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Water resources sustainability in a globalizing world: who uses the water?

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A Fundamental Question: Who Uses the Water?

If a tonne of corn is grown in Illinois but consumed in China, is the water used to grow the corn used by the farmer in Illinois or by the consumer in China? This may come across as a philosophical or polemical question, but in an increasingly globalized world, answering this fundamental attribution question is of critical importance for addressing the issue of water resources sustainability.

Two major frameworks – the freshwater planetary boundary and the water footprint – have emerged over the past decade to advance our understanding of the sustainability of global freshwater resources. The freshwater planetary boundary quantifies the volume of 'blue' water resources (i.e. water in freshwater lakes, rivers and aquifers) that humanity can withdraw and still remain within a presumed, safe ecological operating space (Rockström *et al.*, 2009a). On the other hand, the water footprint concept measures humanity's sourcing and use of all freshwater sources [i.e. blue, 'green' (precipitation that evaporates or transpires through plants) and 'grey' (water required to dilute pollutants)], explicitly recognizing geographical distinctions between production and consumption regions (Hoekstra and Mekonnen, 2012a). Both frameworks strive to quantify the sustainable appropriation of water resources by humanity. The main distinction between the two approaches is in the attribution of final water 'use': The planetary boundary concept attributes use at the point of withdrawal, while the water footprint concept attributes use to the consumer, who may be spatially distinct, yet connected through national, regional and global trade networks. This inconsistency obscures our understanding of human appropriation of freshwater resources and the assignment of responsibility for the stewardship of the water and thus hinders advancement towards sustainable allocation of water resources, especially in a globalized world in which the points of withdrawal and consumption could be as far apart as Illinois and China. Here, we suggest avenues to overcome these inconsistencies, based on ideas from socio-hydrology (Sivapalan *et al.*, 2012; Montanari *et al.*, 2013).

What Do We Mean by Water Use?

The freshwater planetary boundary and the water footprint frameworks guide assessment of the availability, use and sustainability of freshwater resources by humans across local to global scales. Both frameworks rely on often-imprecise and variable water accounting terminology, and also have different objectives. Confusion over what is meant by water use thus stems from inconsistencies in the language used to report water use, as well as different framework objectives for the analysis of that use.

Widely used terms describing ‘water use’ are often ambiguously defined or misused, leading to confusion and debate (e.g. Frederiksen and Allen, 2011; Gleick *et al*., 2011). ‘Consumptive water use’ refers to water that has been permanently removed from its surface or groundwater source because it has evaporated, transpired, been consumed by people or livestock or otherwise been removed from the local environment (Vickers, 2001). ‘Water withdrawals’, on the other hand, are simply quantities of water diverted from a source (Vickers, 2001); the term does not specify the fraction of diverted water that is consumed. Nevertheless, withdrawals are often referred to ambiguously as ‘use’. For example, the US Geological Survey, the agency in the USA that estimates withdrawals every 5 years, refers to their withdrawal data as water use data. These terms capture aspects related to local extraction and/or consumption but fail to account for the final consumer of the water embodied in products, especially when that consumer is in a distant location. The freshwater planetary boundary quantifies local withdrawals, while water footprints are available for both local consumptive uses of water associated with the production of goods as well as the final consumer. These inconsistencies in standard water accounting terminology make comparison across methodologies and frameworks difficult.

The seminal work of Rockström *et al*. (2009a) introduced the concept of planetary boundaries – quantitative, global-scale, biophysical process thresholds whose crossing has unknown, possibly deleterious or even disastrous, consequences for the earth system and humanity as a whole. Quantitative planetary boundaries have been defined for nine earth system processes, including climate change and rate of biodiversity loss (Rockström *et al*., 2009a,2009b). The freshwater boundary is particularly crucial because the biophysical and socio-economic processes that define all other boundaries are strongly dependent upon water (Gleick, 1993; Gleick *et al*., 2013; Vörösmarty *et al*., 2015). Freshwater resources also present quantification challenges due to the unique properties of water in the terrestrial environment (Rockström *et al*., 2012; Bogardi *et al*., 2013; Gerten *et al*., 2013). Improvements to the original freshwater boundary account for water’s uneven spatial and temporal distribution with a river basin level of analysis (Steffen *et al*., 2015), which is especially important in understanding issues of water scarcity, which are local to regional in scale (Vörösmarty *et al*., 2000; Oki and Kanae, 2006; Molden, 2009). The original estimate of the planetary boundary for freshwater use was 4000 $km^3\,year^{-1}$ (Rockström *et al*., 2009a), which has been recently revised to a smaller value of 2800 $km^3\,year^{-1}$ (Gerten *et al*., 2013; Steffen *et al*., 2015). These estimates do not include green water resources but instead focus on renewable blue water resources (Rockström *et al*., 1999; Falkenmark and Rockström, 2004).

