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Evolving water science in the Anthropocene

H. H. G. Savenije et al.

Evolving water science in the Anthropocene

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Abstract

This paper reviews the changing relation between man and water since the industrial revolution, the period that has been called the Anthropocene because of the unprecedented scale at which humans have altered the planet. We show how the rapidly changing reality urges us to continuously improve our understanding of the complex interactions between man and the water system. The paper starts with demonstrating that hydrology and the science of water resources management have played key roles in human and economic development throughout history; yet these roles have often been marginalised or obscured. Knowledge on 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 self-conscious of such mechanisms, exemplified by several concepts that try to internalise them (integrated water resources management, eco-hydrology, socio-hydrology). We have reached a stage where a more systemic understanding of scale interdependencies can inform the sustainable governance of water systems, using new concepts like precipitationsheds, virtual water transfers, water footprint and water value flow.

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 about the latter part of the 18th century, Crutzen and Stoermer (2000) proposed to use the term Anthropocene for the current geological epoch, to emphasize 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 cycles, such as carbon, nitrogen, phosphorus and sulphur, that are fundamental to life on Earth. In addition, our species is strongly modifying the

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terrestrial water cycle by intercepting river flow from uplands to the sea and, through land-cover change, 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 have developed in 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 man and environment.

As shown by L'vovich and White (1990), in the years since the beginning of the Industrial Revolution, which can 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 influencing the flow and storage of water. Humans have changed catchment hydrology in most catchments of the world through one or more of the following means: (i) direct diversion of water flows, including inter-basin transfers, for water supplies to cities, industries and agriculture, (ii) transformation of the stream network, for example through the construction of dams and reservoirs or the canalisation of rivers, (iii) changing drainage basin characteristics, for example through deforestation, urbanisation, drainage of wetlands and agricultural practices, and (iv) activities altering regional or global climate, for instance by enhancing greenhouse gas emissions, land cover changes and consumptive water use. In addition, humans have strongly influenced physical, chemical and biological quality of streams, lakes and groundwater bodies through various sorts of diffuse and point sources of pollution (Meybeck, 2003, 2004). Conversely, freshwater availability and water quality influence and constrain the possibilities for human development, food production and economic growth. There is an increasing number of signals – from declining groundwater and lake levels to disappearing wetlands – showing that the current use of water systems is not sustainable (Molden, 2007; UN Water, 2012; Hoekstra, 2013).

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The increased exploitation of freshwater to the benefit of human development 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 speak about “water resources management” (WRM), and in the 1990s about “integrated water resources management” (IWRM). This change of naming of the field reflects the increasing recognition that water systems are not just to be exploited, but that rather a balance should be sought between fulfilling human needs and sustaining ecosystems (Falkenmark and Rockström, 2004). In this paper, we aim to describe the changing relation between man and water in the Anthropocene, whereby we acknowledge that we are living in just an early stage of this new epoch. In Sect. 2, we look back and show how humanity has started to dominate water systems and how, more recently, water has become a constraint for further development as well. Nature has started to “talk back”. In Sect. 3, we describe some of the early attempts to understand the feedback in the human-water system. In Sect. 4, we look forward and consider emerging new concepts that can help humanity to give shape to 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 international exchange of data and knowledge, and reform our educational programmes.

2 Changing perceptions of water control over time

2.1 Holocene water systems

Freshwater availability in most climate zones 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 must have

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found ways to use water sustainably, 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, such as 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, 1980). Some other societies that were unable to use the water sustainably collapsed (e.g. Mesopotamian civilization, 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 hydroclimatic 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 in this context of interest (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. This could only be accomplished through developing new knowledge and new technologies. A well-known example is the Nilometer (± 1500 BC–1000 AD). 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. Another example is the qanat system first introduced during the Persian empire (about 600 BC) as a successful and sustainable technology to tap groundwater resources, 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.

2.2 The hydraulic mission

The invention of the steam engine and reinforced concrete, together with advances in scientific knowledge on water flows and hydrology (e.g. the Chezy formula for water flow in the late 18th century, the Darcy equation for groundwater flow and the rational

method to calculate storm discharge from a drainage area both mid 19th century, the Manning formula for canal flow end of the 19th century, the work of Horton in the early 20th century, Biswas, 1970: 262–267, 297–299, 301–302, 308, and the Hooghoudt formula for designing polders in 1940, De Vries, 1982) opened up possibilities that hitherto had been unthinkable. This 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; Reisner, 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, 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 electricity 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, were accompanied by unprecedented ecological impacts, with the 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 continuing 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 man crosses 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*

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to trigger such responses given water's vital nature. Debates about the likely causes and remedial action ensue, new hypotheses about the relationship between water and society are formulated, new measures implemented ("building with nature", "room for the river"), system responses monitored and new understandings created. Society thus has to reach a higher level of awareness of the risk to collapse.

The situation we find ourselves in is one of unprecedented growth. We have been able to avoid the Malthusian precipice by our capacity thus far to push back the limits of growth. Trying to avoid 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 sub-compartments, with different societal relevance and behaviour and which interact with other components in the system. For instance, the groundwater sub-system has a much slower dynamic than the surface water sub-system, which makes the former a more reliable resource in terms of timing, but at the same time more vulnerable to overexploitation and pollution, while its use may lead to land subsidence or impacts on the surface water system by reduced seepage to wetlands and streams. More directly visible is the impact that upstream users have on downstream water use in an open water system, both in terms of quantity and quality. The solution of a problem

in one part of a water system frequently leads to the emergence of another problem somewhere else, often related to 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-through and equitable solutions. This idea was termed Integrated Water Resources Management and the concept was officially adopted during the Dublin conference on Water and the Environment in 1992 (ICWE, 1992; Koudstaal et al., 1992).

