanding cannot be brought about solely through modelling, and other, more qualitative studies are of value, particularly in the case of historical investigations (e.g. Paalvast and van der Velde, 2014).

2.2 Forecasting and prediction

Once a system is understood, it may be possible to use models to predict what will happen in the future. Predictive and forecasting models estimate future values of parameters based on the current state of a system and its known (or rather supposed) behaviours. Such models generally require the use of past data in calibration and validation. Being able to forecast future outcomes in socio-hydrological systems would be of great value, as it would aid in developing foresight as to the long-term implications of current decisions, as well as allowing a view to what adaptive actions may be necessary in the future. Wanders and Wada (2014) state that "Better scenarios of future human water demand could lead to more skilful projection for the 21st century", which could

HESSD
12, 8761–8851, 2015

be facilitated by "comprehensive future socio-economic and land use projections that are consistent with each other", as well as the inclusion of human water use and reservoirs, which now have "substantial impacts on global hydrology and water resources", as well as "modelling of interacting processes such as human-nature interactions and feedback"; socio-hydrological modelling may be able to contribute in all of these areas.

An example area of study in prediction/forecasting is resilience: prediction of regime transitions is very important in this sphere (Dakos et al., 2015), and while IWRM does explore the relationship between people and water, it does so in a largely scenario-based fashion, which leaves its predictive capacity for co-evolution behind that of socio-hydrology (Sivapalan et al., 2012), and so in study of such areas a co-evolutionary approach may be more appropriate.

However, there are significant issues in the usage of models for prediction, including the accumulation of enough data for calibration (Kelly (Letcher) et al., 2013). Issues of uncertainty are very important when models are used for forecasting and prediction, as the act of predicting the future will always involve uncertainty. This is a particular issue when social, economic and political systems are included, as they are far more difficult to predict than physically-based systems. Also Wagener et al. (2010) state that "to make predictions in a changing environment, one in which the system structure may no longer be invariant or in which the system might exhibit previously unobserved behaviour due to the exceedance of new thresholds, past observations can no longer serve as a sufficient guide to the future". However, it must surely be that guidance for the future must necessarily be based on past observations, and as such it could be that interpretations of results based on the past should change.

2.3 Policy and decision-making

Decision-making and policy formation are ultimately where model outputs can be put into practice to make a real difference. Models may be used to differentiate between policy alternatives, or optimise management strategies, as well as to frame policy issues, and can be very useful in all of these cases. However, there are real problems

HESSD
12, 8761–8851, 2015

in modelling and implementing policy in areas such as in the management of water resources (Liebman, 1976): it is a commonly stated that planning involves "wicked" problems, plagued by issues of problem formulation, innumerable potential solutions, issue uniqueness and the difficulties involved in testing of solutions (it being very difficult to accurately test policies without implementing them, and then where solutions are implemented, extricating the impact that a particular policy has had is difficult, given the number of variables typically involved in policy problems) (Rittel and Webber, 1973). Models necessarily incorporate the perceptions of developers, which can certainly vary, and so models developed to investigate the same issue can also be very different, and suggest varying solutions (Liebman, 1976). Appropriate timescales should be used in modelling efforts, as unless policy horizons are very short, neglecting slow dynamics in socio-ecological systems has been said to produce indequate results (Crépin, 2007). There are also the issues of policies having time lags before impacts (this is compounded by discounting the value of future benefits), uncertainty in their long-term impacts at time of uptake, route causes of problems being obscured by complex dynamics and the fact that large-scale, top down policy solutions tend not to produce the best results due to the tendency of water systems to be "resistant to fundamental change" (Gober and Wheater, 2014). Complex systems (such as human–water systems) can, however, be good to manage, as multiple drivers and feedbacks mean that there are multiple targets for policy efforts that may make at least a small difference (Underdal, 2010).

Past water resource policy has been built around optimisation efforts, which have been criticised for having "a very tenuous meaning for complex human–water systems decision making" (Reed and Kasprzyk, 2009), since they assume "perfect problem formulations, perfect information and evaluation models that fully capture all states/consequences of the future" (Reed and Kasprzyk, 2009), meaning that they result in the usage of "optimal" policies that are not necessarily optimal for many of the possible future system states. Techniques such as multi-criteria/multi-objective meth-

HESSD
12, 8761–8851, 2015

P. Blair and W. Buytaert

ods (Hurford et al., 2014; Kain et al., 2007) attempt to improve upon this, producing pareto-efficient outcomes, but still rarely account explicitly for human–water feedbacks.

Good evidence is required for the formation of good policy (Ratna Reddy and Syme, 2014), and so providing this evidence to influence, and improve policy and best management practices should be an aim of socio-hydrology (Pataki et al., 2011), in particular socio-hydrological modelling. Changes in land-use are brought about by socio-economic drivers, including policy, but these changes in land-use can have knock-on effects that can impact upon hydrology (Ratna Reddy and Syme, 2014), and so land-productivity, water availability and livelihoods to such an extent that policy may be altered in the future. Socio-hydrology should at least attempt to take account of these future policy decisions, and the interface between science and policy to improve long-term predictive capacity (Gober and Wheater, 2014). There is a call for a shift in the way that water resources are managed, towards an ecosystem-based approach, which will require a "better understanding of the dynamics and links between water resource management actions, ecological side-effects, and associated long-term ramifications for sustainability" (Mirchi et al., 2014). SES analysis has already been used in furthering perceptions on the best governance structures, and has found that polycentric governance can lead to increased robustness (Marshall and Smith, 2010), and it may well be that socio-hydrology leads to a similar view of SHSs.

In order for outputs from policy-making models to be relevant they must be useable by stakeholders and decision-makers, not only experts (Kain et al., 2007). Participatory modelling encourages this through the involvement of stakeholders in model formulation, and often improves "buy-in" of stakeholders, and helps in their making sensible decisions (Kain et al., 2007), as well as an increase in uptake in policy (Sandker et al., 2010). This technique could be well used in socio-hydrological modelling. Gober and Wheater (2015) take the scope of socio-hydrology further, suggesting a need to include a "knowledge exchange" (Gober and Wheater, 2015) component in socio-hydrological study, whereby the communication of results to policy makers and their subsequent decision-making mechanisms are included to fully encompass socio-hydrological inter-

HESSD
12, 8761–8851, 2015

actions. However, Loucks (2015) points out that the prediction of future policy decisions will be one of the most challenging aspects of socio-hydrology.

2.4 Current and future applications

This section follows from the areas of demand for socio-hydrological to give a few examples (not an exhaustive list) of potential, non-location-specific examples of how socio-hydrological modelling could be used. These applications will incorporate system understanding, forecasting and prediction and policy formation, and where these spheres of study are involved they will be highlighted. SES models have been applied to fisheries, rangelands, wildlife management, bioeconomics, ecological economics, resilience and complex systems (Schlüter, 2012), and have resulted in great steps forward. Application of socio-hydrological modelling in the following areas could too result in progress in understanding, forecasting, decision-making and the much-needed modernisation of governance structures (Falkenmark, 2011) in different scenarios. This section should provide insight as to the situations where socio-hydrological modelling may be used in the future, and so guide the discussion of suitable modelling structures.

2.4.1 Understanding system resilience and vulnerability

Resilience can be defined as the ability for a system to persist in a given state subject to perturbations (Folke et al., 2010; Berkes, 2007), and so this “determines the persistence of relationships within a system” and can be used to measure the “ability of these systems to absorb changes of state variables, driving variables, and parameters” (Holling, 1973). Reduced resilience can lead to regime shift, “a relatively sharp change in dynamic state of a system” (Reyer et al., 2015), which can certainly have negative social consequences. SES literature has studied resilience in a great number of ways, and has found it is often the case that natural events do not cause catastrophe on their own, rather catasrophe is caused by the interactions between extreme natural events and a vulnerable social system (Lane, 2014). Design principles to develop resilience

HESSD
12, 8761–8851, 2015

have been developed in many spheres (for instance, design principles for management institutions seeking resilience Anderies et al., 2004), though in a general sense Berkes (2007) terms four clusters of factors which can build resilience:

- “Learning to live with change and uncertainty
- Nuturing various types of ecological, social and political diversity
- Increasing the range of knowledge for learning and problem solving
- Creating opportunities for self-organisation”

Exposure to natural events can lead to emergent resilience consequences in some cases, as in the case where a policy regime may be altered to increase resilience due to the occurrence of a catastrophe (for example London after 1953 Lumbroso and Vinet, 2011, or Vietnamese agriculture, Adger, 1999), where the same event could perhaps have caused a loss in resilience were a different social structure in place (Garmestani, 2013).

In all systems, the ability to adapt to circumstances is critical in creating resilience (though resilience can also breed adaptivity, Folke, 2006; in the sphere of water resources, the adaptive capacity that a society has towards hydrological extremes determines its vulnerability to extremes to a great extent, and so management of water resources in the context of vulnerability reduction should involve an assessment of hydrological risk coupled with societal vulnerability, Pandey et al., 2011). An example scenario where socio-hydrological modelling may be used is in determining resilience/vulnerability to drought; sometimes minor droughts can lead to major crop losses, whereas major droughts can sometimes results in minimal consequences, which would indicate differing socio-economic vulnerabilities between cases which “may either counteract or amplify the climate signal” (Simelton et al., 2009). Studies such as that carried out by Fraser et al. (2013), which uses a hydrological model to predict drought severity and frequency coupled with a socio-economic model to determine vulnerable areas, and Fabre et al. (2015), which looks at the stresses in dif-

HESSD
12, 8761–8851, 2015

ferent basins over time caused by hydrologic and anthropogenic issues, have already integrated socio-economic and hydrologic data to perform vulnerability assessments. Socio-hydrological modelling could make an impact in investigating how the hydrologic and socio-economic systems interact (the mentioned studies involve integration of disciplines, though not feedbacks between systems) to cause long-term impacts, and so determine vulnerabilities over the longer term. The most appropriate form of governance in socio-hydrological systems could also be investigated further, as differing governance strategies lead to differing resilience characteristics (Schlüter and Pahl-Wostl, 2007): Fernald et al. (2015) has investigated community-based irrigation systems (Acequias) and found that they produce great system resilience to drought, due to the "complex self-maintaining interactions between culture and nature" and "hydrologic and human system connections". There is also a question of scale in resilience questions surrounding water resources, which socio-hydrology could be used to investigate: individual resilience may be developed through individuals' use of measures of self-interest (for example digging wells in the case of drought vulnerability), though this may cumulatively result in a long-term decrease in vulnerability (Srinivasan, 2013).

An area that socio-hydrological modelling would be able to contribute in is determining dynamics that are likely to occur in systems: this is highly relevant to resilience study, as system dynamics and characteristics that socio-hydrological models may highlight, such as regime shift, tipping points, bistable states and feedback loops, all feature in resilience science. The long-term view that socio-hydrology should take will be useful in this, as it is often long-term changes in slow drivers that drive systems towards tipping points (Biggs et al., 2009). Modelling of systems also helps to determine indicators of vulnerability that can be monitored in real situations. Areas where desertification has/may take place would be ideal case-studies, since desertification may be viewed as "a transition between stable states in a bistable ecosystem" (D'Odorico et al., 2013), where feedbacks between natural and social systems bring about abrupt changes. Socio-hydrology may be able to forecast indicators of posible regime shifts, utilising SES techniques such as identification of critical slowing down (CSD) (Dakos

HESSD
12, 8761–8851, 2015

et al., 2015), a slowing of returning to "normal" after a perturbation which can point to a loss of system resilience, as well as changes in variance, skewness and autocorrelation, which may all be signs of altered system resilience (Biggs et al., 2009), to determine the most effective methods of combating this problem.

