



Evolving water science in the Anthropocene

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Abstract. This paper reviews the changing relation between human beings and water since the Industrial Revolution, a period that has been called the Anthropocene because of the unprecedented scale at which humans have altered the planet during this time. We show how the rapidly changing world urges us to continuously improve our understanding of the complex interactions between humans and the water system. The paper starts by demonstrating that hydrology and the science of managing water resources have played key roles in human and economic development throughout history; yet these roles have often been marginalised or obscured. Knowledge of hydrology and water resources engineering and management helped to transform the landscape, and thus also the very hydrology within catchments itself. It is only fairly recent that water experts have become conscious of such mechanisms, exemplified by several concepts that try to incorporate them - integrated water resources management, eco-hydrology, socio-hydrology. We have reached a stage at which a more systemic understanding of scale interdependencies can inform the sustainable governance of water systems, using new concepts like precipitation sheds, virtual water transfers, water footprints, and water value flow.

in order to emphasise the central role of mankind in geology and ecology. Humans form a significant geophysical force (Steffen et al., 2007). They have significantly altered several biogeochemical or element (such as carbon, nitrogen, phosphorus and sulphur) cycles that are fundamental to life on Earth. In addition, our species is strongly modifying the terrestrial water cycle by intercepting river flow from uplands to the sea and, through land-cover change, by altering the water-vapour flow from the land to the atmosphere. Finally, humans are likely driving the sixth major extinction event in Earth history (Steffen et al., 2011a). During the Holocene, complex human societies could develop due to a relatively stable, accommodating environment. The emerging Anthropocene world is warmer, with a diminished ice cover, a rising sea level, changing precipitation patterns, a strongly modified and impoverished biosphere, and human-dominated landscapes. According to Steffen et al. (2011b), the need to achieve effective planetary stewardship is urgent in order to regain a stable relation between humans and environment.

As shown by L'vovich and White (1990), in the years since the beginning of the Industrial Revolution, which may be seen as the start of the Anthropocene, the distribution of fresh water on the face of the earth has changed as a result of direct human efforts to manage water and also as a consequence of alterations in urban and rural land use that influenced the flow and storage of water. Humans have changed the hydrological response of many catchments of the world through one or more of the following means: (a) direct diversion of water flows, including inter-basin transfers for water supplies to cities, industries and agriculture, (b) transformation of the stream network, for example through the construction of dams and reservoirs or the canalisation of

1 Introduction

During the Holocene – the post-glacial geological epoch of the past ten to twelve thousand years – mankind's activities gradually grew into a significant geological, morphological force. Given the size of the impacts of human activities on the Earth and its atmosphere since around the latter part of the 18th century, Crutzen and Stoermer (2000) proposed using the term Anthropocene for the current geological epoch,

ivers, (c) changing drainage basin characteristics, for example through deforestation, urbanisation, drainage of wetlands and agricultural practices and (d) activities altering the regional or global climate, for instance by enhancing greenhouse gas emissions, land-cover changes, and consumptive water use. In addition, humans have strongly influenced the physical, chemical and biological quality of streams, lakes and groundwater bodies through various sorts of diffuse and point sources of pollution (Meybeck, 2003, 2004). As a consequence, freshwater availability and water quality currently influence and constrain the possibilities for human development, food production and economic growth. There is an increasing number of signals – from decreasing groundwater and lake levels to disappearing wetlands – that show that the current use of water systems is not sustainable (Molden, 2007; UN Water, 2012; Hoekstra, 2013).

The increased exploitation of freshwater and the related development of societies has been made possible by increasing knowledge of water engineering, large-scale water supply, flood mitigation and irrigation. Until the 1970s the field of water management was known by the term “water resources development”. In the 1980s it became more popular to refer to “water resources management” (WRM), and in the 1990s to “integrated water resources management” (IWRM). This change of names reflects the increasing recognition that water systems are not merely there to be exploited; rather, a balance should be sought between fulfilling human needs and sustaining ecosystems (Falkenmark and Rockström, 2004). In this paper we describe the changing relation between humans and water in the Anthropocene, whereby we acknowledge that we are living in an early stage of this new epoch. In Sect. 2 we look back and show how humanity started to dominate water systems and how, more recently, water has become a constraint for further development. Nature has started to “talk back”. In Sect. 3 we describe some of the early attempts to understand the feedbacks between humans and the water system. In Sect. 4 we look forward and consider emerging new concepts that can help humanity to shape the required transition to a more sustainable relation with freshwater systems. In the final section, we reflect on the need to rephrase our research questions, gather new types of data, facilitate the international exchange of data and knowledge, and reform our educational programmes.

2 Changing perceptions of water control over time

2.1 Holocene water systems

In most climate zones, freshwater availability fluctuates with the seasons and is scarce during some months each year. Given the vital nature of water for humans, all societies located in such climate zones developed ways to arrange and secure access to water for domestic and productive uses. Those societies that survived over time found ways to use

Table 1. Boran hydrogeology and water management (source: adopted from Dahl and Megerssa, 1990).

