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Socio-hydrology: A new science of people and water

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***Humans have changed the way the world works. Now they have to change the way they think about it, too*. The Economist, May 26, 2011**

THE COUPLED HUMAN-WATER SYSTEM

Dateline November 2010, Murrumbidgee River Basin, Australia: Irrigators are up in arms over proposed government plans to cut their water allocations and return flows back to the basin's rivers to support the environment and restore lost biodiversity. *The Australian* of November 04, 2010 reported on the community backlash, including the resort to 'book burning' to highlight their plight. Community backlash and 'book burning' notwithstanding, the reality is that this conflict had been brewing for decades. Now, wind back the clock 100 years to the early 20th century. Up until 1900, there were virtually no dams and almost no irrigation on the Murrumbidgee. With demand for food for a growing population and the possibility of generating agricultural exports, irrigated farming expanded along the river corridor from 1920 onwards. By 1940, abstractions during low flows had increased to 50% of the natural flow and by 1950 to almost 100% (Roderick, 2011). Over this period, the predominant direction of farming development, construction of water 'assets' (e.g. dams and weirs) as well as water extractions was upstream. However, things came to a head in the 1980s, with increasing deterioration of river health and the recognition that previous farming practices were no longer sustainable. Protection of the environment was on the political agenda, along with a commitment not only to return water to rivers to nurse them back to health, but also to help agricultural industries to rise up to the challenge of a drier future. After 30 years of seemingly ongoing crisis conditions, a protracted drought and a looming federal election precipitated government action in early 2007. The result was a concerted plan by government to buy back water rights of willing farmers and build new assets aimed at increasing water use efficiency and protecting the environment [Murray-Darling Basin Authority (MDBA), 2010]. For example, there has been an increasing trend for upstream rice growers to sell back their annual allocations, and for downstream horticulturalists to purchase fresh allocations during low allocation seasons. This meant that, from 2000 onwards, water abstractions as well as water assets that had been migrating upstream in the early 20th century are now beginning to move back downstream (Figure 1). Whereas the sole customer for 100 years was irrigated farming, now there is a new 'customer in town', called the 'environment'. More and more, much of the business of water management in the basin, including the building of new assets, is aimed at satisfying the environment, a phenomenon that wouldn't have been foreseen in the heady days of irrigation development and dam building. No wonder the irrigators are up in arms.

If the competition between irrigation and the riparian environment continues in this way in the Murrumbidgee over the next decades, one can foresee a landscape, including human population patterns and human-induced structures, which could look very different from what it is now (Figure 1). Could we predict this? What will be the role of

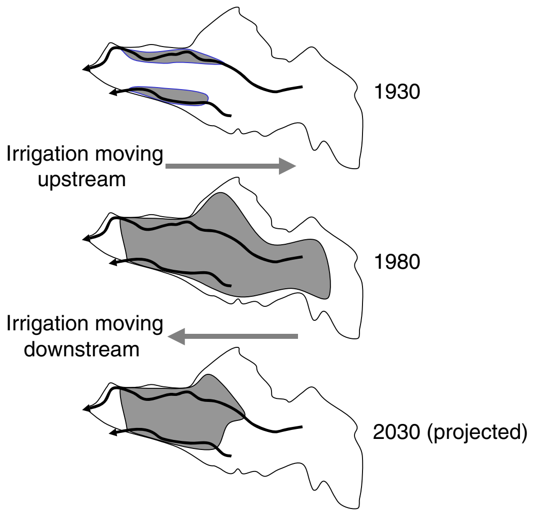

Figure 1. Schematic of the evolution of the spatial patterns of irrigation (shaded area) in the Murrumbidgee system (84,000 km^2), Southeast Australia. In the early 20th century, irrigation moved upstream. Recently, the government has started buying water rights from farmers to protect the environment. Panel 3 is one projection that is based on the possibility of cutting back irrigation upstream.

hydrology in any changes in the landscape including societal changes, and in return, what will be the impact of the societal changes on water cycle dynamics? Should such predictions be the business of hydrologists or social scientists? The common history of hydrology and the societal changes seen in the Murrumbidgee is an example of unexpected process dynamics. With such dramatic changes to the landscape, prediction of water cycle dynamics over long timescales is not feasible without including the interactions and feedbacks with human systems.

