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Freshwater ecosystem services supporting humans: Pivoting from water crisis to water solutions

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ABSTRACT

A new global scale water indicator, the freshwater provisioning index for humans (FPI_h), maps the capacity of upstream source areas to provide water for human populations downstream. The freshwater provisioning index for humans combined with estimates of threats to water source areas assesses the compounded impacts on freshwater provisions at their point-of-service and the humans they support downstream. Nearly the entire world is serviced by freshwater sources compromised to a moderate extent through human activities, with 82% of the world's population served by upstream areas exposed to high levels of threat. Globally, 75% of the world's population benefits from engineered remediation of highly impaired source areas. Despite these gains, more than 80% of the global population still experiences moderate levels of threat impacting their freshwater provisions. Industrialized nations greatly limit their exposure to threats via infrastructure investments whereas regions in the developing world with moderate threat and little means of mitigation are viewed as the most vulnerable. Populations served by water source areas in industrialized countries receive highest threat reductions overall (50–70%) while those served by provision areas in the least developed countries receive <20% threat decrease. Better management of upstream source areas in poorer countries represents an opportunity to reduce threat lessening reliance on costly engineering solutions. Viewing the world in terms of the threats imposed on freshwater provisions combined with regional capacity to abate these impairments through infrastructure investments yields a spatial typology of freshwater resource development states reflecting region-specific challenges with unique management implications. Global mapping of threat development states provides a synoptic-scale diagnosis of key water resource challenges we link with state-specific water service management strategies including service area conservation, threat reduction, and green and gray infrastructure investments to more sustainably manage upstream freshwater provisions. This study provides a functional architecture to assess potential investment strategies to sustainably protect and manage critical upstream freshwater provisions addressing unique challenges faced by different regions of the world.

1. Introduction

Water security issues continue to gain urgency in science and policy circles. Several recent studies justify this concern underscoring the expanding and often unsustainable use of surface and groundwaters (Addams et al., 2009; WWAP, 2009; Bourza, 2013; Foster et al., 2013; Lawford et al., 2013), pollution (Dudgeon et al., 2006), and poorly optimized management of water management systems (Vörösmarty et al., 2013). In addition, the availability of reliable water supplies is a central component within the larger planetary boundary debate, with some studies indicating severe overshoot imminent (Bogardi et al., 2012; Gerten et al., 2013; Steffan et al., 2015). Humans have modified the natural landscapes around rivers and wetlands to the point that their biodiversity is put at risk and the freshwater ecosystem goods and services they

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provide to humans are compromised (Vörösmarty et al., 2010; Russi et al., 2013). These impairments represent pandemic, self-inflicted water security threats that are an apparent byproduct of population growth and economic development and poor environmental stewardship (Vörösmarty et al., 2010).

Industrialized nations that have severely degraded their ecosystems and associated freshwater provisioning services are in a position to attenuate water quality and quantity problems by investing in engineering solutions that emphasize water infrastructure, operations and affiliated technologies (Gleick, 2003; Ashley and Cashman, 2006; Addams et al., 2009; Vörösmarty et al., 2010, 2013). Assuring the world's human water security in this manner requires generally expensive investments in remediation technologies and infrastructure like dams, water treatment facilities or flood protection barriers (Vörösmarty et al., 2013). In addition, substituting engineered fixes in lieu of preserving natural functions (e.g., water purification) or problem prevention (Vörösmarty et al., 2015) can be enormously expensive and wastes the economic benefits of ecosystem services provided by wetlands, forests, mangroves, and other ecosystems and the livelihoods that depend on them ((TEEB) The Economics of Ecosystems and Biodiversity, 2011).

Recognizing the critical role that ecosystem services can play in substituting natural capital for traditional engineering counters conventional 'environment-versus-development' thinking (Palmer, 2010; de Groot et al., 2012; Vörösmarty et al., 2013; Costanza et al., 2014). Developing countries, although highly constrained in their capacity to mobilize hard infrastructure investments, represent a significant global opportunity for adopting new and innovative water management techniques using nature-based or green approaches that could simultaneously promote human well-being and environmental benefits. The practical value of such green technologies and ecosystem services goes beyond traditional infrastructure investment and is at the heart of this new paradigm (Vörösmarty et al., 2005; Palmer, 2010; ten Brink et al., 2012; Sáenz and Mulligan, 2013; Costanza et al., 2014) yet requires systematic evaluation.

