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Key Points:
- Water problems represent a Grand Challenge in the Anthropocene
- Contemporary scholarship on water is fragmented by disciplinary barriers
- Socio-hydrology is a new science useful for water sustainability challenges

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Socio-hydrology: Use-inspired water sustainability science for the Anthropocene

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Abstract Water is at the core of the most difficult sustainability challenges facing humans in the modern era, involving feedbacks across multiple scales, sectors, and agents. We suggest that a transformative new discipline is necessary to address many and varied water-related challenges in the Anthropocene. Specifically, we propose socio-hydrology as a use-inspired scientific discipline to focus on understanding, interpretation, and scenario development of the flows and stocks in the human-modified water cycle across time and space scales. A key aspect of socio-hydrology is explicit inclusion of two-way feedbacks between human and water systems, which differentiates socio-hydrology from other inter-disciplinary disciplines dealing with water. We illustrate the potential of socio-hydrology through three examples of water sustainability problems, defined as paradoxes, which can only be fully resolved within a new socio-hydrologic framework that encompasses such two-way coupling between human and water systems.

1. Need for a Water Focus on Sustainability Science

Water represents a key aspect of sustainability challenges facing humans in the Anthropocene [*Maass et al.*, 1962; *Falkenmark and Rockström*, 2004]. Human appropriation of water resources and modification of landscapes exert an accelerating influence on water-cycle dynamics from local- to global scales and decadal- to century timescales [*Vörösmarty et al.*, 2000]. Human actions scale up in surprising and unpredictable ways to generate a suite of diverse water sustainability challenges that must be incorporated into new approaches to water science and management.

Examples of wicked problems that continue to vex scientists and policy makers include: trade-offs among ecosystems, hydropower, and livelihoods in the transnational Mekong Basin [*Ziv et al.*, 2012]; effects of human settlements in flood-prone areas on increased flood risk and fatalities in Africa [*Di Baldassarre et al.*, 2010]; and expanding hypoxic zones in the Gulf of Mexico resulting from nutrient loading in the agricultural headwaters of the Mississippi River [*Turner and Rabalais*, 2003]. Due to the urgency of these problems, contemporary scholarship should draw from natural sciences, social sciences, and the humanities, to better understand the dynamics arising from the two-way coupling between water and humans in each case.

There have been calls for a transformative new water discipline that integrates the multiple perspectives needed for confronting water challenges in the Anthropocene. For example, we should build upon the tradition in hydrology to study relatively pristine systems, in which human actions tend to be incorporated simply through parametric approximation [*Wagener et al.*, 2010], with richer understanding of coupled human-water system dynamics [*Fishman et al.*, 2011]. Likewise, humanistic approaches to the study of water—law, philosophy, history, and ethics—can be further integrated with scientific knowledge [*Wescoat*, 2013]. The most effective way to create such a new discipline is to frame it as use-inspired science [*Stokes*, 1997; *Clark and Dickson*, 2003; *Thompson et al.*, 2013], focused on addressing urgent water