Welcome to socio-hydrology, the science of people and water, a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems. As pointed out in a recent editorial in the Economist magazine (see below), natural scientists have for too long ignored the human factor. Hydrologists are not exceptions to this. In traditional hydrology, human-induced water resources management activities are prescribed as external forcings in the water cycle dynamics, under the assumption of stationarity (Milly *et al.*, 2008; Peel and Blöschl, 2011). In socio-hydrology, humans and their actions are considered part and parcel of water cycle dynamics, and the aim is to predict the dynamics of both.

> "*Too many natural scientists embrace the comforting assumption that nature can be studied, indeed should be studied, in isolation from the human world, with people as mere observers. Many environmentalists—especially those in the American tradition inspired by Henry David Thoreau—believe that "in wilderness is the preservation of the world". But the wilderness, for good or ill, is increasingly irrelevant.*" – Editorial in the Economist, May 26, 2011

But what of the science of integrated water resources management (IWRM), which has been around for a long time, and is also clearly, and strongly, about people and water. In what way is socio-hydrology different from IWRM? A typical question addressed in IWRM is: in what way does a management decision affect runoff and, conversely, in what way is management constrained by runoff? IWRM is also about interactions of humans and water, and often uses the 'scenario-based' approach as the common means to explore these interactions (Savenije and Van der Zaag, 2008). However, this approach may be unrealistic, especially for long-term predictions, as it does not account for the dynamics of the interactions between water and people. For example, it is unlikely that the coupled system dynamics of the Murrumbidgee basin, as reported above, could have been predicted by a 'scenario-based' approach that does not account for the co-evolutionary dynamics of coupled human-water systems, including spontaneous or unexpected behaviours, as illustrated in Figure 1. Hence, whereas the focus of IWRM is on controlling or managing the water system to reach desired outcomes for society and the environment, the focus of socio-hydrology is on observing, understanding and predicting future trajectories of co-evolution of coupled human-water systems. In this sense, one could say that socio-hydrology is the fundamental science underpinning the practice of IWRM.

There is considerable similarity between the proposed new science of socio-hydrology and the now established field of eco-hydrology. Eco-hydrology explores the co-evolution and self-organisation of *vegetation* in the landscape in relation to water availability (Eagleson, 1982, 2002; Rodriguez-Iturbe, 2000; Berry *et al.*, 2005). Socio-hydrology, on the other hand, explores the co-evolution and self-organisation of *people* in the landscape, also with respect to water availability. We believe that socio-hydrology stands to learn a lot from the success of eco-hydrology, which has added new life to hydrology through introduction of the concepts of co-evolution and optimality that have previously been foreign to hydrology. The introduction of eco-hydrology has helped spawn new connections between hydrology and neighbouring disciplines such as pedology, plant physiology and geomorphology, and in this way it has helped to expand the horizons of hydrology. In the same way, the advent of socio-hydrology could also lead to a similar broadening of the science, extending into the social sciences. However, even while socio-hydrology will take on increasing importance in the context of a changing, human-dominated world, its practice may turn out to be more challenging than eco-hydrology. This is because humans

possess more powerful ways and means of controlling water cycle dynamics beyond the optimality, adaptation and acclimation strategies that natural vegetation possesses and has developed over time.