In studying many aspects of resilience, historical socio-hydrology may be used to examine past instances where vulnerability/resilience has occurred unexpectedly and comparative studies could be conducted to determine how different catchments in similar situations have become either vulnerable or resilient; combinations of these studies could lead to understanding of why different social structure, governance regimes, or policy frameworks result in certain levels of resilience. Modelling of system dynamics for the purposes of system understanding, prediction and policy development are all clearly of relevance when applied to this topic, since in these the coupling is key in determination of the capacity for coping with change (Schlüter and Pahl-Wostl, 2007).

2.4.2 Understanding risk in socio-hydrological systems

Risk is a hugely important area of hydrological study in the wider context: assessing the likelihood and possible consequences of floods and droughts constitutes an area of great importance, and models to determine flood/drought risk help to determine policy regarding large infrastructure decisions, as well as inform insurance markets on the pricing of risk. However, the relationship between humans and hydrological risk is by no means a simple one, due to the differing perceptions of risk as well as the social and cultural links that humans have with water (Linton and Budds, 2013), and so providing adequate evidence for those who require it is a great challenge.

The way in which risk is perceived determines the actions that people take towards it, and this can create potentially unexpected effects. One such impact is known as the "levee effect" (White, 1945), whereby areas protected by levees are perceived as being immune from flooding (though in extreme events floods exceed levees, and the impacts can be catastrophic when they do), and so are often heavily developed, leading people to demand further flood protection and creating a positive feedback cycle. Flood

HESSD
12, 8761–8851, 2015

insurance is also not required in the USA if property is "protected" by levees designed to protect against 100 year events (Ludy and Kondolf, 2012), leading to exposure of residents to extreme events. Socio-hydrologic thinking is slowly being applied to flood risk management, as is seen in work such as that of Falter et al. (2015), which recognises that "A flood loss event is the outcome of complex interactions along the flood risk chain, from the flood-triggering rainfall event through the processes in the catchment and river system, the behaviour of flood defences, the spatial patterns of inundation processes, the superposition of inundation areas with exposure and flood damaging mechanisms", and that determining flood risk involves "not only the flood hazard, e.g. discharge and inundation extent, but also the vulnerability and adaptive capacity of the flood-prone regions." Socio-hydrology could, however, further investigate the link between human perceptions of risk, the actions they take, the hydrological implications that this has, and therefore the impact this has on future risk to determine emergent risk in socio-hydrological systems.

The impact that humans have on drought is another area that socio-hydrology could be used; work on the impact that human water use has upon drought has been done (e.g. Wanders and Wada, 2014), where is was found that human impacts "increased drought deficit volumes up to 100 % compared to pristine conditions", and suggested that "human influences should be included in projections of future drought characteristics, considering their large impact on the changing drought conditions". Socio-hydrology could perhaps take this further and investigate the interaction between humans and drought, determining different responses to past drought and assessing how these responses may influence the probability of future issues and changes in resilience of social systems.

2.4.3 Transboundary water management

Across the World, 276 river basins straddle international boundaries (Dinar, 2014); the issue of transboundary water management is a clear case where social and hydrological systems interact to create a diverse range of impacts that have great social consequences, but which are very hard to predict. These issues draw together wholly socially constructed boundaries with wholly natural hydrologic systems when analysed. The social implications of transboundary water management have been studied and shown to lead to varying international power structures (Zeitoun and Allan, 2008) (e.g. "hydro-hegemony", Zeitoun and Warner, 2006), as well as incidences of both cooperation and conflict (in various guises) (Zeitoun and Mirumachi, 2008) dependent on circumstance. The virtual water trade (Hoekstra and Hung, 2002) also highlights an important issue of transboundary water management: the import and export of goods almost always involves some "virtual water" transfer since those goods will have required water in their production. This alters the spatial scale appropriate to transboundary water management (Zeitoun, 2013) and investigating policy issues related to this would very interesting from a socio-hydrologic perspective (Sivapalan et al., 2012).

Socio-hydrologic modelling could be used to predict the implications that transboundary policies may have on hydrologic systems, and so social impacts for all those involved. However, the prediction of future transboundary is highlty uncertain and subject to a great many factors removed entirely from the hydrologic systems that they may impact, and so presents a significant challenge.

2.4.4 Land-use management

The final example situation where socio-hydrological modelling may be applicable is in land-use management. Changes in land-use can clearly have wide-ranging impacts on land productivity, livelihoods, health, hydrology, ecosystems services, which all interact to create changes in perception, which can feed back to result in actions being taken that impact on land management. Fish et al. (2010) posits the idea of further integrating agricultural and water management: "Given the simultaneously human and non-human complexion of land-water systems it is perhaps not surprising that collaboration across the social and natural sciences is regarded as a necessary, and underpinning, facet of integrated land-water policy". Modelling in socio-hydrology may contribute in this sphere through the development of models which explore the feedbacks mentioned

HESSD
12, 8761–8851, 2015

above, and which can determine the long-term impacts of interaction between human and natural systems in this context.

3 Concepts

Before introducing the techniques that may be used in modelling socio-hydrological systems there are several concepts that should be introduced. These concepts underpin the theory behind socio-hydrology, and as such modelling of SHSs; only when they are properly understood is it possible to develop useful, applicable models.

3.1 Human-water system representations

People interact with water in complex ways which extend between the physical, social, cultural and spiritual (Boelens, 2013). How the human–water system is perceived is a vital component of socio-hydrological modelling, since this perception will feed into the system conceptualisation (Sivapalan et al., 2003), which will then feed into the model, and as such its outputs. In the past, linear, one-way relationships have often been used, which observations have suggested "give a misleading representation of how social-ecological systems work" (Levin et al., 2012). This unidirectional approach may have been more appropriate in the past when anthropogenic influences were smaller, but since the interactions between hydrology and society have changed recently (as has been described previously), "new connections and, in particular, more significant feedbacks which need to be understood, assessed, modelled and predicted by adopting an interdisciplinary approach" (Montanari et al., 2013), and so the view of systems in models should appreciate this. Views and knowledge of the human–water system have changed over time, and these changes themselves have had a great impact on the systems due to the changes in areas of study and policy that perception and knowledge can bring about (Hadfield and Seaton, 1999).

HESSD
12, 8761–8851, 2015

The concept of the hydrosocial cycle has been a step forward in the way that the relationship between humans and water is thought about, as it incorporates both "material and sociocultural relations to water" (Wilson, 2014). This links well with the view of Archer (1995), who pictured society as a "heterogeneous set of evolving structures that are continuously reworked by human action, leading to cyclic change of these structure and their emergent properties" (Mollinga, 2014). Socio-hydrology uses this hydrosocial representation, and also incorporates human influences on hydrology, whereby "aquatic features are shaped by intertwining human and non-human interaction" to form a bi-directional view of the human–water system (Di Baldassarre et al., 2013a). Technology could also be included in these representations, as was the case in a study by Mollinga (2014), where irrigation was considered in both social and technical terms.

Socio-hydrological human–water system representations should be considered in a case-specific manner, due to the fact that the relationship is very different in different climates. To give an extreme example, the way in which humans and water interact is atypical in a location such as Abu Dhabi, where water is scarce, desalination and water recycling provide much of the freshwater, and as such energy plays a key role (McDonnell, 2013). In this case, energy should certainly be included in socio-hydrological problem formulations since it plays such a key role in the relationship (McDonnell, 2013).

Figure 2 shows an example of a conceptualised socio-hydrological system (Elshafei et al., 2014), which gives insight into the view that the author has of the system. It shows the linkage perceived between the social and hydrological systems, and the "order" in which the author feels interactions occur. In this system conceptualisation it is perceived that there are two feedback loops which interact to form system behaviour. One is a reinforcing loop, whereby increases in land productivity lead to economic gain, increased population, a higher demand for water and as such changes in management decisions, likely to be intensification of land-use (and vice versa); the other loop is termed the "sensitivity loop" (Elshafei et al., 2014), whereby land intensification may impact upon ecosystem services, which, when the climate and socio-economic and

HESSD
12, 8761–8851, 2015

political systems are taken into account may increase sensitivity to environmentally detrimental effects, and cause behavioural change. This second loop acts against the former and forms dynamic system behaviour. Others may have different views on the system, for example there may be more (or less) complexity involved in the system, as well as different interconnections between variables, and this would lead to a different conceptual diagram.

When forming a system representation, the topics of complex and co-evolutionary systems should be kept in mind so that these concepts may be applied where appropriate. These concepts are introduced in the following sections.

3.1.1 Complex systems

Complex systems have been studied in many spheres, from economics (Foster, 2005), physics, biology, engineering, mathematics, computer science, and indeed in inter/trans-disciplinary studies involving these areas of study (Chu et al., 2003), or other systems involving interconnected entities within heterogeneous systems (An, 2012). By way of a definition of complex systems, Ladyman et al. (2013) give their view on the necessary and sufficient conditions for a system to be considered complex:

- An "ensemble of many elements": there must be different elements within the system in order for interactions to occur, and patterns to emerge
- "Interactions": elements within a system must be able to exchange or communicate
- "Disorder": the distinguishing feature between simple and complex systems is the apparent disorder created by interactions between elements
- "Robust order": elements must interact in the same way in order for patterns to develop
- "Memory": robust order leads to memory within a system

HESSD
12, 8761–8851, 2015

Complex systems representations rely on mechanistic relationships between variables, meaning that the dynamic relationship between different system components do not change over time (Norgaard, 1981), as opposed to evolutionary relationships, whereby responses between components change over time due to natural selection (Norgaard, 1981). Magliocca (2009) investigates the interactions between humans and their landscapes, and determines that emergent behaviours in these systems are due to the "induced coupling" between them, and so should be modelled and managed using complex-systems-appropriate techniques. Resilience has also been studied with regard to complex systems, and the interactions in complex systems have been said to lead to resilience (Garmestani, 2013). Complex systems are an excellent framework within which to study socio-hydrological systems, since they allow for the discernment of the origin of complex behaviours, such as cross-scale interactions, non-linearity and emergence (Falkenmark and Folke, 2002), due to their structure being decomposable and formed of subsystems that may themselves be analysed.