The last 10–15 years have also brought recognition of the need to express human–water interactions as an inherently geospatial problem defined by the spatial distributions of water availability, human population and their interactions (Lawford et al., 2013). The environmental, development and sustainability communities rely heavily on indicators to benchmark and track trends in different variables, outcomes or system states. Such quantitative measures support both scientific analysis and are important messaging devices from scientists-to-policy-makers and other stakeholders.

There have been numerous attempts to create comparative indicators that capture the nexus of freshwater availability and human water use (Morrison et al., 2010; Brown and Matlock, 2011; Doczi, 2014). The most straightforward constitute single state variables combined into compound indicators, such as the conjunction of population and water supply (Falkenmark, 1989; Gleick, 1996), which is often expressed at the river basin or national scale. Additional degrees of sophistication have included the use of multivariate compound variables, time series data, and high resolution geophysical as well as social science data sets employing measures of water supply, access, use, management capacity, and environmental integrity (Sullivan, 2002; Smakhtin et al., 2005; Chaves and Alipaz, 2007). The concepts of the water footprint and life cycle analysis of water use have emerged over the last decade (Hoekstra et al., 2009; Pfister et al., 2009; Ridoutt et al., 2009) and help to convey to policymakers and the public the cumulative impact of humankind on its water systems.

The majority of water indicators employed to date have focused on point-of-use analysis, where human water requirements, activities and impacts are considered at the locations where water is accessed or withdrawn relative to locally available water supplies (Falkenmark, 1989; Shiklomanov, 1993; Gleick, 1996; Raskin et al., 1997). In this respect, water assessment is viewed as a localized characteristic and measured from the vantage point of the human users. Although, other studies have examined the accumulated impacts of water use and demand along river courses (Vörösmarty et al., 2005; Hanasaki et al., 2013a,b) these also evaluate impacts on the downstream users at their point-of-use, neglecting to identify or address the value of upstream freshwater provision source areas.

The last decade has also seen a more explicit quantification of the value of nature in defining human-water interactions (Farrell et al., 2010; Braat and de Groot, 2012; Russi et al., 2013). Several indices and decision-support systems exist for measuring different aspects of the status of freshwater ecosystems and their importance to humans. These include, for example, the *Water Poverty Index* (Sullivan, 2002); the *River Basin Health Index* (for Asian and Pacific rivers) and the *River Health Report Cards* developed by the River Health and Environmental Flow (RHEF) in China project (Asian Development Bank (ADB), 2013; International WaterCentre, 2013); *America's Great Watershed Report Card* (Great Rivers Partnership, 2013); WWF's (2013a) Freshwater Health Assessment scorecard; The State of the World's Rivers (International Rivers, 2014); and tool kits of Natural Capital Project (2013). While water indicators abound, there are few tools that define the capacity of ecosystems to provide freshwater provision services to downstream users or address management of these critical resources (Farrell et al., 2011). Water resource management requires an holistic approach, linking social and economic development with natural ecosystem protection (International Conference on Water and the Environment (ICWE), 1992; Pahl-Wostl et al., 2013b). Due to regionally unique water resource challenges and significantly different levels of socio-economic development across the world (Hanasaki et al., 2013a,b), it is key for potential management strategies to reflect endemic levels of impairment and development conditions.

We adopt several of these new perspectives and carry them forward by creating a new indicator of human-water interaction, the *freshwater provisioning index* serving downstream *human* populations (FPI_h) that expressly interjects a quantification of freshwater ecosystem services in terms of water provisions. Our indicator moves beyond the *point-of-use* paradigm of existing water indicators by tracing the locally available water for humans to the upstream *point-of-service* domains, thus defining the spatial extent of critical upstream freshwater provision areas by the users they support downstream.

The aim of this paper is to document, through a first global synthesis, the geography of freshwater source areas serving humankind, evaluating jointly the quantity and condition of these resources. We begin by mapping the source areas and the populations served by these, with an accompanying assessment of the condition of those resources. We next present a global geography of the abatement of human-induced impairments to freshwater provisioning areas through investments in infrastructure. We end with a discussion of the implications of these results for potential management and investment strategies to more sustainably protect and manage critical upstream freshwater provisions across different regions of the world.

2. Methods

2.1. Development of FPI_h

The *freshwater provisioning index* serving downstream *human* populations (FPI_h), is calculated as the number of people living