The Boran pastoralists of northern Kenya and Ethiopia have an understanding of groundwater flows in this semi-desert area and how these feed the wells on which they and their cattle rely.

Within a particular area a new well may only be dug when the owners of the existing wells agree that sufficient groundwater is available. Although each well is owned by one clan, other clans may use it but they all need to respect an agreed order of watering the cattle. Watering cattle is very labour-intensive if the well is deep and water levels low: men are positioned at different levels and efficiently pass water buckets made of giraffe skin. Through singing this process is synchronised, minimising the time each herd spends at the well (Dahl and Megerssa, 1990, p. 24).

Digging a new well normally takes a lot of labour, the workers being given ample meat as a way of compensation. This represents an important feedback mechanism: if there are too many animals, there is need to invest in new wells; digging new wells requires many cattle to be slaughtered, reducing stocking rates. One Boran elder formulated it thus (Dahl and Megerssa, 1990, p. 31):

“That’s why we say that the multiplying of cattle is not a serious problem. We can use the excess for the discovery of new sources of water and land. The number of cattle can never be greater than what the land can take.”

water in a sustainable manner, or at least allowed the water resource to regenerate itself and did not destroy the natural cycle. In some instances the institutional arrangements concerning water use are said to have been constitutive to those societies; this was the case, for example, in communities in Indonesia (Geertz, 1980), Sri Lanka (Leach, 1961), Tanzania (Gray, 1963), Spain (Glick, 1970), the Netherlands (Schama, 1987; van de Ven, 1993) and the Andes (Zimmerer, 1995). Some other societies that were unable to use the water in a sustainable manner collapsed (e.g. Mesopotamian civilisation, Adams, 1966). The more successful societies apparently manipulated their environment within the bounds of sustainability, possibly because those societies’ ability to control and exploit the environment remained limited, forcing them to respect biophysical and hydro-climatic constraints. Some water institutions had in-built mechanisms that set limits to overexploitation. The system developed by the Boran pastoralists in northern Kenya and southern Ethiopia is of interest in this context (Table 1).

Successful societies tend to have growing populations and rapidly growing cities. Cities need to be supplied with sufficient water of adequate quality and with sufficient food. Satisfying the demands for both drinking water and food requires substantial organisation, physical planning, and water resources development. This could only be accomplished by developing new knowledge and new technologies.

Interactions between humans and the natural system have always been part of human history, probably starting at relatively small scales, but gradually increasing in scale as the range and command of the technology became greater. Early civilisations, such as the Sumerian empire (3rd–2nd millennium BC), built their wealth on irrigation. Urbanisation was only possible if there was a reliable supply of food from specialised farmers; this need led to large-scale agricultural development, specialisation, and division of labour, followed by the need for administration and the development of written language. More importantly, it triggered technological development in the field of geodesy, mathematics, hydraulics and engineering. Yet, apparently it was hard to make such interventions sustainable. The Sumerian empire is known to have collapsed due to the ecological impacts of salinization for which the Sumerians did not yet have the technology (Ponting, 1991). The need to administer water in a water-dependent society led to the establishment of a gauging network, of which the Nilometer (~1500 BC–1000 AD) is the most well-known example. The Nile was equipped with several gauging stations where water levels were measured. This information was used in Egypt to plan the start of the irrigation season and to tax irrigators, but more generally, to gain control over the complex interactions between humans and society. Another example of a complex system that was developed to provide a reliable water supply in a semi-arid environment is the qanat system, which taps groundwater resources. This technology was invented during the Persian empire (about 600 BC) and proved successful not in the least because of the well-anchored and robust institutional arrangements among users. This technology spread throughout the Middle East, where qanats are still in use (see www.waterhistory.org/histories/qanats). Similar to surface water irrigation in the more water-rich regions of the world, the development of qanats for groundwater exploration required specialisation, the development of mathematical and technological skills, institutional development, and cooperation among stakeholders.

2.2 The hydraulic mission

In modern times, the invention of the steam engine and reinforced concrete, together with advances in scientific knowledge on water flows and hydrology opened up possibilities that hitherto had been unthinkable. Science and technology to control the aquatic environment developed rapidly starting in the late 18th century. Examples are the Chezy (1718–1798) formula for water flow, the Darcy (1803–1858) equation for groundwater flow and Darcy's rational method of calculating storm discharge from a drainage area, the Manning (1816–1897) formula for canal flow, the pioneering work of Horton (1875–1945) regarding the calculation of runoff (Biswas, 1970), and the method of designing polders developed by Hooghoudt in 1940 (De Vries, 1982). These innovations influenced the way people viewed nature. Equipped

with new technological powers, a new generation of engineers emerged that had a new hydraulic mission: that of “taming” nature and making it orderly (Worster, 1985; Reiser, 1986; Swyngedouw, 1999; Allan, 2003). During the last decades of the 19th century and the first decades of the 20th century, the water landscape was transformed in various places, including but not limited to India, Sudan, Mali, Egypt, the USA, Brazil, Spain and the Netherlands. These developments, associated with large and powerful water bureaucracies (Molle et al., 2009), allowed for unprecedented growth in the production of agricultural commodities and energy and confirmed the belief that man could fully control water and be the master of nature.