3.1.2 Co-evolutionary systems

A related, though subtly different view of the human–water relationship is that of a co-evolutionary system. The strict meaning of a co-evolutionary system is occasionally "diluted" (Winder et al., 2005) in discussions of CHANS and socio-hydrology, though a looser usage of the term is certainly of relevance. In a strict application of the term co-evolutionary, two or more evolutionary systems are linked such that the evolution of each system influences that of the other (Winder et al., 2005); an evolutionary system is one in which entities exists, include responses that may vary with time (as opposed to mechanistic systems, in which responses are time-invariant), involving the mechanisms of "variation, inheritance and selection" (Hodgson, 2003). Jeffrey and McIntosh (2006) gives a guide in identification of co-evolutionary systems:

- Identify evolutionary (sub)systems and entities
- Provide a characterisation of variation in each system

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

- Identify mechanisms that generate, winnow and provide continuity for variation in each system
- Describe one or more potential sequences of reciprocal change that result in an evolutionary change in one or more systems
- Identify possible reciprocal interactions between systems
- Identify effects of reciprocal interactions

Whether or not the biophysical, hydrological system is viewed as evolutionary in nature determines whether socio-hydrological dynamics may be termed co-evolutionary, since Winder et al. (2005) state that "Linking an evolutionary system to a non-evolutionary system does not produce co-evolutionary dynamics. It produces simple evolutionary dynamics coupled to a mechanistic environment", which would imply that socio-hydrological systems are not co-evolutionary in nature, perhaps rather being complex systems, or systems of "cultural ecodynamics" (Winder et al., 2005). Norgaard (1984, 1981) allows for a looser definition of a co-evolutionary relationship, whereby two systems interact and impact one another such that they impact one another's developmental trajectory. Norgaard (1981, 1984) gives the example of paddy rice agriculture as an example of a co-evolutionary system: in this example, changes in agricultural practice (investment in irrigation systems for example) led to higher land productivity and to societal development; the usage of paddy-based techniques then required the development of social constructs (water-management institutions and property rights) to sustain such farming methods, which served to socially perpetuate paddy farming and to alter ecosystems further in ways that made the gap between land productivity between farming techniques greater, and so led to yet greater societal and ecosystem change. Western monoculture may also be viewed in the same light, with social systems such as insurance markets, government bodies and agro-technological and agro-chemical industries developed to be perfectly suited to current agriculture (Norgaard, 1984), but these constructs having been borne out of requirements by monocultures

HESSD
12, 8761–8851, 2015

previously, and also serving to perpetuate monoculture and make its usage more attractive. The crucial difference between the two views is that Winder et al. (2005) do not consider biophysical systems, such as hydrological or agricultural systems, evolutionary in their nature (Kallis, 2007), since the biophysical mechanisms behind interactions in these systems are governed by Newtonian, rather than Darwinian, mechanisms.

Even if the strict definition of a co-evolutionary system does not apply to socio-hydrology, the co-evolutionary framework may be used as an epistemological tool (Jeffrey and McIntosh, 2006), a way to develop understanding, and so the subtle difference between complex and co-evolutionary systems should be kept in mind when developing socio-hydrological models, if for no other reason than it may remind developers that non-stationary responses may exist (whether this implies co-evolution or not), largely in terms of social response to hydrological change. The usage of a co-evolutionary framework also allows the usage of the teleological principle (i.e. an end outcome has a finite cause), which allows, for example, for policy implications to be drawn (Winder et al., 2005).

There are already examples where a co-evolutionary perspective has been taken on an issue that may be termed socio-hydrological/-ecological; these examples and how useful the co-evolutionary analogy is are examined here. Kallis (2010) uses a co-evolutionary perspective to look at how water resources have been developed in the past: Athens in Greece is used as an example, where expansions in water supply led to increases in demands, which required further expansion. However, this cycle is not seen as predetermined and unstoppable, rather it is dependent on environmental conditions, governance regimes, technology and geo-politics, all of which are impacted by, and evolve with, the changes in water supply and demand, as well as each other. The relationship between the biophysical environment and technology is particularly interesting: the environment is non-stationary as water supply expands, as innovation and policy, driven by necessity to overcome environmental constraints, result in environmental changes, both expected and unforeseen, which then result in socioeconomic changes and new environmental challenges to be solved. The evolutionary perspective

HESSD
12, 8761–8851, 2015
Modelling socio-hydrological systems
P. Blair and W. Buytaert

used in looking at innovation overcoming temporary environmental constraints, but also creating new issues in the future is very useful in understanding how human–water systems develop. A study by Lorenzoni et al. (2000); Lorenzoni and Jordan (2000) takes a co-evolutionary approach to climate change impact assessment and determines that using indicators of sustainability in a bi-directional manner (both as inputs to and outputs from climate scenarios) is possible, and that a co-evolutionary view of the human-climate system, involving adaptation as well as mitigation measures, results in a "more sophisticated and dynamic account of the potential feedbacks" (Lorenzoni et al., 2000). The dynamics that are implied using co-evolutionary frameworks are also interesting, as shown in studies by Liu et al. (2014), whereby the co-evolution of humans and water in a river basin system brings about long stable periods of system equilibrium, punctuated by shifts due to internal or external factors, which indicates a "resonance rather than a cause-effect relationship" (Falkenmark, 2003) between the systems.

The usage of a co-evolutionary framework could be beneficial in governance and modelling of socio-hydrological systems, and the previously mentioned IAHS paper (Montanari et al., 2013) states that the co-evolution of humans and water "needs to be recognized and modelled with a suitable approach, in order to predict their reaction to change". The "lock-in" that is created by technological and policy changes in co-evolutionary systems, which can limit reversibility of decisions in terms of how resources are allocated (Van den Bergh and Gowdy, 2000), also means that improving the predictive approach taken should be a matter of priority, decisions taken now may result in co-evolutionary pathways being taken that cannot be altered later (Thompson et al., 2013). The implication of a potential lack of knowledge of long-term path dependencies for current policy decisions should be that, rather than seeking optimal policies in the short term, current decisions should be made that allow development in the long term and maintain the potential for system evolution in many directions (Rammel and van den Bergh, 2003).

HESSD
12, 8761–8851, 2015

P. Blair and W. Buytaert

3.1.3 Complex adaptive systems

In understanding the concept of sustainability, Jeffrey and McIntosh (2006) explains that the dynamic behaviour seen in natural systems, "is distinct from (simple or complex) dynamic or (merely) evolutionary change", and is instead a complex mixture of mechanistic and evolutionary behaviours. However, as was previously explained, the strict use of the term "co-evolutionary" is perhaps not applicable in socio-ecological systems, and so perhaps a better term to be used would be "complex adaptive systems" (Levin et al., 2012). Complex adaptive systems are a subset of complex systems in which systems or system components that exhibit adaptivity (not necessarily all elements or subsystems); Lansing (2003) gives a good introduction. The important distinction between complex systems and complex *adaptive* systems is that, in complex systems, if a system reaches a previously seen state, this indicates a cycle, and so the system will return to this state at another point. Due to the adaptivity and time-variant responses, this is not the case in complex adaptive systems.

The complex adaptive systems paradigm has already been used in a socio-hydrological context, being used to investigate Balinese water temples that are used in irrigation (Lansing et al., 2009; Lansing and Kremer, 1993; Falvo, 2000). Policy implications of complex adaptive systems have also been investigated by Levin et al. (2012) and Rammel et al. (2007), and are summarised as:

- Nonlinearilty – should be included in models such that surprises aren't so surprising. Time variant responses also mean that adaptive, changing management practices should be used, as opposed to stationary practices
- Scale issues – processes occur on different spatial scales and timescales, and so analysis of policy impacts should be conducted on appropriate, and possible on multiple, scales
- Heterogeneity – heterogeneity in complex systems results in the application of homogeneous policies often being sub-optimal

HESSD
12, 8761–8851, 2015
Modelling socio-hydrological systems
P. Blair and W. Buytaert

- Risk and uncertainty – Knightian (irreducible) uncertainty exists in complex adaptive systems
- Emergence – surprising results should not be seen as surprising, due to the complex, changing resposnes within systems
- Nested hierarchies – impacts of decisions can be seen on multiple system levels due to the hierarchies within complex adaptive systems

As can be seen, these policy issues are very similar to those mentioned in previous sections relating to management of socio-hydrological and socio-ecological systems, which is not surprising.

Ultimately, in the modelling of socio-hydrological systems, it is not necessary to state whether the system is being treated as a complex system, a co-evolutionary system or a complex adaptive system, rather it is the implications that the lens through which the system is seen has, via the representation of the system in model equations, that are most important. There are clearly dynamics that both do and do not vary in time in socio-hydrological systems, and so these should all be treated appropriately. Perhaps the most important outcome of the human–water system representation should be a mindset to be applied in socio-hydrological modelling, whereby mechanistic system components are used in harmony with evolutionary and adaptive components to best represent the system.

3.2 Space and time in socio-hydrological modelling

In several previous sections, the issues of scale that socio-ecological and socio-hydrological systems can face were presented and their significance stressed. As such, a section looking at space and time in socio-hydrology is warranted. Hydrology involves "feedbacks that operate at multiple spatiotemporal scales" (Ehret et al., 2014), and when coupled with human activities, which are also complex on spatial and temporal scales (Ren et al., 2002), this picture becomes yet more complicated, though these

HESSD
12, 8761–8851, 2015

cross-scale interactions are the “essence of the human–water relationship” (Liu et al., 2014). As a method of enquiry, modelling allows for investigations to be conducted on spatiotemporal scales that are not feasible using other methods, such as experiments and observations (though the advent of global satellite observations is changing the role that observations have and the relationship between observations and modelling to one of modelling downscaling observations and converting raw observations into actionable information) (Reyer et al., 2015) (see Fig. 3), and so is a useful tool in investigating socio-hydrology. However, ensuring the correct scale for modelling and policy implementation is of great importance, as both of these factors can have great impacts on the end results (Manson, 2008).

In terms of space, the interactions that occur between natural and constructed scales are superimposed with interactions occuring between local, regional and global spatial scales. Basins and watersheds are seen as “natural” (Blomquist and Schlager, 2005) scales for analysis, since these are the spatial units in which water flows (though there are of course watersheds of different scales and watersheds within basins, and so watershed-scale analysis does not answer the question of spatial scale on its own), however these often do not match with the scales on which human activities occur, and indeed human intervention has, in some cases, rendered the meaning of a “basin” less relevant due to water transfers (Bourblanc and Blanchon, 2013). The importance of regional and global scales has been recognised, with Falkenmark (2011) stating that “the meso-scale focus on river basins will no longer suffice”. Another issue of spatial scale is that of the extents on which issues are created and experienced (Zeitoun, 2013): some issues, for instance point-source pollution, are created locally and experienced more widely, whereas issues of climate are created globally, but problems are experienced more locally in the form of droughts and floods. This dissonance between cause and effect can only be combated with policy on the correct scale. Creating models involves scale decisions, often involving trade-offs between practicalities of computing power and coarseness of representation (Evans and Kelley, 2004), which can impact the quality of model output. The previous points all indicate there being no single spatial scale

HESSD
12, 8761–8851, 2015

appropriate for socio-hydrological analysis; instead, each problem should be considered individually, with the relevant processes and their scales identified and modelling scales determined accordingly. This could result in potentially heterogeneous spatial scales within a model.

The interactions between slow and fast processes create the temporal dynamics seen in socio-ecological systems (Crépin, 2007); slow, often unnoticed, processes can be driven which lead to regime shift on a much shorter timescale (Hughes et al., 2013), and in modelling efforts these slow processes must be incorporated with faster processes. Different locations will evolve in a socio-hydrological sense at different paces, due to hydrogeological (Perdigão and Blöschl, 2014) and social factors, and so socio-hydrological models should be devloped with this in mind. Also, different policy options are appropriate on different timescales, with efforts such as rationing and source-switching appropriate in the short-term, as opposed to infrastructure decisions and water rights changes being more appropriate in the long term (Srinivasan et al., 2013). All of these factors mean that a variety of timescales, and interactions between these, should be included in models, and analyses on different timescales should not be seen as incompatible (Ertsen et al., 2014).

3.3 Data

One of the cornerstones of study in hydrological sciences is data. However, there are significant problems in obtaining the data required in a socio-hydrological sense. Some of the issues present in this area are:

- Timescales: an issue in accruing data for long-term hydrological studies is that "detailed hydrologic data has a finite history" (Troy et al., 2015b). Good data from historical case studies is difficult to obtain, and so shorter-term studies sometimes have to suffice. The focus on long-term analysis that socio-hydrology takes exacerbates this problem, particularly since historical case studies are of great use during the system-understanding phase that the subject is currently in.