Alternately, the water footprint concept – introduced by Hoekstra and Hung (2002) – seeks to quantify the total water resources that a community uses through its consumption of economic goods and services. In this way, the water footprint is one of a family of environmental footprints that quantifies how the production and consumption decisions of humans affect the availability of natural resources (Global Footprint Network, 2014). In the case of the water footprint, the focus is on water resources and how much water is used to produce the items that we consume in our everyday lives, including the water that is polluted in the process and thus rendered unavailable (Hoekstra and Mekonnen, 2012b; Hoekstra, 2014). As such, quantitative estimates of water footprints exist for blue, green and grey water resources. The water resources that are embodied throughout the entire production process of the goods and/or services that are traded locally, regionally and globally are referred to as ‘virtual water’ (Hoekstra and Hung, 2005).

Three Tenets of Sustainability: Environment, Economy and Equity as Applied to Water

There are three long-established tenets of sustainability: environment, economics and equity (Rogers *et al*., 2002). Indeed, the major goal of both the freshwater planetary boundary and water footprint concepts is to guide sustainable water use at the global scale. The freshwater planetary boundary concept focuses on measures of local abstractions of physical water resources, critical levels of which determine global-level limits for sustainable use. In addition to physical limits to local withdrawals, the water footprint concept incorporates important aspects of economics and equity, as necessitated by the idea of sustainability. However, the water footprint literature defines ‘sustainable use of physical water resources’ with local caps to consumptive water use, for example, per river basin (Hoekstra, 2014). We argue that all three aspects of sustainability must be included in order to achieve sustainable appropriation of water resources. As such, achieving water footprint caps per river basin (environment), water footprint benchmarks per product (economics) and fair water footprint shares per community or household (equity) should all be considered integral to the sustainability of water resources.

Human Activities Alter Flows and Stocks of Freshwater and Thus Its Sustainability

Traditional hydrology focuses on physical flows and stocks of water in which the watershed is the principal unit of analysis (Blöschl *et al*., 2013). Hydrology models typically rely on physical principles of mass and momentum balance to determine flows and stocks of water at a range of space and time scales (Dingman, 2008). Figure 1A presents a conceptual diagram of physical hydrology. Precipitation represents a key input of freshwater to the land surface, while evapotranspiration represents a key pathway for freshwater to return to the atmosphere. Surface freshwater flows indicate the movement of water over the land surface. The watershed is the key unit of analysis in physical hydrology owing to the importance of landscape topography in determining the surface flow of water. Watersheds are connected with one another by surface water routing from upstream to downstream parts (Islam *et al*., 2007), e.g. headwaters to estuaries or deltas, eventually draining into the ocean or – in relatively rare circumstances – closed inland basins. Groundwater flows are organized into sub-surface aquifers and represent an important water resource for physical hydrologists (Dingman, 2008).

Advances in physical hydrology have enabled great strides to be made in our understanding of water flows and stocks on the land surface (Oki and Kanae, 2006) and in the sub-surface (Wada *et al*., 2010). However, physical hydrology often does not incorporate many of the human-mediated flows and stocks of freshwater. In the era of the Anthropocene (Crutzen, 2002; Wagener *et al*., 2010), it is increasingly important to explicitly incorporate human dimensions of freshwater use, manipulation and change, in order to more accurately understand and predict the distribution of global freshwater resources. Failure to account for direct and indirect human actions and resulting feedbacks, such as through water resources infrastructure, will lead to incorrect estimates of local and global water scarcity (McDonald *et al*., 2014). However, human impacts on the hydrologic cycle are only recently beginning to be included in regional hydrologic distortion metrics (e.g. Weiskel *et al*. (2014)). Even so, human impacts on freshwater resources are typically not included as an endogenous process but may be incorporated simply as a parameter in a model or as an externally specified driver of the model (Troy *et al*., 2015; Levy *et al*., 2016).