Finally, the timing is just right for the launch of socio-hydrology, as a new interdisciplinary but quantitative science of people and water, with the ambition to make predictions of water cycle dynamics, and thus underpin sustainable water management. At a time when hydrology textbooks continue to dwell on the complexities of processes occurring in undisturbed places or under idealized conditions, which are the exception rather than the rule in the real world, and almost all water bodies are affected by people in one way or another, there is an urgent need for hydrology itself to adapt and evolve to cope with the emergent scientific and practical challenges in a changing world (Wagener *et al*., 2010), and prevent and resolve conflicts between humans and the environment, and amongst humans themselves (Postel, 2011; Koutsoyiannis, 2011). Socio-hydrology addresses this strongly felt need. In fact, there have already been several early attempts at exploring the co-evolution of human-water systems. For example, Geels (2005) studied the trajectories of co-evolution of water technology and society in present-day Netherlands. Kallis (2010) studied the co-evolution of water resource development in ancient Athens. Pataki *et al.* (2011) have provided an outline of the interplay of sociological and ecological processes in urban water management.

EMERGENT DYNAMICS ACROSS SPACE AND TIME

The essence of socio-hydrology, the point of departure from IWRM, is, as mentioned before, the study of the co-evolution of humans and water on the landscape. Winder *et al.* (2005) and Kallis (2007) have pointed out that for a system to be considered co-evolutionary, there must be a process of generation of 'new variations', as they called them. New variations, also known as 'emergent behaviour', are brought about by feedbacks between processes at a range of scales, and may lead to exceedance of 'tipping points' through which the systems may evolve into new, perhaps previously unobserved, states. The Murrumbidgee example is a case in point.

In the Murrumbidgee basin, the spatial patterns of organisation arising from co-evolutionary dynamics are nevertheless underpinned by a directed stream network. This is often the case; water abstraction upstream will invariably affect people living downstream, and so will changes to water quality. However, one can think of cases where such connections and feedbacks are less obvious. The Sahel drought in the 1980s led to widespread famine and involuntary human migration. One of the compounding factors that contributed to the drought was land use change in upwind areas (i.e. East Africa), leading to reduced moisture cycling westward, and the consequent reduction of precipitation locally. The nature of moisture recycling that contributed to drought in the Sahel is illustrated in Figure 2, which was obtained by analysing 10 years of re-analysis data on global water circulation (Van der Ent *et al*., 2010; Van der Ent and Savenije, 2011), and shows that 60% of the rainfall in the Sahel is derived from terrestrial evaporation upwind (see Figure 2). Reduction in moisture recycling from upwind can introduce a positive feedback locally, with the reduced precipitation leading to overgrazing, which then leads to lower evaporation, which in turn leads to

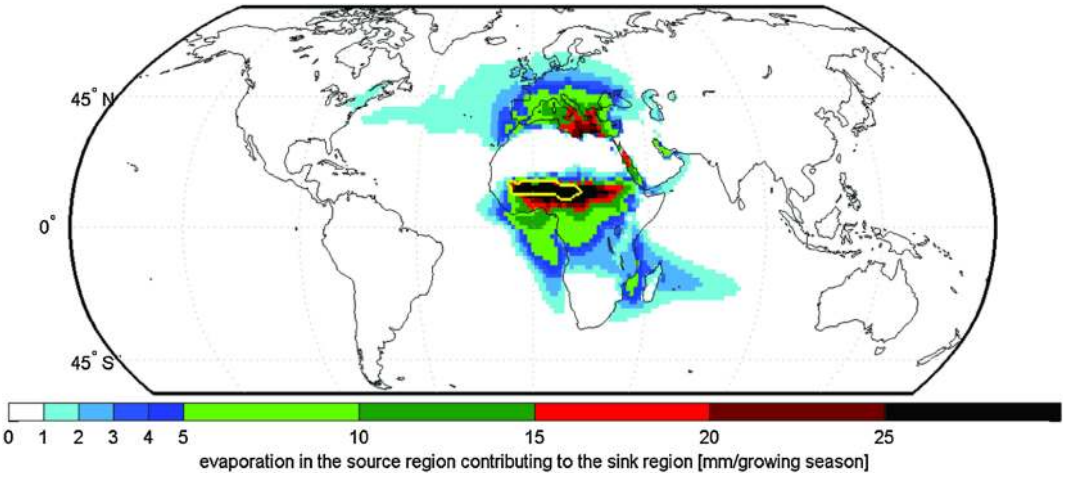

Figure 2. Precipitation shed of the Sahel (yellow contour). The scale indicates how much each coloured region contributes to the rainfall in the growing season, in absolute terms. Hence, from each pixel in the black region, 25–30 mm of the evaporation contributes to the rainfall in the Sahel during the growing season. This has to be multiplied by the ratio of the contributing area to the target area (the yellow contour) to obtain the contribution to the rainfall in the target area (personal communication by Van der Ent).