HESSD
12, 8761–8851, 2015

- Availability: where data is widely available, it may be possible for minimal analysis to be carried out, and for data-centric studies to be carried out (Showqi et al., 2013), but when the boundaries of the system of interest are expanded to include the social side of the system, data requirements naturally increase, and modellers are exposed to data scarcity in multiple disciplines (Cotter et al., 2014). Hydrological modelling often suffers from data unavailability (Srinivasan et al., 2015), but significant work has recently been carried out in recent years on prediction in ungauged basins (Hrachowitz et al., 2013; Wagener and Montanari, 2011) to reduce this, and so perhaps the potential multi-disciplinary data scarcity issues in socio-hydrology could borrow and adapt some techniques. Papers discussing solutions for a lack of data in a socio-hydrologic context are also already appearing (Zlinszky and Timár, 2013). Data scarcity can heavily influence the modelling technique used (Odongo et al., 2014): lumped conceptual models tend to have "more modest … data requirements" (Sivapalan et al., 2003), whereas distributed, physically-based models tend to have "large data and computer requirements" (Sivapalan et al., 2003). A smaller amount of data may be necessary in some socio-hydrological studies, since the collection of a significant quantity of extra data (when compared to hydrological studies) also incurs an extra cost, both in terms of cost and time (Pataki et al., 2011).

- Inter-disciplinary Integration: the integration of different data types from different fields is complex (Cotter et al., 2014); socio-hydrology will have to cope with this, since some aspects of socio-hydrological study are necessarily quantitative and some qualitative. Since the subject of socio-hydrology has come largely from those with a hydrology background, integrating qualitative data sources with more quantitative sources that hydrologists are commonly more comfortable with could pose some issues (Troy et al., 2015b). However, the necessary interdisciplinary nature of socio-hydrology also means that communication between model developers from different subject areas should be enhanced (Cotter et al., 2014), so that everyone may gain.

HESSD
12, 8761–8851, 2015

3.4 Complexity

The expansion of system boundaries to include both social and hydrological systems introduces more complexity than when each system is considered separately. The increased complexity of the system leads to a greater degree of emergence present in the system, though this doesn't necessarily mean more complex behaviours (Kumar, 2011). The level of complexity required in a model of a more complex system will probably itself be more complex (though not necessarily, as Levin et al., 2012 said, "the art of modelling is to incorporate the essential details, and no more") than that of a simpler system, since model quality should be judged by the ability to match the emergent properties of the behaviour a system (Kumar, 2011). Manson (2001) introduces the different types of complexity:

- Algorithmic complexity: this may be split into two varieties of complexity. One is the computational effort required to solve a problem, and the other is complexity of the simplest algorithm capable of reproducing system behaviour.
  - While the first side of algorithmic complexity is important in socio-hydrological modelling, since mathematical problems should be kept as simple as is practicable, the second facet of algorithmic complexity is most applicable to socio-hydrologic modelling, as modellers should be seeking to develop the simplest possible models that can replicate the behaviour of socio-hydrological systems.
- Deterministic complexity: the notion that every outcome has a root cause that may be determined, however detached they may seemingly be, is at the heart of deterministic complexity. Feedbacks, sensitivities to changes in parameters and tipping points are all part of deterministic complexity.
  - The study of complex systems using mechanistic equations implies that there are deterministic relationships within a system; since socio-hydrological modelling will use such techniques, deterministic complexity is of interest. Using

HESSD
12, 8761–8851, 2015

deterministic principles, modellers may seek to determine the overall impacts that alterations to a system may have.

- Aggregate complexity: this is concerned with the interactions within a system causing overall system changes. The relationships within a system lead to the emergent behaviours that are of such interest, and determining the strengths of various correlations and how different interactions lead to system level behaviours gives an idea of the aggregate complexity of a system.

  - Aggregate complexity is of great interest to modellers of socio-hydrological systems. Determining how macro-scale impacts are created via interactions between system variables is a central challenge in the subject, and so determining the aggregate complexity of socio-hydrological systems may be an interesting area of study.

The increased complexity of the system, and the previously mentioned issues of possible data scarcity from multiple disciplines, could lead to issues. Including more complexity in models does not necessarily make them more accurate, particularly in the case of uncertain or poor resolution input data (Orth et al., 2015); this should be kept in mind when developing socio-hydrological models, and in some cases simple models may outperform more complex models. Keeping in mind the various forms of complexity when developing models, socio-hydrologists should have an idea of how models should be developed and what they may be capable of telling us.

3.5 Model resolution

As well as being structured in different ways, there are different ways in which models can be used to obtain results via different resolutions. Methods include analytical resolution, Monte Carlo simulations, scenario-based techniques and optimisation (Kelly (Letcher) et al., 2013). Analytical resolutions, while they give a very good analysis of systems in which they are applied, will generally be inapplicable in socio-hydrological

HESSD
12, 8761–8851, 2015

applications, due to the lack of certain mathematical formulations and deterministic relationships between variables which are required for analytical solutions. Monte Carlo analyses involve running a model multiple times using various input parameters and initial conditions. This is a good method for investigating the impacts that uncertainties can have (an important aspect in socio-hydrology), though the large number of model runs required can lead to large computational requirements. Optimisation techniques are useful when decisions are to be made; using computer programs to determine the "best" decision can aid in policy-making, however, optimisation techniques should be used with care: the impacts that uncertainties can have, as well as issues of subjectivity and model imperfections can (and have) lead to sub-optimal decisions being made. Techniques such as multi-objective optimisation (Hurford et al., 2014) seek to make more clear the trade-offs involved in determining "optimal" strategies.

3.6 Uncertainty

Uncertainty is an issue to be kept at the forefront of a modeller's mind before a modelling technique is chosen, while models are being developed and once they produce results. There are implications that uncertainty has in all modelling applications, and so it is important to cope appropriately with them, as well as to communicate their existence (Welsh et al., 2013). Some of the modelling techniques, for instance Bayesian Networks, deal with uncertainty in an explicit fashion, while other techniques may require sensitivity analyses or scenario-based methods to deal with uncertainty. In any case, the method by which uncertainty is dealt with is an important consideration in determining an appropriate modelling technique.

3.6.1 Uncertainty in hydrological models

Hydrological models on their own are subject to great uncertainties, which arise for an array of reasons and from different places, including external sources (for instance uncertainties in precipitation or human agency, internal sources (model structure and

HESSD
12, 8761–8851, 2015

parameterisation), as well as data issues and problem uniqueness (Welsh et al., 2013). In the current changing world, many of the assumptions on which hydrological models have been built, for instance non-stationarity (Milly et al., 2008), have been challenged, and new uncertainties are arising (Peel and Blöschl, 2011). However, the extensive investigations into dealing with uncertainty (particularly the recent focus on prediction in ungauged basins Wagener and Montanari, 2011) can only be of benefit to studies which widen system boundaries. The trade-offs between model complexity and "empirical risk" (Arkesteijn and Pande, 2013) in modelling, ways to deal with large numbers of parameters and limited data (Welsh et al., 2013), as well as statistical techniques to cope with uncertainties (Wang and Huang, 2014) have all been well investigated, and knowledge from these areas can certainly be applied to future studies.

3.6.2 Uncertainty in coupled socio-hydrological models

Interactive and compound uncertainties are an issue in many subjects, and indeed already in water science (particularly the policy domain). Techniques already exist in water resource management for taking action under such uncertainties, for instance the method used by Wang and Huang (2014), whereby upper and lower bounds are found for an objective function that is to be minimised/maximised to help identify the "best" decision, and to identify those that may suffer due to various uncertainties. This approach extends that taken in sensitivity analyses, and is a step forward, since sensitivity analyses usually examine "the effects of changes in a single parameter ... assuming no changes in all other parameters" (Wang and Huang, 2014), which can fail to detect the impact of combined uncertainies in systems with a great deal of interconnections and feedbacks. The amplifications that feedback loops can induce in dynamic systems mean that the impact of uncertainties, particularly initial condition uncertainties, can be great (Kumar, 2011).

One issue that exists in socio-hydrological systems is that of Knightian uncertainty. This is more difficult to deal with than other uncertainties in a modelling sense, since it is the inherent indeterminacy of the system ("that which cannot be known" Lane,

HESSD
12, 8761–8851, 2015

2014), as opposed to quantifiable uncertainties, though the use of adaptive management techniques (Garmestani, 2013) is an effective way of dealing with indeterminacy in a practical sense.

4 Modelling

Given that the focal point of this paper is the modelling of socio-hydrological systems, the following sections will introduce the modelling approaches that may be used in socio-hydrological contexts. It will outline the background of the techniques, detail how a model would be developed, the results that could be obtained, and how it may be appropriate to be used. The above sections on concepts and applications will be utilised to aid in these discussions. Table 1 shows some examples of modelling studies that may be deemed socio-hydrologic in nature, including details of the technique that is used, the case studied and the reason for modelling.

Liebman (1976) said that "modelling is thinking made public", and so models may be used to demonstrate the knowledge currently held in a community. Troy et al. (2015a) even state that socio-hydrological models at present may be thought of as hypotheses (rather than predictive tools), and so reinforce this view. With the current feeling in socio-hydrological circles being that the integration of the social and economic interactions with water is a vital component of study, this integration should be seen, and should be included centrally in models in such a way that demonstrates the importance of these interactions to modellers (Lane, 2014). This should mean integration of the two disciplines in a holistic sense, including integrating the issues faced across hydrological, social and economic spheres, the integration of different processes from the different areas of study, integration of different levels of scale (hydrologic processes will operate on a different scale to social and economic processes), as well as the integration of different stakeholders across the different disciplines (Kelly (Letcher) et al., 2013).

HESSD
12, 8761–8851, 2015

There are numerous ways to classify models, and so before each individual modelling technique is detailed, the more general classifications will be detailed.

4.1 Model classifications

4.1.1 Data-based vs. physics-based vs. conceptual

The distinction between these different types of model is fairly clear: physics-based models use mathematical representations of physical processes to determine system response, data-based models seek to reproduce system behaviour utilising available data (Pechlivanidis and Jackson, 2011) (there also exist hybrid models using a combination of these two approaches), and conceptual models are based on a modeller's conceptual view of a system. The common criticisms of the two approaches are that physics-based model results are not always supported by the available data (Wheater, 2002) and are limited due to the homogenous nature of equations in a heterogeneous world (Beven, 1989), while metric models can represent processes that have no physical relevance (Malanson, 1999).

4.1.2 Bottom-up vs. top-down

There is a similar distinction between bottom-up and top-down models as between metric and physically-based. Bottom-up modelling techniques involve the representation of processes (not necessarily physical) to develop system behaviour, whereas top-down approaches look at system outcomes and try to look for correlations to determine system behaviours. Top-down approaches have been criticised for their inability to determine base-level processes within a system, and so their inability to model the impact of implementing policies and technologies (Srinivasan et al., 2012). Bottom-up methods, while the message they present doesn't need to be "disentangled" (Lorenzoni et al., 2000), require a great deal of knowledge regarding specific processes and sites, which in social circumstances in particular can be very challenging (Sivapalan, 2015)

HESSD
12, 8761–8851, 2015

and specific in both a spatial and temporal sense. More detail on bottom-up and top-down modelling approaches will be given in the sections on agent based modelling and system dynamics modelling, since these are the archetypal bottom-up and top-down approaches respectively.