Socio-hydrology is the study of two-way interactions between human and water systems, which may be coupled over a range of scales (Sivapalan *et al*., 2012, 2014). Figure 1B presents a conceptual diagram of socio-hydrologic flows and stocks (i.e. those that are impacted by human activities). In this new socio-hydrology framework, we propose three pathways through which humans modify hydrologic flows and stocks: internal modifications, infrastructure-based external transfers and virtual transfers. First, humans may implement local, small-scale changes to water resources that are contained within the watershed unit, such as local modifications to the land surface (e.g. urbanization or land cover change), which impact intra-watershed hydrologic processes, such as runoff (Meierdiercks *et al*., 2010). We refer to these human impacts as 'internal modifications' in Figure 1B.

Importantly, human activities transgress the physical boundaries of watersheds, making it critical that

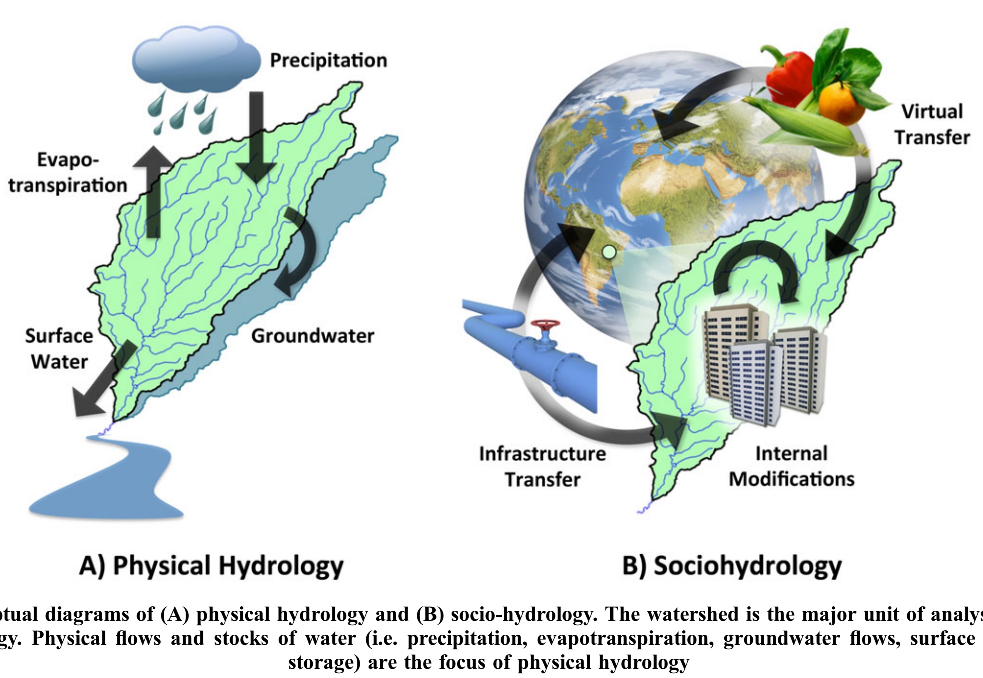

Figure 1. Conceptual diagrams of (A) physical hydrology and (B) socio-hydrology. The watershed is the major unit of analysis in traditional, physical hydrology. Physical flows and stocks of water (i.e. precipitation, evapotranspiration, groundwater flows, surface water flows and storage) are the focus of physical hydrology

watersheds are linked in some way to the social and economic drivers that operate across different spatial and temporal boundaries and scales. For example, humans develop infrastructure in order to alter the flow or storage of water with the aim of ensuring human water security, but which, in many cases, compromise the integrity of aquatic ecosystems and the productive services they provide (Vörösmarty *et al.*, 2010). Infrastructure includes both 'hard' engineering projects (McDonald *et al.*, 2011) and 'soft-path measures' (Gleick, 2003), such as water allocation rules, demand management practices (e.g. through pricing) or other policies that directly and indirectly influence human use of water resources. Here, institutions may include a range of human responses to a water resource signal, which transcend the watershed boundary. This socio-hydrologic framing enables the consideration of distinct human responses to water scarcity – such as governance or infrastructure development – that are important feedbacks in the coupled human–water system (Srinivasan *et al.*, 2012). We refer to these inter-watershed, human-mediated processes (i.e. hard-path or soft-path measures) that result in physical transfers as 'infrastructure transfers' in Figure 1B.

Globalization Necessitates Multi-scale Understanding

We live in an increasingly globalized world, in which exchanges of commodities and services are essential to the functioning of modern society. These exchanges connect production in one location (that uses water resources) with consumption in a distant location. Thus, local water resources are linked to the global economy through societal teleconnections (Seto *et al.*, 2012; Liu *et al.*, 2013). Owing to the increasingly interconnected nature of modern human society, we therefore need to explicitly include human activities that operate at different spatial and temporal scales into traditional physical hydrology models. We refer to these inter-watershed human-mediated virtual water exchanges as 'virtual transfers' in Figure 1B. Virtual transfers do not result in changes to physical water budgets but may affect how people draw upon local water resources and are essential for understanding patterns of non-local consumption of water resources.