still lower precipitation. The Sahel example is one where, rather than being affected by human activities *upstream*, the water cycle is affected by human activities *upwind*. Consequently, instead of having to deal with a 'watershed', we now have to deal with a 'precipitation shed'. The critical issue facing socio-hydrology is that the local people are powerless to affect the 'precipitation shed'. How could people in the Sahel seek local solutions outside of the watershed? The traditional way under such circumstances is via food imports. Unfortunately, war and conquest tend to be other unintended consequences. This is an example of the primary challenges of the new field of socio-hydrology.

As mentioned before, while eco-hydrology studies how *vegetation* organises itself in the landscape with respect to water, socio-hydrology studies how *people* organise themselves in the landscape with respect to water. Ancient human settlements were mostly organised along streams, which they used as a means of transport and water supply, and therefore access and proximity to water courses or sources governed the primary human settlement patterns. With increasing technological capability, humans could manage to settle away from streams and access water through recourse to technology and to use alternative means for transport. Therefore, just as eco-hydrology aims to learn from vegetation patterns and their evolution, socio-hydrology can potentially learn from human settlement patterns, through interpreting them in terms of access and proximity to water resources and socio-economic and technological factors impacting differentially on these in different parts of the world. In other words, there are many parallels between eco-hydrology and socio-hydrology, even as there are substantial differences.

An important feature of non-linear systems is that fast processes interact with slow processes to produce complex and rich dynamics. For example, these interactions may lead to exceedance of critical thresholds or tipping points. Resilient social-ecological systems are those that continually change and adapt yet remain within critical thresholds (Folke *et al*., 2010). Climatic, hydrological and societal drivers often appear as shocks (floods, droughts, wars, economic collapse) and may push the system beyond these resilience thresholds. In a hydrological landscape such as the Sahel, resilience may be low, so change to a different mode – e.g. desertification, famine and human migration in the case of the Sahel – may occur more readily (Folke *et al*., 2004). On the other hand, in temperate climates the resilience thresholds tend to be higher. But even in relatively wet regions, unexpected changes of the system may yet occur. For example, the traditional source of drinking water in Bangladesh used to be rainfed ponds. When the community switched to groundwater as a source of water supply in the 1980s, responding to the contamination of the ponds by pathogens, there was not the expectation that the pumping would lead to arsenic mobilisation and widespread poisoning.

In classical hydrology, feedbacks across space and time scales are very important (Blöschl, 2001; Merz and Blöschl, 2008; Montanari *et al*., 2010), but due to non-linear feedbacks with human activities, the socio-hydrologic system has the tendency to lead to surprises (Gordon *et al*., 2008), otherwise known as Black Swan events (Taleb, 2007), which therefore make predictions a real challenge. A better understanding of the resilience thresholds and the likelihood for surprises may assist in management decision making by accounting for wider process dynamics (Kumar, 2011). As socio-hydrology is concerned with longer term dynamics, predicting possible trajectories of the system dynamics are of most interest to governments who are faced with making strategic, long term-decisions.