4.1.3 Distributed vs. lumped

The final distinction that is drawn here is that of distributed and lumped models. Distributed models include provisions for spatial, as well as temporal, heterogeneity, while lumped models concentrate study at discrete spatial points, where dynamics vary only in time. The advantages of distributed models are clear, particularly in a hydrological context where spatial heterogeneity is of such importance, however the drawbacks of high-resolution data requirements, with high potential for uncertainty, and larger computational requirements (Sivapalan et al., 2003) mean that lumped models can be an attractive choice.

4.2 Approaches

Kelly (Letcher) et al. (2013) give an excellent view of which modelling approaches may be taken in modelling socio-ecological systems. As socio-hydrology is so closely linked to socio-ecology, the approaches are largely the same. The modelling techniques that will be discussed here are:

- Agent-based Modelling (ABM)
- Scenario-based Modelling
- System Dynamics
- Pattern-oriented Modelling (POM)
- Heuristic/Knowledge-based Modelling

HESSD
12, 8761–8851, 2015

In the discussions that follow, the factors that would affect the choice of modelling approach will also be used. These are:

- Model purpose
- Data availability (quantity, quality and whether it is quantitative or qualitative)
- Treatment of space
- Treatment of time
- Treatment of system entities
- Uncertainty (see later section)
- Model resolution (also see later section)

Now that these pre-discussions have been included, a section on the importance of model conceptualisation is included, before each modelling approach is focused on.

4.3 The importance of model conceptualisation

The previously mentioned statement of modelling being “thinking made public” (Liebman, 1976) highlights the significance of the process behind model development for the distribution of knowledge. The conceptual basis on which a model is built defines the vision that a developer has of a system (“framing the problem” Srinivasan, 2015), and is therefore both a vital step in model development and a way that understanding can be shared. Conceptualisations often involve “pictures”, whether these be mental or physical pictures, and these pictures can be an excellent point of access for those who wish to understand a system, but who do not wish to delve into the potentially more quantitative or involved aspects. In some cases, a conceptual modelling study can also be an important first step towards the creation of a later quantified model (e.g. Liu et al., 2014; Liu, D. et al., 2015).

HESSD
12, 8761–8851, 2015

There are certain facets of socio-hydrology that should be captured in all SHS models, and so frameworks for socio-hydrological models should underly conceptualisations. Two frameworks for socio-hydrological models that have been developed thus far are those of Carey et al. (2014) and Elshafei et al. (2014). The framework of Carey et al. (2014) highlights some key facets of the human side of the system that are important to capture:

- "Political agenda and economic development
- Governance: laws and institutions
- Technology and engineering
- Land and resource use
- Societal response"

The framework presented by Elshafei et al. (2014) present a framework for the whole system, which is composed of:

- Catchment hydrology
- Population dynamics
- Economics
- Ecosystem services
- Societal sensitivity
- Behavioural response

Both of these frameworks give a view of the key parts of socio-hydrological systems: the second gives a good base for modelling the entirety of the system, and has a very abstracted point of view of the societal dynamics, whereas the former takes a more

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

detailed look at the societal constructs that lead to a particular response. Depending on the level of detail that is sought, either or both of these frameworks could be used as a basis for a socio-hydrological conceptualisation.

4.4 Agent-based modelling (ABM)

Having its origins in object-oriented programming, game theory and cognitive psychology (An, 2012), ABM is a bottom-up approach to the modelling of a system, in which the focus is on the behaviour and decision-making of individual "agents" within a system (Bousquet and Le Page, 2004). These agents may be individuals, groups of individuals, or institutions, but are defined by the attributes of being autonomous and self-contained, the presence of a state and the existence of interactions with other agents and/or the environment in which an agent exists (Macal and North, 2010). Decision rules are determined for agents (these may be homogeneous or heterogeneous), which determine the interactions and feedbacks that occur between agents (often agents on different organisational levels Valbuena et al., 2009), as well as between agents and the environment. ABMs are almost necessarily coupled in a socio-ecological sense (though they are often not necessarily termed as such), given that they use the decision-making processes of those within a society to determine the actions that they will take, and as such their impacts upon the environment and associated feedbacks, though they might not fully look at impacts that society has upon the environment, and rather look at human reactions to environmental changes.

Agent-based models themselves come in many forms, for example:

- Microeconomic: agent rules are prescribed to optimise a given variable, for instance profit, and make rational (or bounded rational) choices with regards to this (e.g. Becu et al., 2003; Filatova et al., 2009; Nautiyal and Kaechele, 2009).

- Evolutionary: agent decision-making processes change over time as agents "learn" (e.g. Manson and Evans, 2007) and test strategies (e.g. Evans et al., 2006).

HESSD
12, 8761–8851, 2015

– Heuristic/Experience-based: agents' rules are determined either through via either experience, or the examination of data (e.g. Deadman et al., 2004; An et al., 2005; Matthews, 2006; Gibon et al., 2010; Valbuena et al., 2010, 2009).

– Scenario-based: various environmental scenarios are investigated to see the impact upon behaviours, or different scenarios of societal behaviours are investigated to see impacts upon the environment (e.g. Murray-Rust et al., 2013).

The development of an ABM involves a fairly set method, the general steps of which are:

1. Problem definition
2. Determination of relevant system agents
3. Description of the environment in which agents exist
4. Elicitation of agent decision-making process and behaviours (Elsawah et al., 2015)
5. Determination of the interactions between agents
6. Determination of the interactions between agents and the environment
7. Development of computational algorithms to represent agents, environment, decision-making processes, behaviours and interactions
8. Model validation and calibration

The results from ABMs will generally be spatially explicit representations of system evolution over time, and so lend themselves well to integration with GIS software (Parker et al., 2005).

ABMs may be used in socio-hydrological modelling in two contexts: firstly, the discovery of emergent behaviour (Kelly (Letcher) et al., 2013) in a system, and secondly determining the macro-scale consequences that arise from interactions between many individual heterogeneous agents and the environment. ABM may be used for a number of different reasons: in the context of system understanding, the elicitation of emergent behaviours and outcomes leads to an understanding of the system, and in particular decision-making mechanisms where they can represent important phenomena that may be difficult to represent mathematically (Lempert, 2002). ABMs are also very applicable in the area of policy-making, as the outcomes of different policy options may be compared when the impact of agent behaviours are accounted for; for instance, O'Connell and O'Donnell (2014) suggest that ABMs may be more useful in determining appropriate flood investments than current cost-benefit analysis (CBA) methods. In the area of resilience, the importance of human behaviours in creating adaptive capacity of socio-ecological systems (Elsawah et al., 2015) has meant that ABMs have been used to look at the varying levels of differing levels of resilience in different governance regimes (Schlüter and Pahl-Wostl, 2007). The usage of ABM can be particularly strong in participatory modelling (Purnomo et al., 2005), where agents may be interviewed to determine their strategies, and then included in subsequent modelling stages. While ABM is seen by many as a technique with a wide range of uses, others are less sure of it's powers (Couclelis, 2001), particularly in predictive power at small scales (An, 2012), along with the difficulties that can be present in validation and verification of decision-making mechanisms (An, 2012). One study that has been carried out in the specific area of socio-hydrology which incorporates agent-based aspects is that of Srinivasan (2013). In this historical study, social and hydrological change in Chennai, India (Srinivasan, 2013) was investigated to determine the vulnerability of those within the city to water supply issues. The model was successfully able to incorporate different temporal scales, and was able to identify the possibility for vulnerability of water supplies on both a macro- and micro-scale level; the adaptive decisions of agents that the model was able to account for played a big part in this success. This work has been carried on via another study (Srinivasan, 2015) in which alternative trajectories are investigated

HESSD
12, 8761–8851, 2015

to examine how the system might now be different had different decisions been made in the past.

4.4.1 Game theory

"Game theory asks what moves or choices or allocations are consistent with (are optimal given) other agents' moves or choices or allocations in a strategic situation." (Arthur, 1999), and so is potentially very applicable to agent-based modelling in determining the decisions that agents make (Bousquet and Le Page, 2004). For a great deal of time, game theory has been used to determine outcomes in socio-ecological systems (for example the tragedy of the commons, Hardin, 1968), game theory has been used extensively in water resource management problems (Madani and Hooshyar, 2014), and so there is no reason why this would not extend to problems in a socio-hydrological setting.

4.5 System dynamics (SD)

System dynamics (and the linked technique of system analysis, Dooge, 1973) takes a very much top-down view of a system; rather than focusing on the individual processes that lead to overall system behaviours, system dynamics looks at the way a system converts inputs to outputs and uses this as a way to determine overall system behaviour. In system dynamics, describing the way a system "works" is the goal rather than determining the "nature of the system" (Dooge, 1973) by examining the system components and the physical laws that connect them. System dynamics can, therefore, avoid the potentially "misleading" analysis of the interactions and scaling up of small-scale processes (potentially misleading due to the complexity present in small-scale interactions not scaling up) (Sivapalan et al., 2003). Macro-scale outcomes such as non-linearities, emergence, cross-scale interactions and surprise can all be investigated well using system dynamics (Liao, 2013), and it's high-level system outlook allows for holism in system comprehension (Mirchi et al., 2012).

HESSD
12, 8761–8851, 2015

An important facet of the system dynamics approach is the development procedure: a clear and helpful framework that is integral in the development of a successful model, and also provides an important part of the learning experience. As with other modelling techniques, this begins with a system conceptualisation, which, in this case, involves the development of a causal loop diagram (CLD). A CLD (see examples in Figs. 4 and 5) is a qualitative, pictorial view of the components of a system and the linkages between them. This allows for a model developer to visualise the potential feedbacks and interconnections that may lead to system-level behaviours (Mirchi et al., 2012) from a qualitative perspective, without needing to delve into the quantitative identification of the significance of the different interconnections. Depending on how a modeller wishes to represent a system, different levels of complexity may be included in a CLD (this complexity may then later be revisited during the more quantitative model development phases), and CLDs (and indeed SD models) of different complexity may be useful in different circumstances. The differences in complexity between Figs. 4 and 5 show very different levels of complexity that modellers may choose to use (particularly since Fig. 4 is only a CLD for one of four linked subsystems). Once a CLD has been devised, the next stage in model development is to turn the CLD into a Stocks and Flows Diagram (SFD). This process is detailed in Table 2, and essentially involves a qualitative process of determining the accumulation and transfer of "stocks" (the variables, or proxy variables used to measure the various resources and drivers) in and around a system. Figure 6 shows the SFD developed from a CLD. SFD formulation lends itself better to subsequent development into a full quantitative model, though is still qualitative in nature and fairly simple to develop, requiring little or no computer simulation (a good thing, as Mirchi et al., 2012 says, "extensive computer simulations should be performed only after a clear picture . . . has been established"). Once a SFD has been developed, this then leads into the development of a full quantitative model, which will help 'better understand the magnitude and directionality of the different variables within each subsystem (Fernald et al., 2012) and the overall impacts that the interactions between variables have. Turning the SFD into a quantitative model essentially involves the ap-

HESSD
12, 8761–8851, 2015

plication of mathematical computations in the form of differential/difference equations to each of the interactions highlighted in the SFD. As with other modelling techniques, this quantitative model should go through full validation and calibration steps before it is used.