The importance of sub-global spatial heterogeneity has prompted an update to the original planetary boundaries estimate that explicitly links regional and global spatial scales (Steffen *et al.*, 2015). Initially, the freshwater planetary boundary was estimated as a single numeric value at the global scale, although sub-global spatial heterogeneity was acknowledged (Rockström *et al.*, 2009a) and has remained a point of debate in the literature (Molden, 2009; Carpenter and Benett, 2011). To this end, recent efforts have attempted to reconcile the global scale of the planetary boundaries concept with the traditionally local scale of hydrology and water management (Rockström *et al.*, 2012; Bogardi *et al.*, 2013; Gerten *et al.*, 2013). However, this approach still fails to capture human-mediated flows of water that operate at scales incongruent with the watershed scale, such as infrastructure or virtual transfers. Additionally, connections between basins exist, such that some basins may operate within a 'safe' operating space at the expense of other 'less safe' basins. A palpable difference of opinion also exists within the community regarding the value of local (Hering *et al.*, 2015) or the rising necessity of fully global-scale perspectives (Vörösmarty *et al.*, 2015).

Conversely, regional heterogeneities do not complicate quantification of the global water footprint of human consumption as they do the freshwater planetary boundary. This is because the global water footprint of human consumption is a consumption-based measure (Hoekstra and Mekonnen, 2012a), such that local, physical heterogeneities do not complicate the global value. However, the local watershed-level production footprints must additionally remain below certain caps in order to fulfil the environmental requirement of sustainable allocation of freshwater resources (Hoekstra, 2014). In this way, both the planetary boundary and water footprint concepts for freshwater sustainability highlight the importance of taking a global viewpoint, as advocated by Vörösmarty *et al.* (2015), but are subject to different complexities in terms of how they scale.

Hydrology Models Need to Include Human Dimensions of Water Use

It is essential that we incorporate understanding of human-mediated flows and stocks of water into hydrological analyses so that we can identify the local and/or non-local causes of unsustainable freshwater use and guide sustainable water management across scales. Here, we introduce the blueprint of a socio-hydrology model that captures primary interactions in complex water-resource systems. First, we use a watershed unit of analysis, as is standard in physical hydrology models. Next, we use a water balance approach in which both the physical and human-mediated flows of water are explicitly incorporated into the model. The addition of social dynamics to hydrological systems analysis builds upon classical models in physical hydrology and is intended to represent the societal forces (e.g. economics, politics, governance and culture) that operate differently at different scales and within boundaries different than those of driving hydrological processes.

We present a schematic of a traditional hydrology model in Figure 2A. Water flows from upstream to downstream watersheds based upon physical laws in Figure 2A. The corresponding water balance equation is provided in Figure 2A. Physical inflows of water are equated with physical outflows of water. A change in storage term is included to close the continuity of mass equation, while an error term is included to account for measurement or model errors. We suggest a schematic for a new socio-hydrology model in Figure 2B. In the socio-hydrology model, physical flows of water still move from upstream to downstream. However, human-mediated flows of water now enable water to be transferred between upstream and downstream watersheds in either direction. Additionally, each watershed may now be connected with any other watershed through infrastructure and virtual water transfers. The corresponding water balance equation for the socio-hydrology model is provided in Figure 2B, although water balance closure may not occur because socially mediated flows are not simple mass balances.

Infrastructure and virtual water transfers in the socio-hydrology water balance model represent human-mediated transfers of water. As these transfers occur for societal reasons (e.g. price, technology and human perceptions of environment), they are driven by