2.3 Nature talks back

The great benefits created by the hydraulic mission, however, have been accompanied by unprecedented ecological impacts, with associated costs to the livelihoods of people who rely on aquatic ecosystems goods and services (Postel, 2000). These impacts have been widely described and include the heavily modified flow regimes of rivers due to upstream damming and water withdrawals, overexploited groundwater bodies with continuously declining water levels, polluted rivers and aquifers and eutrophied lakes, and disappearing natural lakes in closing basins (Vörösmarty et al., 1997; De Villiers, 2000; Pearce, 2006; Brichieri-Colombi, 2009; Molle et al., 2010). These impacts are unmistakable manifestations that the Anthropocene is a fact, and that nature talks back when people cross certain boundaries. But there is an additional, and very important, dimension: these water systems in crisis invariably trigger reflection and responses - by local communities, academics, civil society, governments and regional and international organisations (Cosgrove and Rijsberman, 2000; UN Water, 2012). They *have* to trigger such responses given water's vital nature. We witness a process of co-evolution between the natural system and society, whereby the limits of the environmental support system force societies to take actions, whether they are defensive, evasive, offensive, remedial or accommodative. In our time, debates about the likely causes and remedial action take place, new hypotheses about the relationship between water and society are formulated, new measures are implemented (“building with nature”, “room for the river”), system responses are monitored, and new understandings are created. Society is gradually becoming aware of the risk of collapse well in advance of such disasters happening. This does not mean that adequate actions are indeed always taken, but, together, the awareness and the technological capacity of society to curb undesirable developments have mobilised the global society to pursue “sustainable development” (WCED, 1987).

However, the challenges faced by humanity are enormous. The situation in which we find ourselves is one of unprecedented growth. Until now, we have been able to avoid the Malthusian precipice by using our capacity to push back the

limits of growth, but avoiding the impact of an eventual crash is now the greatest challenge that humanity has faced since it started to manipulate its environment.

3 First attempts to understand the evolving relation between man and water

The last decade of the 20th century saw the beginning of a new way of understanding water and its role in society. This section describes five important aspects.

3.1 The IWRM concept

The IWRM concept originated from the recognition that the water resources system, representing the interaction between the hydrological system and society, was complex. The hydrological system typically acts at different temporal scales and consists of a variety of subcompartments, with different societal relevance and behaviour, interacting with other components in the system. For instance, the groundwater subsystem has a much slower dynamic than the surface water subsystem. This makes the former a more reliable resource in terms of timing, but at the same time causes it to be more vulnerable to overexploitation and pollution, as its use may lead to land subsidence or impacts on the surface water system by reduced seepage to wetlands and streams. IWRM recognises that groundwater is part and parcel of the water resources system and that, by considering groundwater in isolation, serious misallocations can be made. Groundwater has many characteristics of a common pool resource where the sustainable management depends on a thorough understanding of the connections with other components of the water resources system, as well as an adequate regulatory framework that prevents free riding. Groundwater withdrawal from (naturally recharged) aquifers eventually leads to reduction of stream flow downstream, even though this is not always obvious to the water users. More directly visible is the impact that upstream users have on downstream water availability in an open water system, both in terms of quantity and quality. As a result, the solution to a problem in one part of a water system frequently leads to the emergence of another problem somewhere else in the system, which in turn impacts other stakeholders or users.

This insight led to the idea that the water resources system and its variety of users should be studied in an integrated manner, whereby all the costs and benefits of an intervention are assessed and weighed, so as to come to balanced, well-thought-out and equitable solutions. This idea was termed integrated water resources management (IWRM), and the concept was officially adopted during the International Conference on Water and the Environment (ICWE) held in Dublin in 1992 (1992; Koudstaal et al., 1992).

An early criticism of IWRM was that it was too impact-orientated and that there was not enough focus on adaptation,

or learning by doing. The concept of adaptive water management (AWM) was proposed to incorporate social learning in a more systematic manner, recognising uncertainty as a key feature in water management (e.g. Pahl-Wostl et al., 2007).

Originally the focus of IWRM was on understanding the physical interactions in the system in quantitative (and qualitative) terms, and quantifying the benefits and costs of alternative interventions; this would enable a trade-off to be made between all the costs and benefits that society and water users would experience as a result of these interventions. This would allow decisions to be taken on the basis of an objective weighing of all societal and private interests. At least that was the theory.

3.2 Water as an economic good

A key question was how to weigh alternatives in a broad societal context. One way of weighing alternatives was by considering the economic value of the interventions within the context of the national objectives and constraints, whereby all societal costs and benefits were to be taken into account. This would include environmental, cultural and other non-tangible costs and benefits.