The application of a top-down modelling strategy, such as system dynamics, carries with it certain advantages. The impact that individual system processes and interactions thereof may be identified, as the root causes of feedbacks, time-lags and other non-linear effects can be traced. This trait makes system dynamics modelling particularly good in system understanding applications. The usefulness of SD in learning circumstances is increased by the different levels on which system understanding can be generated: the different stages of model development, varying from entirely qualitative and visual to entirely quantitative, allow for those with different levels of understanding and inclination to garner insight at their own level, and during different stages of model development. As such, system dynamics is an excellent tool for use in participatory modelling circumstances. SD techniques also give a fairly good level of control over model complexity to the developer, since the level at which subsystems and interactions is defined by the model developer. There are clear outcomes that emerge in many socio-ecological and socio-hydrological systems, but the inherent complexity and levels of interaction of small-scale processes “prohibits accurate mechanistic modelling” (Scheffer et al., 2012), and so viewing (and modelling) the system from a level at which complexity is appreciated but not overwhelming allows for modelling and analyses. Another advantage that follows from this point is that system dynamics may be used in situations where the physical basis for a relationship is either unknown or difficult to represent, since correlative relationships may be used as a basis for modelling (Öztürk et al., 2013). The nature of SD models also makes it easy to integrate the important (Gordon et al., 2008) aspect of spatio-temporal scale integration, and the data-based typology of system dynamics means that the “opportunity” (Rosenberg and Madani, 2014) presented by big data can be harnessed in water resource management.

HESSD
12, 8761–8851, 2015

There are, of course, reasons why system dynamics would not be chosen as a modelling technique. The first of these is the fundamental issue that all models that view systems from a top-down perspective, inferring system characteristics from behaviours, can only produce deterministic results (Liu et al., 2006). Great care must also be taken with the level of complexity included in a system dynamics model, since very simplistic relationships between variables will fail to capture the complexity that is present (Kandasamy et al., 2014), while the inclusion of too much complexity is easy, and can result in relationships that do not occur in the real world (Kelly (Letcher) et al., 2013). In systems of evolution and co-evolution, using SD techniques may also be difficult, as the "very nature of systems may change over time" (Folke et al., 2010), and so time invariant equations may not properly model long-term dynamics, though the use of time-variant equations may result in difficulties in calibration when using data from the past.

Of all of the modelling techniques detailed in this review, system dynamics has perhaps seen the most explicit usage in socio-hydrology thus far. This is perhaps due to the usefulness of SD in developing system understanding (the stage that socio-hydrology would currently be characterised as being at), and the ease with which disciplines may be integrated. Models thus far have generally been fairly simple, involving five or so system components, using proxy measures for high-level system "parameters". Examples include the work of Di Baldassarre et al. (2013b) in which there are five system parameters with a total of seven difference equations governing the behaviour of a fictional system investigating the coupled dynamics of flood control infrastructure, development and population in a flood-prone area. The parameters used are proxies for the subsystems of the economy, politics, hydrology, technology and societal sensitivity. The usage of a fairly simple model has allowed for further work using this model, in which the impact of changing parameters which represent the risk taking attitude of a society, its collective memory and trust in risk-reduction strategies are investigated, alongside a development in which a stochastic hydrologic input was used (Viglione et al., 2014). The model was further developed, this time simplified in structure, by Di

Baldassarre et al. (2015); here, the core dynamics were focused on, and the number of parameters and variables reduced. This step of simplification is surely good in system dynamics models, isolating the core features and relationships which produce system-level outcomes, while reducing the risks of overparameterisation and excessive model complexity. The structure of the modelling framework allowed for the development of a fairly simple model that could show complex interactions between society and hydrology, producing emergent outcomes, and lead to development in thought around the subject. Another example of a system dynamics approach being taken in socio-hydrological study is the work of Kandasamy et al. (2014), where the co-evolution of human and water systems in the Murrumbidgee Basin (part of the Murray–Darling Basin) was investigated in a qualitative sense to form a system conceptualisation; this was then followed by work by van Emmerik et al. (2014) in which this conceptualised system view was turned into a quantitative model, formed of coupled differential equations, capable of modelling past system behaviour. In this case, a slightly different set of variables are investigated (reservoir storage, irrigated area, human population, ecosystem health and environmental awareness), which provide indicators of the economic and political systems in a more indirect (e.g. the irrigated area giving an idea of economic agricultural production), but directly measurable way. Again, this fairly simple mathematical model was able to replicate the complex, emergent behaviours seen in the system, particularly the "pendulum swing" between behaviours of environmental exploitation and restoration. Studies investigating the Tarim Basin, Western China, have followed a similar development process, with a conceptual model developed (Liu et al., 2014) first to examine the system from a qualitative, historical perspective, before a quantitative approach (Liu, D. et al., 2015), including proxy variables for hydrological, ecological, economic and social sub-systems, is taken to develop further understanding of how and why specific co-evolutionary dynamics have occurred; the focus in this study was on system learning, and so a simple model was developed to facilitate easy understanding. The final socio-hydrological study that explicitly takes a system dynamics approach looks at the dynamics of lake systems (Liu, H. et al., 2015); this study involves a slightly more complex SD model, but is an excellent example of the development path through conceptualisation, CLD formation, conversion to an SFD and subsequent quantitative analysis. The five feedback loops that exist within the model, and their significance in terms of system behaviour, are well explained. Again, similar (though a slightly higher number of) variables are used in the model, including population, economics, water demand, discharge, pollutant load and water quality. As is clear from the choice of variables, the hydrological system is viewed in more detail in this study, and the aspect of community sensitivity and behavioural responses are not included explicitly.

As is clear from the studies highlighted, system dynamics has been well applied to socio-hydrological studies. The ease with which SD facilitates system learning, the ability for relatively simple models to (re)produce emergent phenomena seen in socio-hydrological systems, and the clear model development process have led to this being a common choice of modelling framework in early socio-hydrological system study. The highlighted studies make clear the aspects of integrated socio-hydrological systems that should be included in all such studies (i.e. some inclusion of hydrological systems, impacts on livelihoods and societal responses), but also the importance of tailoring models to show in more detail those aspects that are pertinent to a particular case study.

4.6 Pattern-oriented modelling (POM)

The previously described techniques of agent-based modelling and system dynamics are archetypal examples of bottom-up and top-down modelling frameworks respectively. The advantages and disadvantages of these approaches have been detailed earlier, but are summed up in Table 3. Overcoming these deficiencies is key in furthering the pursuit of accurate, useful modelling. One way of attempting to overcome the difficulties posed by top-down and bottom-up strategies is to attempt to "meet in the middle" (something that has been called for a long while Veldkamp and Verburg, 2004), and this is where POM sits. Pattern-oriented models are essentially process-based

HESSD
12, 8761–8851, 2015

(and so bottom-up) models where system results are matched to observed patterns of behaviour in the model calibration/validation stage (Grimm et al., 1996). The use of patterns in calibration, as opposed to exact magnitudes of output parameters, makes validation simpler (Railsback, 2001), since maximum use may be found for data that is available, and the often impracticable collection of data regarding all output parameters becomes less necessary. Also, imperfect knowledge of base-level processes may be overcome through emergent pattern identification (Magliocca and Ellis, 2013). The use of POM would allow for a simpler process-based model, with few parameters, overcoming the problems associated with the complexity in bottom-up models, whereby overparameterisation may lead to the tendency for models to be able to fit data despite potentially incorrect processes and structure, as well as reducing model uncertainty, while also being defined by processes, rather than data, and so overcoming the criticisms commonly levelled at top-down approaches. There are, of course, drawbacks to the use of POM: a model being able to fit patterns does not necessarily mean that the mechanisms included in the model are correct, and the data required for model validation may be quite different to that which is commonly required at present, and so using POM may require a different approach to data collection (Wiegand et al., 2003). Also, pattern-oriented models may still be significantly more complex than system dynamics models, due to the modelling of base-level processes.

The model development process in POM is thus (Wiegand et al., 2003):

1. Identification of processes and development of process-based model
2. Model parameterisation
3. Aggregation of relevant data and identification of patterns
4. Comparison of observed patterns and those predicted by model
5. Comparison of model results with other predictions (key model outputs may need to be validated against as well as patterns)

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

6. Necessary cyclical repetition of previous steps

Pattern-oriented models would be well applied in socio-hydrological situations. The various emergent characteristics and patterns that are created in coupled socio-ecological and socio-hydrological systems lend themselves perfectly to the integrated use of processes and patterns, particularly since there are sub-systems and processes which are well understood and the dynamics of which can be well modelled, but also those system components which are less well understood. In less well understood system sections, underlying processes may be uncovered by using the patterns which define the system (Grimm et al., 2005). POM has already found applications in socio-ecological investigations into land-use change (Evans and Kelley, 2008; Iwamura et al., 2014), though it has potential uses in many other areas.

4.7 Bayesian networks (BN)

Often, relationships between variables are stochastic, rather than deterministic, i.e. a given input does not always give the same output and instead there is a distribution of possible outputs. In such situations, Bayesian networks are well applied. The advantages of using Bayesian Networks come directly from the modelling approach: uncertainties are directly and explicitly accounted for since all inputs and outputs are stochastic (Kelly (Letcher) et al., 2013), and the use of Bayes' theorem means that probability distributions of output variables may be "updated" as new knowledge and data becomes available (Barton et al., 2012). Using Bayes' theorem also allows the use of prior knowledge, since distributions of output parameters are required to be specified prior to model start-up (to then be changed and updated), and these prior distributions may be informed by literature (Barton et al., 2012). The fact that there are relationships (albeit stochastic rather than deterministic) between variables also means that direct causal links between variables may be established (Jellinek et al., 2014). The drawbacks in using BNs are the difficulties present in modelling dynamic systems, since BNs tend to be set up as "acyclic" (Barton et al., 2012) (though object-

HESSD
12, 8761–8851, 2015

oriented Barton et al., 2012 and Dynamic Bayesian Networks Nicholson and Flores, 2011, which can model dynamic feedbacks, are being developed and becoming more prevalent), and in the potential statistical complexities present. A Bayesian Network may be seen as a stochastic version of a system dynamics model, and so many of the criticisms of SD models may also be applicable to BNs; in particular, the fact that BNs are largely based around data-defined relationships (as opposed to physically determined or process-based relationships) between variables means that BNs can only yield determinstic (albiet stochastically deterministic) results that arise from data.

The model development process for a Bayesian Network follows the following basic outline:

1. The model is conceptualised, with variables represented as "nodes" in the network and causal linkages between variables determined
2. "Parent" and "child" nodes are related with a conditional probability distribution determining how a "child" node changes in relation to parent nodes (Jellinek et al., 2014)
3. Data is collected and fed into the model
4. This new data causes output probability distributions to be updated
5. As new data and knowledge is accumulated, the network can be continually updated, and so the previous two points may be carried out cyclically

Many uncertain relationships exist within hydrology and sociology, and indeed in the linkages between the two. Perhaps the use of stochastic relationships and the BN framework would be an appropriate technique in socio-hydrological studies. van Dam et al. (2013) has applied an acyclic BN to a wetlands scenario to determine how wetlands may be impacted by both natural and anthropogenic factors in an ecosystem functionality sense and how change in wetlands ecosystems may impact upon livelihoods, however this model could not account for potentially significant dynamic feedbacks. The development of Dynamic Bayesian Networks in a socio-hydrological context

HESSD
12, 8761–8851, 2015

should be a research priority in this area; the development of such models would be of value in contexts of system understanding, policy development and forecasting, due to the vital role that uncertainties play in all of these areas.