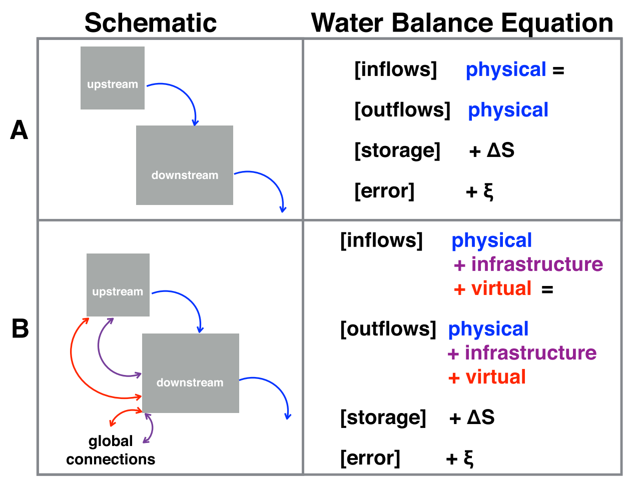

Figure 2. Schematic of (A) physical and (B) proposed socio-hydrology water balance models. Panel (A) presents a schematic of two watersheds connected through physical water flows that move from upstream watersheds to downstream watersheds. The water balance equation represents the physical water flows of the downstream watershed. Physical inflows include precipitation, groundwater flows and surface water flows; physical outflows include evapotranspiration, groundwater flows and surface water flows; ΔS indicates the change in storage term; and ξ indicates the error term. The physical flows that connect watershed units are highlighted with blue arrows and text. Panel (B) presents additional human-mediated flows of water to the traditional, physical water balance approach. In (B), infrastructure flows (purple) and virtual water flows (red) connect watershed units with one another in ways that break the traditional upstream–downstream flow trajectory, as well as connect distant watersheds

underlying socio-economic (supply and demand) and cultural processes (Reimer, 2012; Debaere, 2014). Costs of constructing the necessary water resources and transportation infrastructure (Lin *et al.*, 2014) – while accounting for relevant policies, government subsidies or cultural values – would impact the price and, therefore, the demand for those transfers of water resources. There are many alternate formulations that could be used to model the socio-economic drivers of infrastructure or virtual water transfers, such as the gravity model of trade (Tinbergen, 1962), or parameterization of existing infrastructure based on empirical data (McDonald *et al.*, 2011). We do not specify the underlying socio-economic functional forms here but highlight that it is important that the chosen functional form is capable of operating across watershed units.

The socio-hydrology model incorporates multi-scale complexities, such that the global impact of human water appropriation would be more than the individual use impacts across all of the local watershed units. The watershed units are connected through global economic teleconnections, and there is potential for this to lead to emergent behaviour that is difficult to predict from local-scale understanding alone. Importantly, the socio-hydrology model that we present here explicitly acknowledges that human actions (infrastructure and virtual water trade) modify local-level water resources in a way that is consistent with the global and sub-global scales yet true to the physical watershed scale. We suggest that this socio-hydrology model provides an opportunity to operationalize links between regional and global spatial scales, which has been suggested by Steffen *et al.* (2015) to move the planetary boundaries concept forward. Critically, this socio-hydrology model could be operationalized at regional scales to identify the capacity of current and future infrastructure to address sub-regional water shortages. This socio-hydrologically informed water balance could then be scaled up to larger spatial extents to match sub-national and national decision-making jurisdictions, which often do not overlap with the geographic boundaries defined by hydrological systems.

By incorporating human–water interactions and feedbacks at the scale of watersheds, the model is able to assess issues of local water availability at a scale commensurate with human decision-making and yet assess how these are up-scaled to regional, national and global scales and ultimately reflected in the freshwater planetary boundary. Likewise, the availability of such a fully configured multi-scale model can serve as a useful instrument to cascade global-scale decisions and policy prescriptions (i.e. in light of the planetary boundary) down to smaller national, regional and watershed scales at which human decisions are made. A further advantage of a coupled socio-hydrology model is that it enables tracking of the propagation of changes in both exogenous drivers (i.e. climate change) and endogenous processes (i.e. human responses to water scarcity or surplus), resulting in an ability not only to monitor the time evolution of the freshwater planetary boundary but also to use it as an indicator of how changes in human values, preferences and behaviours manifest at the global scale (Thompson *et al.*, 2013; Vörösmarty *et al.*, 2013).

Concluding Remarks

The planetary boundary and water footprint concepts have energized both scientific and policy circles, providing a tremendous opportunity to bring together diverse research in sustainable water resources. A major distinction between the two approaches is in their attribution of water 'use', which leads to inconsistencies in our understanding of the human appropriation of freshwater resources and hinders advancement towards water resources sustainability in a globalized world. To reconcile these differences, we presented a blueprint of a socio-hydrology model that could be used to explicitly track both the supply and demand flows of water resources to better understand the use of water, reconciling the planetary boundary and water footprint concepts. We hope these key socio-hydrology concepts will be incorporated into future model development efforts and help us to more clearly articulate water use and its degree of sustainability.

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