During the Dublin conference, the concept of considering “water as an economic good” was launched as a management principle with exactly this objective in mind: assisting the trade-off of all societal costs and benefits. But during the Dublin conference, economic valuation was already confused with economic (or financial) pricing. Making decisions on interventions on the basis of economic analysis is not the same as pricing water at its economic value, but this latter meaning was unfortunately how many parties interpreted this Dublin principle. To prevent confusion, a disclaimer was added stating that “it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price”. But this addition only led to more confusion, because by adding this sentence it was inferred that the concept indeed was about pricing and not about economic trade-off analysis (Savenije and Van der Zaag, 2002; Savenije, 2002).

3.3 IWRM as a process

Another Dublin principle was that “water resources management should be based on a participatory approach, involving users, planners and policy makers at all levels”. Since this was an obvious element that had been lacking in many anecdotal examples of unsuccessful projects, in which planners had disregarded or overlooked the negative impacts of their interventions, this principle became more and more prominent in the further development of the concept of IWRM. It was the Global Water Partnership that defined IWRM as “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in

an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2000). This definition equates IWRM with a process for coordinated action, which differs from the original idea of considering all interdependencies of the system and providing insight into the implications, costs and benefits of interventions. As a result, managers skilled in negotiating with stakeholders, but often lacking knowledge about the physical interactions and feedbacks in the water resources system, embraced this new interpretation of IWRM and came to see themselves as the “new” water resources managers, sometimes marginalising more analytically oriented experts who focused instead on understanding and quantifying the dynamics of the system in terms of their complex interactions with societal demands.

3.4 Green and blue water

Scientists continued to be fascinated by the complexity of the water resources system. The emphasis of IWRM originally was to try to integrate surface water, groundwater and water quality with the different uses of the system, but thanks to the relentless efforts of Malin Falkenmark, the “green water resources” were put on the research agenda as well (Falkenmark, 1997). Green water was understood to be the part of the precipitation that ends up in the soil and is used by plants to produce biomass. Green water is a very large resource on which the bulk of global food production and ecosystems services depend. Global estimates are that 80 % of global food production relies on rain-fed agriculture (green water), and in sub-Saharan Africa, even 90 % (Rockström et al., 2009a). Yet in most analyses of global water scarcity, the availability and use of green water is largely neglected, leading to deceptive and pessimistic estimates of global water scarcity (Savenije, 1998, 2000). We have slowly begun to realise that improving the efficiency and productivity of rain-fed agriculture (e.g. by soil and water conservation, rainwater harvesting, improved farming practices and supplementary irrigation) would make a substantial contribution to global food production, poverty alleviation and soil conservation at the same time.

3.5 From hydrology to eco-hydrology and socio-hydrology

Over the course of the 1990s it was increasingly recognised that the water system is part and parcel of the ecosystem. This led to eco-hydrology as a new field of science and to the understanding that the water resources system is the result of co-evolution of the landscape, the hydrology, the ecology and society. We have thus seen an evolution from hydrology to eco-hydrology and subsequently to socio-hydrology (Sivapalan et al., 2012).

A puzzle that researchers of water resources management found hard to solve is how to deal with the environmental interests in a water resources system, and how to value the environment or ecosystems. In the classical definition of IWRM

(Koudstaal et al., 1992) this is not a problem, because giving importance to the environment does not require the valuation in monetary terms; it is sufficient to give an adequate weight to environmental criteria. In the monetary interpretation of “water as an economic good”, however, the valuation of ecosystem services in monetary terms became imperative (Rogers et al., 1998, 2002; Rogers and Leal, 2010). This is not a simple exercise. Can, for example, the function of aquatic ecosystems as safety net for rural livelihoods be adequately captured in a monetised metric? On top of that, environmental needs were often translated into simplified concepts such as environmental flows: a minimum amount of water that should be left untouched so as to allow the survival of aquatic life. Ironically, these environmental flows were sometimes proposed in areas where streams have the natural habit of falling dry. By contrast, new insights focus on maintaining the essential dynamics of an aquatic system, rather than maintaining minimum flows (King and Brown, 2010; Poff et al., 2010).

In summary, the concept of IWRM has evolved since 1992. In the water management practice the emphasis was increasingly put on the interactions between planners, decision makers and stakeholders, in line with the perception of IWRM as a process (GWP, 2000). As a result, communicating about water became more important than understanding how the system works. In the scientific community, on the other hand, researchers gradually enhanced the scope of their analysis from hydrology to eco-hydrology and to socio-hydrology, in an effort to better understand the metabolism of the complex system and the dynamics of co-evolution and development. A similar trend can be discerned in the social sciences, where some scholars have been analysing “hydro-social” dynamics (e.g. Swyngedouw, 2009; Norgaard et al., 2009; Linton, 2008).