4.8 Coupled component modelling (CCM)

Coupled component models take specialised, disciplinary models for each part of a system and integrate them to form a model for the whole system. Kelly (Letcher) et al., (2013) describe how this may be "loose", involving the external coupling of models, or much more "tight", involving the integrated use of inputs and outputs. CCM therefore offers a flexibility of levels of integration (this is of course dependent on the degree to which models are compatible), and can be a very efficient method of model development, since it takes knowledge from models that already exist, and will already have some degree of validity in the system that they are modelling. The flexibility also extends into the fact that different modelling techniques may be integrated, and so those techniques that suit specific disciplines may be utilised. CCM can also be an excellent catalyst for interdisciplinary communication; models that experts from different disciplines have developed may be integrated, necessitating communication between modellers and leading to development in understanding of modelling in different disciplines.

However, there are of course drawbacks to using CCM; the models used may not be built for integration (Kelly (Letcher) et al., 2013), which may lead to difficulties and necessitate significant recoding. There may also be aspects of models that cannot be fully integrated, which could potentially lead to feedbacks being lost. Different treatments of space and time could potentially create difficulties in integration (though this could also be a positive, since aspects that do not require computationally intensive models may be coupled with those that do and result in savings). Uncertainties could also be an issue when coupling models directly: models will have been developed such that the outputs they generate have acceptable levels of uncertainty, though when integrated these uncertainties may snowball.

HESSD
12, 8761–8851, 2015

Models have certainly been coupled between hydrology and other disciplines (for example economics e.g., Akter et al., 2014), and indeed different aspects of hydrology have been integrated using CCM (Falter et al., 2015), however no specific studies have been carried out in socio-hydrology which directly couple discipline specific models, though this could be a future development as more experts from both disciplines participate.

4.9 Scenario-based modelling

While perhaps not a "modelling technique" per se, and rather a method of resolution that can be applied, the usage of scenarios in analysis has important implications for modelling that warrant discussion. Scenario-based approaches fall into two main categories, those which investigate different policy implementation scenarios, and those which use scenarios of different initial conditions (within this, initial conditions could be for instance different socio-economic behavioural patterns, or future system states). This means that the impact that policies may have can be analysed from two angles; that of assuming knowledge of system behaviour and comparing decisions that may be made, as well as admitting lack of system knowledge and analysing how different system behaviour may impact the results that decisions have (indeed these may also be mixed). There are several issues that socio-hydrological modelling studies may encounter that will lead to scenario-based techniques being applicable. Firstly, long-term modelling of systems that will involve a large amount of uncertainty, particularly in terms of socio-economic development, is difficult due to the snowballing of uncertainties; as such, using likely scenarios of future development may be a more prudent starting point for modelling studies that go a long way into the future. Even if uncertainties are deemed acceptable, the computational effort required to conduct integrated modelling studies far into the future may make such studies infeasible, and so the use of scenarios as future initial conditions may be necessary. Thirdly, particularly in a policy context, policies are generally discrete options, and so the first use of scenario-based approaches mentioned (comparing options) certainly makes sense.

HESSD
12, 8761–8851, 2015

Studies conducted on the subject of climate change tend to use a scenario-based approach for socio-economic development, and CHANS studies also sometimes use scenario-based approaches (e.g. Monticino et al., 2007). The usage of scenarios has been said to have improved recently (Haasnoot and Middelkoop, 2012), with more scenarios generally being used, and appropriate interpretation of the relative probabilities of different scenarios occurring being investigated. While the use of a scenario-based approach for analysing policy alternatives involves very few compromises, the use of scenarios as initial conditions for modelling future system states can involve compromise in that the "dynamic interactions" between social and hydrological systems will be lost (Carey et al., 2014) in the intervening period between model development and the time at which the model is analysing.

4.10 Heuristic/knowledge-based modelling

Heuristic modelling involves collecting knowledge of a system and using logic or rules to infer outcomes (Kelly (Letcher) et al., 2013). The process of model development here is quite clear, with an establishment of the system boundaries and processes, and simply gathering knowledge of system behaviour to determine outcomes. As with scenario-based modelling and coupled component modelling, the use of heurism in models allows the use of different modelling techniques within the tag of "heurism", for example Acevedo et al. (2008); Huigen (2006) have used ABMs encoded with a great deal of heuristic knowledge. The advantage of heuristic modelling is in the heurism: experience and knowledge of systems is a valuable source of information, and if system processes are understood well enough that logic may be used to determine outcomes, then this is an excellent method. However, where system knowledge is incomplete, or imperfect in any way, then the usefulness of experience-based techniques falls down. Heuristic modelling is also not generally all that useful in system learning applications, though in cases where disciplinary models are integrated, new heurism may be generated in the interplay between subjects.

HESSD
12, 8761–8851, 2015
Modelling socio-hydrological systems
P. Blair and W. Buytaert

Gober and Wheater (2015) have identified that some current socio-hydrological models (that of Di Baldassarre et al., 2015) may have "heuristic value" (Gober and Wheater, 2015), as opposed to practical, applicable value, in that some conceptualised models of socio-hydrological systems tend to assume relationships between variables, rather than define them via data. This gives a different value to the term heuristic, and implies the development of models of different structure via heuristic means. The challenge in taking this approach "is to avoid biasing the model to predict the social behaviour that we think should happen" (Loucks, 2015).

5 Conclusions

This paper has reviewed the literature surrounding the modelling of socio-hydrological systems, including concepts that underpin all such models (for example conceptualisation, data and complexity) and modelling techniques that have and/or could been applied in socio-hydrological study. It shows that there is a breadth of issues to consider when undertaking model-based study in socio-hydrology, and also a wide range of techniques and approaches that may be used. Essentially, however, in socio-hydrological modelling, there is a decision to be made between top-down and bottom-up modelling, which represents a choice between representing individual system processes (including the behaviours and decisions of people in this case) and viewing the system as a whole; both of these approaches have advantages and disadvantages, and the task to the modeller is to maximise the advantages and minimise the disadvantages. There are significant challenges in representing, modelling and analysing coupled human–water systems, though the importance of the interactions that now occur between humans and water means that these challenges should be the focus of significant research efforts. With regards to future research that could be conducted following the work that has been reviewed here, without resorting to the platitudes of improving predictions, reducing and managing uncertainties, increasing interdisciplinary integration and improving data, there are several examples of areas in which research

HESSD
12, 8761–8851, 2015

would be of benefit. Some of these topics are common to other subjects, however there are specific aspects that are of particular importance in socio-hydrology:

- Conceptual models of stylised socio-hydrological systems, for example systems of inter-basin water transfer, drought or agricultural water use: the strength that socio-hydrology should bring is a greater understanding of how human–water interaction affects overall system behaviour. A great deal of understanding can be generated through conceptual studies of generalised systems, and so modelling of archetypal systems would be of benefit. The challenge here is to move beyond models developed to mimic behaviour that we expect, towards those capable of giving insight.

- Determining the appropriate complexity for models of highly interconnected socio-hydrological systems: the broadening of system boundaries brings issues regarding model complexity and trade-offs between deterministic uncertainty and uncertainty propogation. Quantifying these trade-offs in socio-hydrological circumstances, and so determining the appropriate level of abstraction for modelling would allow for more effective modelling efforts.

- Gathering data in socio-hydrological studies: as an interdisciplinary subject, data in socio-hydrological study will come from a variety of sources. While methods for collection of hydrological data are well established, the social data that will be required (beyond population statistics) may pose issues in availability and collection. The challenge here is to maximise the utility of what is available, and to adapt models accordingly.

- Determining methods for calibration and validation in socio-hydrology: calibration and validation are issues in almost all modelling areas. However, as a new subject, there is no calibration/validation protocol for socio-hydrological modelling, and with the aforementioned issues with social science data, conducting formal calibration and validation may be difficult. As such, the development of guidelines

HESSD
12, 8761–8851, 2015
Modelling socio-hydrological systems
P. Blair and W. Buytaert

regarding what constitutes "validation" in socio-hydrology would be worthy of investigation.

- Discussion of emergence in socio-hydrological systems, particularly emergence of more abstract properties, such as risk, vulnerability and resilience: the stochastic nature of hydrological drivers and the unpredictability of human responses renders any definite statement regarding system behaviour largely anecdotal (though often anecdotes of merit), and so acknowledging this stochasticity in analysis and discussion, using properties of more abstract meaning to describe the system may be useful in socio-hydrology.

- More in-depth socio-hydrological modelling studies across social, economic and hydrological gradients: while conceptual modelling can build understanding to a point, case-based models can often give a greater insight into specific system behaviours. Applying socio-hydrological models to a range of cases will help build understanding in this way, particularly if these cases are similar, but differentiated in some way (e.g. responses to drought across a range of levels of economic development). The challenge (and opportunity) that this presents is understanding the dynamics which are general across cases, those which vary across gradients and those which are place-specific.

- Determining how best to present and use findings from socio-hydrological studies in policy applications: the way that socio-hydrological understanding will likely be applied in the real world is via policy decisions. As such, understanding the best way to communicate findings in socio-hydrology is vital. The challenge here is to communicate the differences between the outcomes predicted by traditional analyses and socio-hydrological studies regarding the way that policy decisions may impact the system in the long term, while acknowledging the limitations in both approaches.

The unifying feature of these future research topics is the development of understanding regarding socio-hydrological systems. The most important way in which socio-

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

hydrology differs from other water management subjects is in understanding the system as a whole, as opposed to focusing on problem solving. As such, the research priorities at this stage are focused on different ways of improving and communicating understanding.

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HESSD

12, 8761–8851, 2015

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P. Blair and W. Buytaert

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HESSD
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P. Blair and W. Buytaert

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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HESSD
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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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HESSD

12, 8761–8851, 2015

Table 1. Examples of modelling studies that could be deemed socio-hydrological in scope.

Reference	Approach	Case Studied	Reason for Modelling
Barreteau et al. (2004)	ABM	Irrigation system, Senegal River Valley	Determining suitability of modelling approach to application
Becu et al. (2003)	ABM	Water Management, Northern Thailand	Analysis of Policy Approaches
Medellín-Azuara et al. (2012)	ABM	Prediction of farmer responses to policy options	Understanding behavioural processes
Schlüter and Pahl-Wostl (2007)	ABM	Amu Darya River Basin, Central Asia	Determining origins of system resilience
Fabre et al. (2015)	CCM	Herault (France) and Ebro (Spain) catchments	Understanding supply-demand dynamics
Fraser et al. (2013)	CCM	Worldwide, areas of cereal production	Predicting areas of future vulnerability
Dougill et al. (2010)	SD	Pastoral Drylands, Kalahari, Botswana	Predicting areas of future vulnerability
Elshafei et al. (2014)	SD	Murrumbidgee Catchment, Australia	System Understanding
van Emmerik et al. (2014)	SD	Murrumbidgee Catchment, Australia	System Understanding
Liu, H. et al. (2015)	SD	Water quality of Dianchi Lake, Yunnan Province, China	Decision-support
Liu, D. et al. (2015)	SD	Tarim River Basin, Western China	System Understanding
Fernald et al. (2012)	SD	Acequia irrigation systems, New Mexico, USA	System understanding; stakeholder participation; prediction of future scenarios
Di Baldassarre et al. (2013b)	SD	Human-flood interactions, fictional catchment	System understanding
Viglione et al. (2014)	SD	Human-flood interactions, fictional catchment	System understanding
Madani and Hooshyar (2014)	GT	Multi-operator reservoir systems (no specific case)	Policy
van Dam et al. (2013)	BN	Nyando Papyrus Wetlands, Kenya	System understanding; evaluation of policy options
Srinivasan (2015)	Other	Water supply and demand, Chennai, India	System understanding; analysis of possible alternative historical trajectories
Srinivasan et al. (2015)	Other	Decreasing flows in the Arkavathy River, South India	Policy; focusing future research efforts
Odongo et al. (2014)	Other	Social, ecological and hydrological dynamics of the Lake Naivasha Basin, Kenya	System Understanding

ABM: Agent-based Modelling; CCM: Coupled Component Modelling; SD: System Dynamics; GT: Game Theory; BN: Bayesian Network; POM: Pattern-oriented Modelling.