At first, the focus of IWRM was on understanding the physical interactions in the system in quantitative (and qualitative) terms and to quantify the benefits and costs of alternative interventions, after which a trade-off could 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: to assist the trade-off of all societal costs and benefits. But already during the Dublin conference, economic valuation was 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 ac-

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cess 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, where 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 is rather different from the earlier idea of considering all the interdependencies of the system and providing insight into all the implications, costs and benefits of interventions. As a result, experts skilled in negotiating with stakeholders embraced this interpretation of IWRM and came to see themselves as the “new” water resources managers, sometimes marginalising more analytically oriented experts who rather focussed on understanding and quantifying the dynamics of the system in its complex interactions with societal demands.

3.4 Green and blue water

Scientists continued to be fascinated by the complexity of the water resources system. In the beginning, the emphasis of IWRM was on trying to integrate surface water, groundwater and water quality with the different uses of the system, but thanks to the

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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 the global food production and ecosystems services depend. Global estimates are that 80 % of the global food production relies on rain-fed agriculture (green water), and in sub-Saharan Africa even 90 % (Rockström et al., 2009). Yet, in most analyses of global water scarcity the availability and use of green water was largely neglected, leading to deceptive and pessimistic estimates of global water scarcity (Savenije, 1998, 2000). Now we realize 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) could 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

In 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 the understanding that the water resources system resulted from co-evolution of the landscape, the hydrology, the ecology and society. As a result, we have seen an evolution from hydrology to eco-hydrology and subsequently socio-hydrology (Sivapalan et al., 2012).

A puzzle that researchers on water resources management have 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. But in the monetary interpretation of “water as an economic good”, the valuation of ecosystem services in monetary terms became imperative (Rogers et al., 1998, 2002; Rogers and Leal, 2010). But this is not a trivial

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exercise. Can, for example, the function of aquatic ecosystems as safety net for rural livelihoods be adequately captured in a monetized 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. New insights rather focus on maintaining the essential dynamics of an aquatic system, rather than maintaining base 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). In the meantime, scientists have 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 this complex system and the dynamics of its 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).

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

4.1 Emerging new concepts

In an effort to make societal and system interdependencies in IWRM tangible and explicit, a number of new approaches emerged since the beginning of this millennium that allow to quantify 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, re-use, international distribution of resources and trade in water depen-

dent 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 life styles (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 that it can result in a global water saving as well, namely when the trade occurs from a region with high 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 rain. The 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 recognizing that freshwater is a global resource and that all water consumption and pollution ultimately link to con-

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sumer 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 organization, 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 tool in practice 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 resources linkages through the atmosphere and that land use in one part of the world would impact (positively or negatively) precipitation downwind (Savenije, 1995). The existence of local moisture recycling was recognised, but the larger scale linkages were not considered of relevance. Recent work in this field has led to global moisture recycling maps (Van der Ent et al., 2010) and the definition of precipitationsheds (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 to yield, process and share data on water resources availability and use at a high spatial and temporal resolution. Water resources management in the past 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, whereby one can think of ground truthing of remotely sensed data by individuals, reporting water pollution instances by the public, or 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 that through water exist between and among water users, communities, countries and regions. In fact, water weaves webs of dependencies between these social entities that pose institutional

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challenges. This is most clearly demonstrated by the upstream-downstream dynamics in 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 negative externalities from upstream actors on downstream actors. Social actors located within a shared water system are not only condemned to deal with each other, 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. This is not trivial because of (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 transboundary context and represents a progres-

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sive 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 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) propose 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., 2010; De Groot et al., 2010), alternatively named Compensation and Rewards for Environmental Services (Swallow et al., 2009). ISRIC 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.

Recent developments in earth observation offer for the first time the possibility to estimate 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

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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 transboundary contexts, for example for monitoring water levels of reservoirs by laser altimetry (e.g. Duan and Bastiaanssen, 2013), or the storage 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 becoming a constraint to 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). But 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 bread baskets 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 re-

ducing 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 to manage groundwater and policies to manage 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 internalize 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. 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 (Gerbens-Leenes et al., 2009). Integrating water concerns in energy policy 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).

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 generally seen as pollution and rarely as an essential resource to be recycled or re-used. 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, which at the same time 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. In the Anthropocene, a strategy for recycling and reusing nutrients will

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become an essential strategy for survival. With phosphate there is an inevitable need to recycle (since our sheer survival depends on it), but the same can be said of all scarce minerals, complex organic substances, medicines and the like. A sustainable society in the Anthropocene is only possible if minerals are fully recycled.

5 4.2.4 Global instruments

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, water footprint caps for river basins, water footprint benchmarks for products and 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. Farmers in Africa are for the vast majority 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, it 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 flow mostly into the expansion and production of

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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 The possible role of companies

A development of the past five years is the increased recognition in the world of companies that they 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 recognize 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 water knowledge 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 it had learned to describe and analyse. The resulting unprecedented growth in the production of agricultural commodities and electricity since the industrial revolution confirmed the belief that man could master nature.

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However, we have in many instances exceeded sustainability limits, leading to heavily modified rivers, declining groundwater tables, 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 of the risk to 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 precipitationsheds, 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 man 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. 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 will 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. The global nature of freshwater resources urges international cooperation and common understanding of mutual dependencies in water supply. In many universities, educational programmes are still largely oriented in a disciplinary way, 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 from the social, economic and policy sciences.

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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 other 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: 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: 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.”