Compared to eco-hydrology, socio-hydrology has far more complex feedback mechanisms, largely due to the capacity of humans to adjust the environment to their wishes. Humans, in comparison to ecosystems, are more mobile and have the capacity to change their environment by using rapid communication, setting up of institutions, developing technology, implementing engineering interventions, and establishing economic incentives. In short, humans can learn, which leads to the phenomenon of double hermeneutics, whereby “the ‘findings’ of the... sciences (may)... enter constitutively into the world they describe” (Giddens, 1987, p. 20). This makes prediction within the complex human–water system far less certain than within the ecosystem–water system interaction, although the latter can also experience unpredictable system shifts (e.g. Scheffer et al., 2001).

4 The quest for sustainable systems through systemic understanding and acknowledging interdependencies

The water resources system is highly complex. It has multiple scales and multiple feedbacks with a variety of physical, biological and societal processes. The landscape is multi-sectoral, multi-actor and interdisciplinary. The quest for managing this system in a sustainable fashion requires systematic understanding of the system processes, acknowledgement of the interdependencies and new approaches to deal with this complexity at global and local scales. Moreover, it requires governance systems appropriate to manage this complex system. In this section we highlight new concepts and governance mechanisms that have recently come to the fore.

4.1 Emerging new concepts

In an effort to make societal and system interdependencies in IWRM tangible and explicit, a number of new approaches have emerged since the beginning of this millennium that allow for the quantification of the temporal and spatial balances between water demand and water resources availability. In classical water scarcity analysis there was a focus on blue water resources, with limited account for spatial and temporal variability and no account for green water, reuse, international distribution of resources and trade in water dependent products, the different types of water needs (drinking water, agricultural, industrial, environmental, etc.) and the impacts of population growth, land use changes, climate change and changing lifestyles (Savenije, 1998, 2000; Liu and Savenije, 2008).

A number of important innovations emerged relatively recently. After the coining of the green water concept discussed above (Falkenmark, 1997, 2003), it was recognised that huge amounts of water are traded across the world in a virtual form (Allan, 1996, 2001; Hoekstra and Hung, 2005) and that those virtual water flows can result in substantial national water savings (Oki and Kanae, 2004; Chapagain et al., 2006; Yang et al., 2006). In addition, it was recognised that virtual water trade does not only result in national water savings for the importing countries, but also that it can result in a global water saving as well, namely when the trade occurs from a region with high water productivity to a region with low water productivity (Hoekstra and Chapagain, 2008).

Another new idea was that one may account for the value of water resources within river basins by tracking water value flows (Hoekstra et al., 2001; Seyam et al., 2002, 2003). The hypothesis is that the full value of a water particle depends on the path it follows within the hydrological cycle and the values generated along this path. The full value of a water particle in a certain spot at a certain point in time is supposed to be the sum of its in situ value and all values that will be generated along its path later (Seyam et al., 2003). It follows that all values generated by water can ultimately be

attributed to precipitation. This concept implies that there is a direct analogy between the flow of water and the flow of values, with one crucial difference: water values flow backward in time and in a direction opposite to that of the water. In other words, the value-flow attributes local water values to the upstream water flows within the natural system. Allocation of water at a certain place should take into account not only the alternative uses and associated values at that location, but also the possible downstream values. Seyam et al. (2000) and Van der Zaag et al. (2002) showed how such allocations can be made transparent and accountable by allocation algorithms.

Building on the concept of virtual water trade and recognising that freshwater is a global resource and that all water consumption and pollution ultimately link to consumer goods, Hoekstra (2003) introduced the water footprint concept. The water footprint is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer (Hoekstra and Chapagain, 2008). The water footprint of an individual, community or business is defined as the total volume of freshwater used to produce the goods and services consumed by the individual or community or produced by the business. Water use is measured in terms of water volumes consumed (evaporated or incorporated into a product) and/or polluted per unit of time. A water footprint can be calculated for a particular product, for any well-defined group of consumers (for example, an individual, family, village, city, province, state or nation) or producers (for example, a public organisation, private enterprise or economic sector). The water footprint is a geographically explicit indicator, showing not only volumes of water use and pollution, but also the locations. The further development of water footprint assessment as a research field (Hoekstra et al., 2011) went hand in hand with an uptake of the method by companies and governments.

Another recent insight is that water resources are part of the global hydrological cycle, whereby terrestrial resources are connected through atmospheric teleconnections that transcend river basins. Until recently, there was a complete disregard for water resource linkages through the atmosphere, and the fact that that land use in one part of the world impacts (positively or negatively) precipitation downwind (Savenije, 1995). The existence of local moisture recycling was recognised, but the larger-scale linkages were not considered to be of relevance. Recent work in this field has led to global moisture recycling maps (Van der Ent et al., 2010) and the definition of precipitation sheds (Keys et al., 2012), which provide direct insight into the effect of land use change or increased water consumption in one region on precipitation downwind.