HESSD
12, 8761–8851, 2015

Table 2. Procedure for building SFD using CLD (from Mirchi et al., 2012).

Step	Purpose
Key variable recognition	Identify main drivers
Stock identification	Identify system resources (stocks) associated with the main drivers
Flow module development	Provide rates of change and represent processes governing each stock
Qualitative analysis	Identify (i) additional main drivers that may have been overlooked; (ii) causal relationships that require further analyzing by specific methods; (iii) controllable variables and their controllers; (iv) systemic impact of changes to controllable variables; (v) system's vulnerability to changes in uncontrollable variables

HESSD
12, 8761–8851, 2015

Table 3. Key advantages and disadvantages of top-down and bottom-up modelling techniques.

	Advantages	Disadvantages
Top-down	– Incomplete knowledge of system and/or processes acceptable – Complexity determined more by modeller	– Difficult to determine underlying processes – Correlations in data may be coincidental, rather than due to underlying processes
Bottom-up	– Processes properly represented (where they are understood) – Causal link between process and outcome discernable	– Large amount of system knowledge required – Model complexity determined in part by process complexities

HESSD
12, 8761–8851, 2015

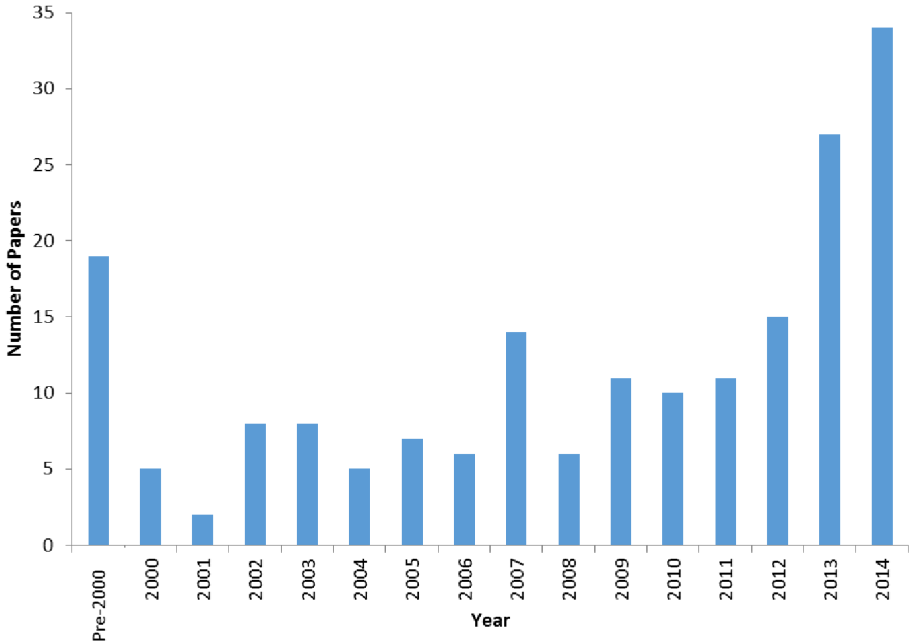

Figure 1. Distribution of years in which papers included in this review were published.

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

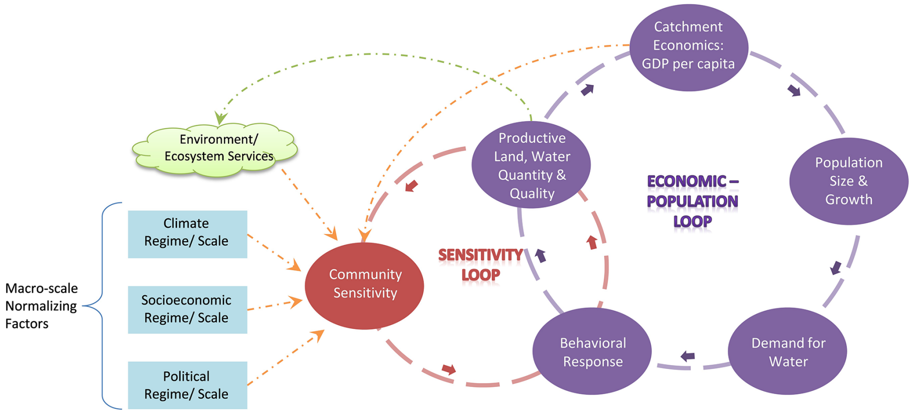

Figure 2. © Elshafei et al. (2014), reproduced with permission under the CC Attribution License 3.0. A conceptual representation of a socio-hydrological system (Elshafei et al., 2014).

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

Title Page
Abstract Introduction
Conclusions References
Tables Figures
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

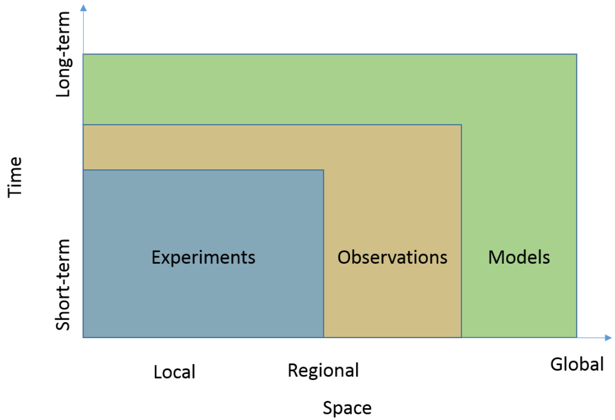

Figure 3. Temporal and spatial scales at which different research approaches are appropriate (adapted with permission from Reyer et al., 2015, © Reyer et al. (2015), used under the CC Attribution License 3.0).

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

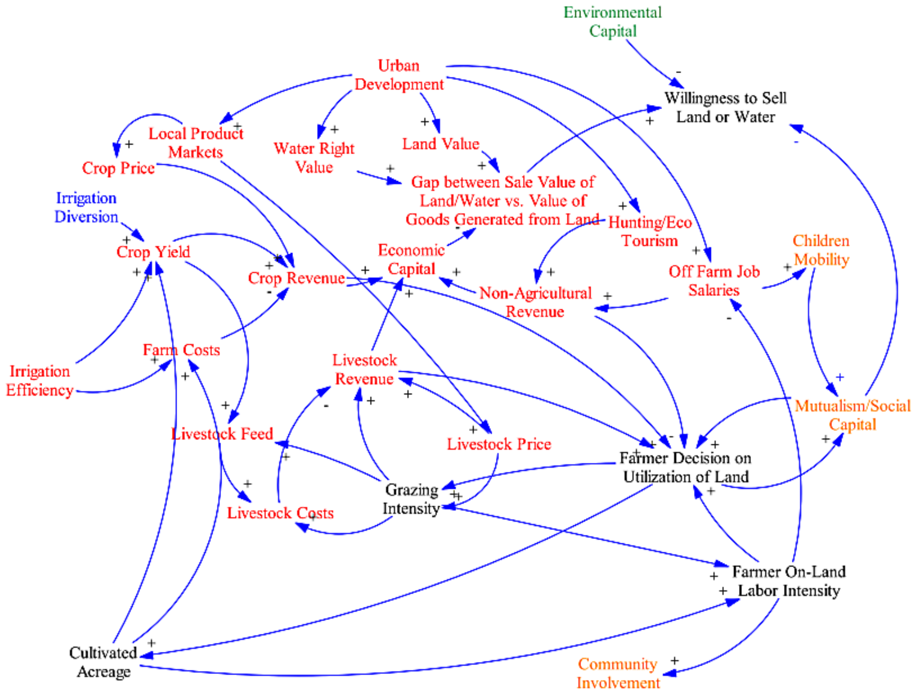

Figure 4. © Fernald et al. (2012), reproduced under the CC Attibution License 3.0. An example of a complex CLD (this is approximately one quarter of the complete diagram).

HESSD

12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc

Printer-friendly Version
Interactive Discussion

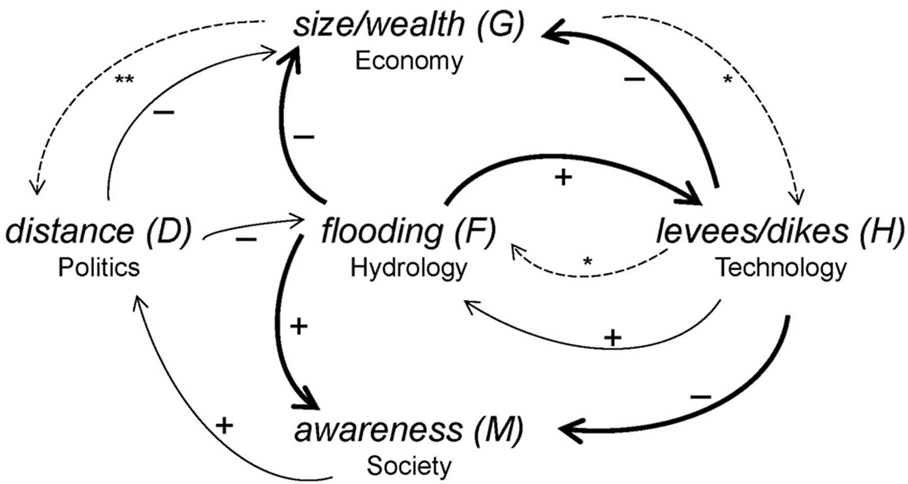

Figure 5. © Di Baldassarre et al. (2013b), reproduced with permission under the CC Attribution License 3.0. An example of a simple CLD from Di Baldassarre et al. (2013b).

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert

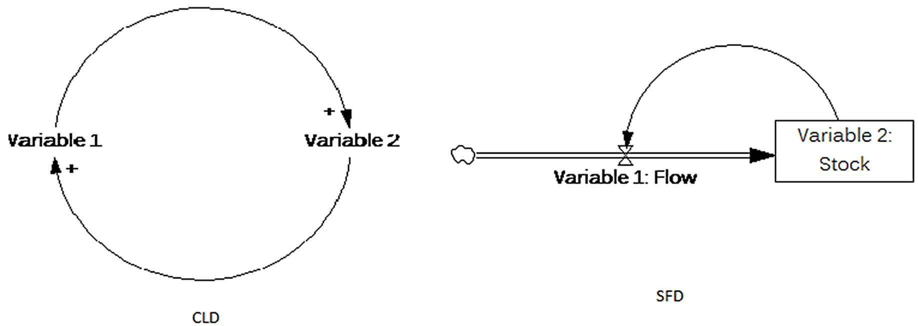

Figure 6. An example of a Stocks and Flows Diagram (SFD) developed from a Causal Loop Diagram (CLD).

HESSD
12, 8761–8851, 2015

Modelling socio-hydrological systems

P. Blair and W. Buytaert