DRIVERS OF SOCIO-HYDROLOGIC PROCESSES

An important part of understanding socio-hydrologic processes is to understand which way the water is flowing and why this is so. In subsurface hydrology, the main driver of flow and transport is a potential gradient. Streams flow in response to topographic gradients, and evaporation occurs due to humidity gradients. In socio-hydrology there is a wider range of controls related to the interplay of socio-economic and hydrologic processes at a range of scales. For example, water flows downhill except in the case of diversions when it can be pumped uphill. The pumping is the social component and demonstrates that social factors can be a powerful force. An example of flows that socio-hydrology might address is the so-called 'virtual water trade'. Figure 3 illustrates the fluxes of virtual water along shipping lanes in relation to wheat. Virtual water refers to the amount of water needed to produce food (or other commodities), which is then transported to the place of consumption (Chapagain *et al*., 2006; Mekonnen and Hoekstra, 2010; Koutsoyiannis, 2011). The gradients that drive the flow of virtual water tend to be differences in policies, subsidies, economic incentives, technologies, fuel costs and historical factors. Trade barriers also play a role. In principle, one could argue that the flows should be from regions that are water abundant and produce more efficiently in respect of water use to those that have less access to fresh water and produce less efficiently with respect to water use. Increasingly, however, policies and markets tend to be the main drivers. For example, the world food market is increasingly controlled by multinationals, retailers, supermarkets and powerful countries. The interplay of these global interests with the temporal and spatial variations of the water resources at the local level, which are often the determining factors for water scarcity, leads to complex systems dynamics (Savenije, 2000).

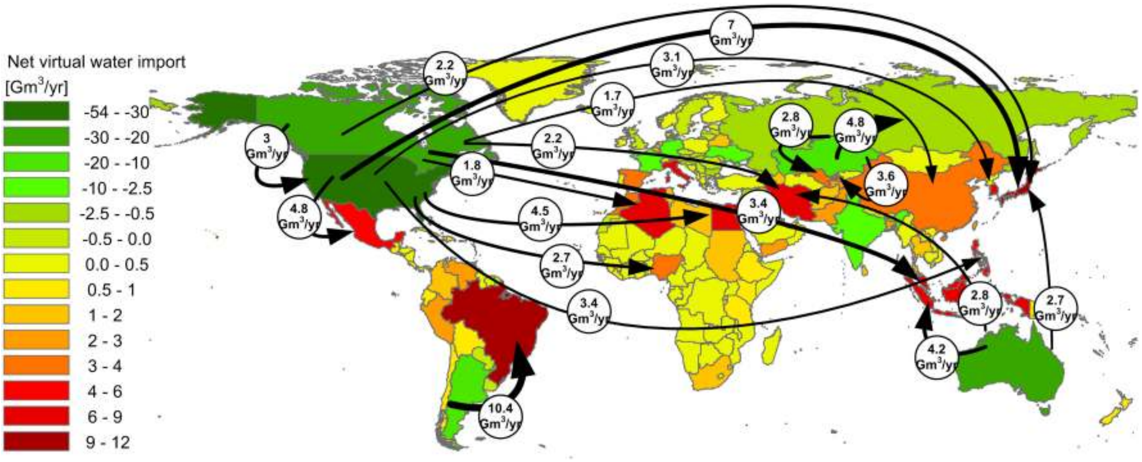

Figure 3. National virtual water balances and net virtual water flows related to trade in wheat products in the period 1996–2005. Only the largest net flows ($>2Gm^3$/year) are shown (taken from Mekonnen and Hoekstra, 2010).

Socio-hydrology is therefore concerned with analysing the following why questions: What drives this system (for example, as a part of the international trade of food)? What are the fluxes, what are the gradients and can they be related? But quantity of water is not the only factor; water quality may be equally or even more important, in particular in water-rich countries. The European Water Framework Directive and the Clean Water Act in the US have both led to a major wave of human actions. Non-consumptive water transfers (such as water use in industry and households) often change the quality or reduce the opportunity for beneficial use both in terms of location and quality. In particular, this reduces the opportunities for other functional uses, or ecosystem services. For example, the food industry in Holland uses imported food from Brazil (soybean, tapioca) for pork production. This is tantamount to the import of nutrients from Brazil (which itself is nutrient poor) and its transport to the Netherlands (which has a nutrient rich environment). The resulting financial profit is not in balance with the environmental harm that such imports cause. Furthermore, there is a perverse incentive introduced by the fact that the environmental costs are not charged to the consumer. An interesting socio-hydrologic challenge will be how virtual water flows will change and co-evolve if taxes were placed on the virtual water trade.