Finally, developments in river basin modelling, in information and communication technology, and in the field of remote sensing open up new possibilities of yielding, processing, and sharing data on water resources availability and use at a high spatial and temporal resolution. In the past, water

resources management was mostly based on (often poor) statistics composed of point measurements of precipitation, river runoff and water withdrawals. Data and modelling platforms nowadays allow for integrating different data sources and integrated analysis. Remote sensing is increasingly used to feed our knowledge base, for example by providing detailed information on where, when and how much irrigation is needed for optimal crop growth, and on the irrigation volumes actually applied and consumed (Bastiaanssen et al., 2000; Su, 2002; Zwart et al., 2010; Romaguera et al., 2010, 2012). Developments in communication technology open up new possibilities for data management for IWRM, including the ground-truthing of remotely sensed data by individuals, the reporting of water pollution instances by the public, and real-time support to farmers or water managers.

4.2 Implications for water governance

The challenge of sustainable development calls for different institutional arrangements for water planning and management at the local level (e.g. an irrigation scheme) and the watershed or river basin level. In addition, it becomes increasingly clear that wise water governance includes a proper reflection of water concerns and constraints in other policy domains, such as in agricultural, energy and trade policies. A specific concern is also that water quality management should be seen in a much broader context, namely the recycling and reuse of minerals. The global character of the hydrological cycle and the economics of water urge for institutional arrangements at the global level as well, in addition to arrangements at local, national and river basin level. Finally, good water governance is not only the responsibility of the public sector – the private sector can and should play a significant role as well.

4.2.1 Water governance at the local, watershed and river basin level

The new, emerging concepts as discussed in the previous section help us to appreciate and better understand the geographical interconnections through water that exist between and among water users, communities, countries and regions. In fact, water weaves webs of dependencies between these social entities that pose institutional challenges. This is most clearly demonstrated by the upstream–downstream dynamics of many water systems. At the scale of an irrigation scheme, the challenge is to create institutional arrangements that help to overcome head- and tail-end problems; at the scale of a watershed or river basin management, the challenge is to prevent or compensate for the impact of negative externalities from upstream actors on downstream actors. Social actors located within a shared water system are not simply condemned to deal with each other while fighting for their own interests; often they can also identify comparative advantages relative to social actors in other water systems because of

differences in geographical, climatologic, biogeochemical, technological, cultural, social and economic endowments. This implies that the exchange of goods and services between actors and social entities that are fundamentally different has the potential of leaving many (if not all) better off (Komakech et al., 2012). This forms the basis of benefit-sharing, a concept proposed by Sadoff and Grey (2002, 2005), and which should be used with care (Van der Zaag, 2007).

The challenge is how to give institutional form to the interdependencies between social entities. Different factors contribute to make this complex, including (a) the asymmetry problem caused by the water flow itself (upstream actors can easily harm downstream actors, but the reverse is less obvious in most situations), (b) the differences and heterogeneities between the social actors involved, and (c) the need to consider all costs and benefits from the perspective of fairness. There are numerous historical examples of how these interdependencies have been institutionalised. One example is from Ethiopia and described in the Fetha Negast (“Justice of the Kings”) and dates back to the 15th century (as cited in Arsano, 2007, p. 110): “With regard to the flow of water: The downstream inhabitants have the right to receive the flow of water that comes down from the source in the upstream region. The upstream inhabitants have the right of compensation for the increased fertility of the soils received by the downstream inhabitants due to the flow of the water. The compensation may be in kind, for instance, in the form of cereals.”

In modern times, two typical arrangements have been proposed. The first is joint infrastructure development in a trans-boundary context and represents a progressive form of water cooperation. By ignoring national boundaries, the optimal location of, e.g. reservoirs can be chosen that will maximise net benefits and strengthen the riparian relationships through deepening the mutual dependencies. Typical examples are Kariba (Zambia/Zimbabwe, 1959), Itaipú (Brazil/Paraguay, 1982), Manantali (Mali/Senegal/Mauretania, 1988/2001), Khatse (Lesotho/South Africa, 1997), and the Maguga dams (Swaziland/South Africa, 2001). In all these cases, the ownership and governance structures are explicitly and clearly defined and based on bilateral or multilateral treaties. In the same spirit, Goor et al. (2010) proposed a solution for the Blue Nile.

The second typical arrangement in modern times focuses on land use, whereby upstream land users are encouraged by downstream counterparts to invest in soil and water conservation practices through systems that are known as payment for environmental (or ecosystem) services, abbreviated as PES (e.g. Daily et al., 2009; De Groot et al., 2010), alternatively named compensation and rewards for environmental services (Swallow et al., 2009). ISRIC (the International Soil Reference and Information Centre) has pioneered the green credits programme (Hunink et al., 2012), emphasising the relevance of green water use in upper catchments for downstream blue water users. There are several challenges related to PES-type

of institutional arrangements. One is concerned with the role of governments in taking responsibility for public goods such as ecological integrity, which may be undermined by monetising, and thereby, in a way, privatising, environmental services. Another is that introducing monetary compensation mechanisms implies that precise “dose–response” relationships are known – e.g. a certain type of intervention on a given surface area will reduce erosion and silt loads in downstream rivers by a given amount. Such relationships are, however, often not known, which raises the question of what one is paying for.