SOCIO-HYDROLOGY: THE WAY FORWARD

We argue in this paper for a new science of socio-hydrology that treats people as an endogenous part of the water cycle, interacting with the system in multiple ways, including through water consumption for food, energy and drinking water supply, through pollution of freshwater resources, and through policies, markets, and technology. What sets socio-hydrology apart from IWRM is that socio-hydrology explicitly studies the co-evolution of humans and water. It explores the way the coupled human-water system evolves and possible trajectories of its co-evolution, including the possibility of generating emergent, even unexpected, behaviours. Socio-hydrology is aimed as a discovery-based fundamental science, whose practice is informed through observing, understanding and predicting socio-hydrologic phenomena in real places in the landscape where real people live. Socio-hydrology will also have to accommodate the time arrow by focusing on longer time scales including on dynamics we never had to deal with. We insist, however, that socio-hydrology must strive to be a quantitative science. While broad narratives may be important for context, quantitative descriptions are needed for testing hypotheses, for modelling the system and for predicting possible future trajectories of system states.

What is the way forward in socio-hydrology? We believe there are at least three avenues through which socio-hydrology can advance:

1. Historical socio-hydrology: First and foremost, we can learn from reconstructing and studying the past, both in the immediate past, and in the distant past. Indeed, water has played a key role in the growth, evolution and eventual collapse of numerous ancient (and not so ancient) civilisations. The collapse of the Sumerian civilisation has been attributed to rising water tables and salinisation as a result of extensive irrigation (Ponting, 1991). Apart from collapse of civilisations, interesting patterns of water governance and technologies have evolved throughout history. For example, Iran saw the development and evolution of 'Qanats', sloping tunnels that tap into the groundwater without the need for pumping, which have survived the test of time over millennia.
2. Comparative socio-hydrology: Sivapalan (2009, p.1395) has suggested that '. . . instead of attempting to reproduce the response of individual catchments,

research should advance comparative hydrology, aiming to characterize and learn from the similarities and differences between catchments in different places, and interpret these in terms of underlying climate-landscape-human controls.' In the context of socio-hydrology, this implies a comparative analysis of human-water interactions across socio-economic gradients, as well as climatic and other gradients, to map any spatial or regional differences back to processes and their temporal dynamics (Blöschl *et al.*, 2007; Wagener *et al.*, 2010; Peel and Blöschl, 2011).

3. Process socio-hydrology: To complement the temporal and spatial analyses, it would be of interest to study a small number of human-water systems in more detail, including routine monitoring, to gain more detailed insights into causal relationships. This may involve detailed data collection of the hydrological and sociological processes involved, including real-time learning, to understand human-water system functions in the present to be able to predict possible trajectories in the future. To make headway in the new science, we need new scientific laws at the scales of interest, but particularly dealing with human-nature interactions. Examples of such laws are flux-gradient relationships, which have served classical hydrology well in many ways. Since socio-hydrology is about co-evolution and feedbacks operating at multiple scales, the notions of optimality and goal functions are likely to be important and useful, just as they have been in eco-hydrology (Schymanski *et al.*, 2009; Schaefli *et al.*, 2011).

The important feature in all three areas of enquiry, to reiterate, is the focus on co-evolution and emergent patterns, including the unexpected, which are the main points of departure from the recourse to scenario analyses that is common in IWRM. With the advent of socio-hydrology, the way we will do our science, as well as the way we teach, will be different as humans begin to play a much bigger role in water cycle dynamics. Just as in the case of eco-hydrology, there will be a need for new partnerships that go beyond our usual networks. As socio-hydrology embraces processes beyond purely physical (or biological) relationships, Sivapalan's (2005) call for a paradigm shift towards more holistic descriptions and process interactions may become critically important. All of these point to both challenging and exciting times for the future of hydrologic science.

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