A promising technology introduced in Tanzania (Makurira et al., 2009, 2010) is that of the Fanya Juu: a way to divert surface runoff into infiltration furrows and onto terraces, whereby not only is the soil moisture storage increased, but also the groundwater is recharged with water which would otherwise run off superficially. In this way land and water are conserved, farmers have more water available on their plots and, at the same time, groundwater is recharged for use further downstream. When implemented on a large scale, these small-scale technologies could curb processes of land degradation and at the same time enhance the productivity of the system as a whole.

Recent developments in earth observation offer, for the first time, the possibility of estimating actual evaporation and biomass production in a spatially explicit manner, and from these derive water productivity estimates (e.g. Zwart et al., 2010). Moreover, measured actual evaporation can be used to constrain hydrological models, using evaporation as an input rather than an output (Winsemius et al., 2008), and thereby inferring which land use types use blue water (Romaguera et al., 2012). With these developments, water managers can have access to independent sources of information with which they can monitor land and water use, and enforce regulations and permits. These tools could also help to monitor the state of ecosystems and quantify the increase or loss of biomass, and assign values to the various land uses. These tools can become indispensable not only for establishing and monitoring PES-like arrangements but also for land use planning. As such they allow for more transparent and inclusive water governance.

Similarly, earth observation can also be used in trans-boundary contexts, for example for monitoring water levels of reservoirs by laser altimetry (e.g., Munyaneza et al., 2009; Duan and Bastiaanssen, 2013), or the storage variation in groundwater bodies by using gravity observations from space (Wahr et al., 2009).

4.2.2 Water governance: from internal to external integration

The increasing recognition that water does not only play a key role in terms of serving societies and economies, but also in terms of constraining development, has important implications on what actually is good water governance. Good water

governance does not simply mean “securing water supply” when needed. It also means “managing water demand”, in such a way that demands do not exceed supply (Koudstaal et al., 1992). However, a shift from supply management to a more balanced combination of supply and demand management is not sufficient either. Water demand management focuses on using water more efficiently but does not address processes that lie at the root of many of the problems of water overexploitation and pollution. Many megacities are located in places where water shortages put severe limitations to further growth (Varis et al., 2006); the real solution here is to integrate water concerns in spatial planning. Similarly, many breadbaskets in the world are situated in regions where water scarcity threatens sustainable production (Ma et al., 2006). The solution to these challenges requires measures that go beyond improving water supply and reducing demand by increasing efficiency. Water concerns and constraints need to play a role in agriculture and other policies (Hoekstra, 2013).

We thus need to move from “internal integration” in water resources planning and management towards “external integration”. Internal integration aims for coherence between different water policies, for instance between water supply and water demand policies, between policies regarding the management of groundwater and policies regarding the management of surface water, and between policies aimed at water flow regulation and policies aimed at water quality management. External integration refers to integrating water challenges into other policy domains. With good spatial planning and agricultural policies that internalise the challenge of wise water governance, probably half of the water problems could be solved already. But getting the factor water reflected in other policy domains will be important as well, for instance in the energy sector. There is a strong water–energy nexus and we have to realise that it is agricultural and energy development rather than production that has transformed the Earth system, the landscape and water management (e.g. Scott et al., 2011). Current policies that stimulate the production of biofuels aggravate many of the existing water problems in the world, simply because growing crops for bioenergy requires a lot of water (De Fraiture et al., 2008; Gerbens-Leenes et al., 2009). Integrating water concerns into energy policies would lead to a wiser choice regarding the future’s best energy mix (e.g. using sugar beet rather than rapeseed for producing biofuel, reducing the water demand per unit of energy produced, investing in electrical or hydrogen-based transport modes). Also trade policies could benefit if informed by information on the relation between trade and water scarcity (Allan, 2001; Hoekstra and Chapagain, 2008). Furthermore, given the fact that about 30 per cent of the water footprint of humanity relates to consumption of animal products (Mekonnen and Hoekstra, 2012), there is a huge potential for water saving through addressing diets (Vanham et al., 2013).

4.2.3 Managing water in connection to its mineral content

The link between water quantity and quality underlies the IWRM concept. However, the minerals contained in water are generally seen as pollution and rarely as an essential resource to be recycled or reused. A case in point, touching on the fundamentals of our global society, is the pollution by and the demand for phosphate. Phosphate is a finite nutrient on which global food security depends, but nevertheless, it causes massive pollution and eutrophication (Neset and Cordell, 2012; Liu et al. 2012). In the past the disposal of nutrients into the environment was merely seen as a water quality issue. At some point in the Anthropocene, a strategy for recycling and reusing nutrients will become essential. There is an inevitable need to recycle phosphate, since the resource is a mined resource of limited extent and our sheer survival depends on it (Edixhoven et al., 2013), but similar considerations apply to all scarce minerals, complex organic substances, medicines and the like. A sustainable society in the Anthropocene is only possible if minerals are fully recycled.

4.2.4 Water governance: instruments at the global scale

When water problems extend beyond the borders of local communities, the river basin is generally seen as the most appropriate unit for analysis, planning, and institutional arrangements. It has been argued that addressing water problems at the river-basin level is not always sufficient (Hoekstra and Chapagain, 2008). Many of today's seemingly local water issues carry a (sub)continental or even global dimension, which urges for a governance approach that comprises institutional arrangements at a level beyond that of the river basin (Hoekstra, 2011). Different directions have been suggested and explored, ranging from an international protocol on full-cost water pricing, to water footprint caps for river basins, to water footprint benchmarks for products, to a water label for water-intensive products to international water footprint reduction targets (Hoekstra, 2013).

It has also been proposed to channel funds for carbon footprint reduction to sustainable land and water use in poor regions of the world. The large majority of farmers in Africa are dependent on rainfall (Rockström, 2003). Large-scale irrigation is hardly feasible for a wide range of reasons (Van der Zaag, 2010). The introduction of smallholder system innovations, such as rainwater harvesting, supplementary irrigation from shallow groundwater, small-scale water diversions and crop diversification (Bossio et al., 2011; Mul et al., 2011; Ngigi et al., 2005, 2006, 2007; Makurira et al., 2007, 2009, 2011; Rockström et al., 2004; Temesgen et al., 2008, 2009, 2012; Vishnudas et al., 2012) would not only improve farm productivity by soil and water conservation, but would also increase carbon storage in the soil and enhance carbon sequestration in farming produce. If implemented at global scale, this would reduce carbon emissions substantially. At

present carbon funds mostly flow into the expansion and production of commercial plantations, of which the effectiveness and benefits are doubtful, whereas investments into smallholder farming would generate multiple benefits: enhance carbon sequestration, enhance soil and water conservation, reduce soil erosion, enhance soil fertility, diversify agricultural production, contribute to poverty reduction, increase the resilience of rural livelihoods, boost regional development and increase of food production for local and global markets. It will require a global convention to redirect revenue from carbon taxes to support policies that aim for a more effective, more equitable and more sustainable future.

4.2.5 Water governance: the role of non-traditional actors

A development of the past five years is the increased recognition in the corporate world that companies themselves can play a significant role in shifting towards more sustainable water use (Sarni, 2011). The increasing awareness among consumers about the water footprint of many consumer goods, drives companies to take this seriously. Particularly companies in the food and beverage sector and in the apparel sector have started to recognise that their products often rely on unsustainable use of freshwater resources. Reducing the water footprint in the supply chain is now often regarded as a mandatory element of corporate social responsibility strategies. New topics being discussed are water labelling of products in the interest of consumers and water disclosure in the interest of investors (Hoekstra, 2013).

5 Discussion

We have shown that it is not only the water interventions per se, but also, and importantly, the water knowledge itself that has played a key role in the socio-economic development of societies. This knowledge helped humans to transform the landscape, and with it the hydrological processes they had learned to describe and analyse. The resulting unprecedented growth in the production of agricultural commodities and energy since the Industrial Revolution confirmed the belief that humanity could master nature. However, in many instances we have exceeded sustainability limits, leading to heavily modified rivers, declining groundwater tables, and eutrophied and disappearing lakes. These water systems in crisis trigger reflection and responses because of water's vital nature. Society thus has to reach a higher level of consciousness regarding the risk of collapse. The new millennium saw the development of new concepts and methods that allow a more systemic understanding of scale interdependencies, including concepts such as precipitation sheds, virtual water transfers, water footprint and water value flow. These concepts can help to inform the sustainable governance of water systems.

In order to properly understand the evolving relation between humans and water and to be able to address the challenges that lie ahead of us, we need to rephrase our research questions, gather new types of data, facilitate international exchange of data and knowledge, and reform our educational programmes. Scientists and water managers should make good use of new global initiatives, such as Future Earth by the International Council of Scientific Unions (ICSU) and *Panta Rhei* of the International Association of hydrological Sciences (IAHS) aimed at understanding the interactions between society and water (Montanari et al., 2013) and the limits to which our planet can be developed (Rockström et al., 2009b). Future-oriented research questions relate to sustainable, efficient and equitable water allocation and use and the governance structures that can facilitate effective water management. The new types of data we need include water and mineral accounts along supply chains, national water footprint and virtual water trade accounts, water value accounts, better estimates of environmental water requirements, and data on moisture recycling within and between river basins. Addressing global research questions will require the sharing and comparison of data, methods and experiences and the use of virtual observatories and laboratories.

The global nature of freshwater resources urges international cooperation and common understanding of mutual dependencies in water supply. Global efforts to share information and to try to achieve consensus on the ways forward are strongly needed. Initiatives taken by the World Water Forums, the Global Water Partnership, the CEO Water Mandate and UN Water to come to shared agendas and action programmes, such as the Sustainable Development Goals, are essential for addressing the complex and highly interdependent water issues the world is facing.

In many universities, educational programmes are still largely oriented towards single disciplines, while the need is to understand the dynamic and recursive relation between the physics and ecology of water systems and social and economic developments. This requires an interdisciplinary approach, which combines insights from hydrology and water engineering with knowledge of the social, economic and policy sciences.

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