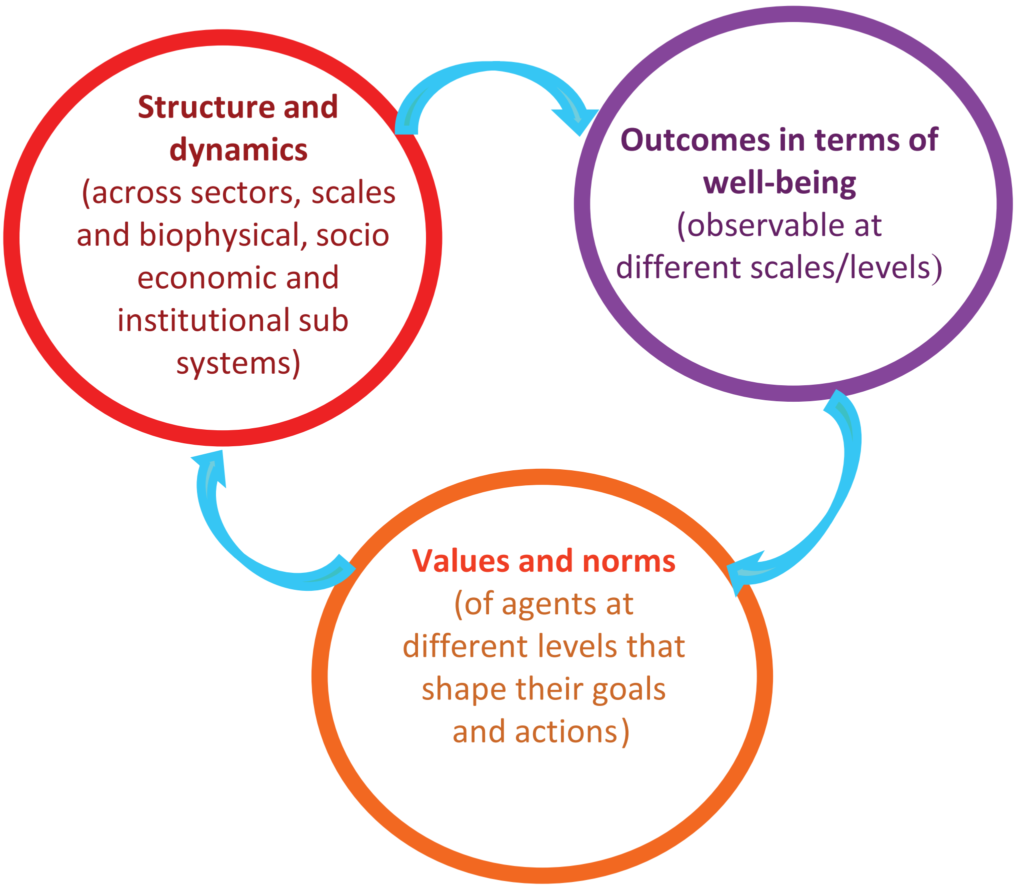

Figure 1. Organizational framework for socio-hydrology.

sustainability problems through integration of existing scientific theories and methods while at the same time creating new knowledge and understanding of emergent system dynamics.

2. Socio-hydrology, a New Science of Humans and Water

Inspired by the vast water security and society literature, we propose socio-hydrology as a use-inspired scientific discipline with a focus on the understanding, interpretation, and scenario development of the flows and stocks in the human-modified water cycle at multiple scales, with explicit inclusion of the two-way feedbacks between human and water systems [*Sivapalan et al*., 2012]. Socio-hydrology is aimed at uncovering the dynamic cross-scale interactions and feedbacks between the natural and human processes that may give rise to water sustainability challenges that we face in the Anthropocene.

Socio-hydrology has three goals: (1) analyze multiscale, space-time patterns and dynamics of socio-hydrologic processes, and interpret them in terms of the underlying structural features of biophysical and human systems and their interactions; (2) explain and interpret socio-hydrologic responses in terms of outcomes relevant to human well-being, and discern possible future scenarios of their evolution; and (3) understand the meaning and value of water as a culturally, politically, and economically embodied resource necessary to human life, and do so in a manner that explicitly accounts for biophysical and human interactions.

We propose a broad theoretical framework that builds on the relationships among three crucial aspects of the socio-hydrologic system (Figure 1): (a) multiscale water system structures and dynamics, (b) water-related human well-being outcomes that emerge across physical scales and governance levels, and (c) normative goals of individuals and whole societies with respect to water use, conservation, and sustainability. This theoretical framework formalizes the feedbacks between human and water systems in an explicit way that can help us explain the past, understand the present, and illuminate sustainable future trajectories of their coevolution.

3. Socio-hydrologic Perspective on Water Sustainability Challenges

Current approaches to studying water sustainability challenges lack explanatory and predictive power because of the inadequate treatment of the two-way dynamic feedbacks between human and water systems. Inadequate explanatory power gives rise to paradoxes, which frustrate efforts to resolve problems in societally relevant ways. Furthermore, the lack of predictive power over long time scales or large space scales produces over-simplified—often internally inconsistent—technical fixes [*Gleick*, 2003]. We illustrate the potential of socio-hydrology through three examples of water sustainability problems that cannot be fully resolved using conventional approaches.

3.1. Virtual Water Trade Paradox

When the concept of virtual water was introduced [*Allan*, 1997], many researchers predicted that the global commodities trade would self-organize to alleviate water stress. This was certainly true at the global scale (see Figure 2). For example, in 2008, the global staple food trade saved approximately 238 km^3 yr^{-1}, a doubling in less than 20 years [*Dalin et al*., 2012]. However, many local and regional trade relationships lead to irrational water resource outcomes [*Chapagain et al*., 2006]. For example, food trade from northern to southern China amounts to a virtual water flow of 52 km^3 yr^{-1}, more than the proposed diversion of real water through the South-North Water Transfer Project [*Ma et al*., 2006]. This paradoxical outcome can only be explained when local norms and values prioritizing food security over

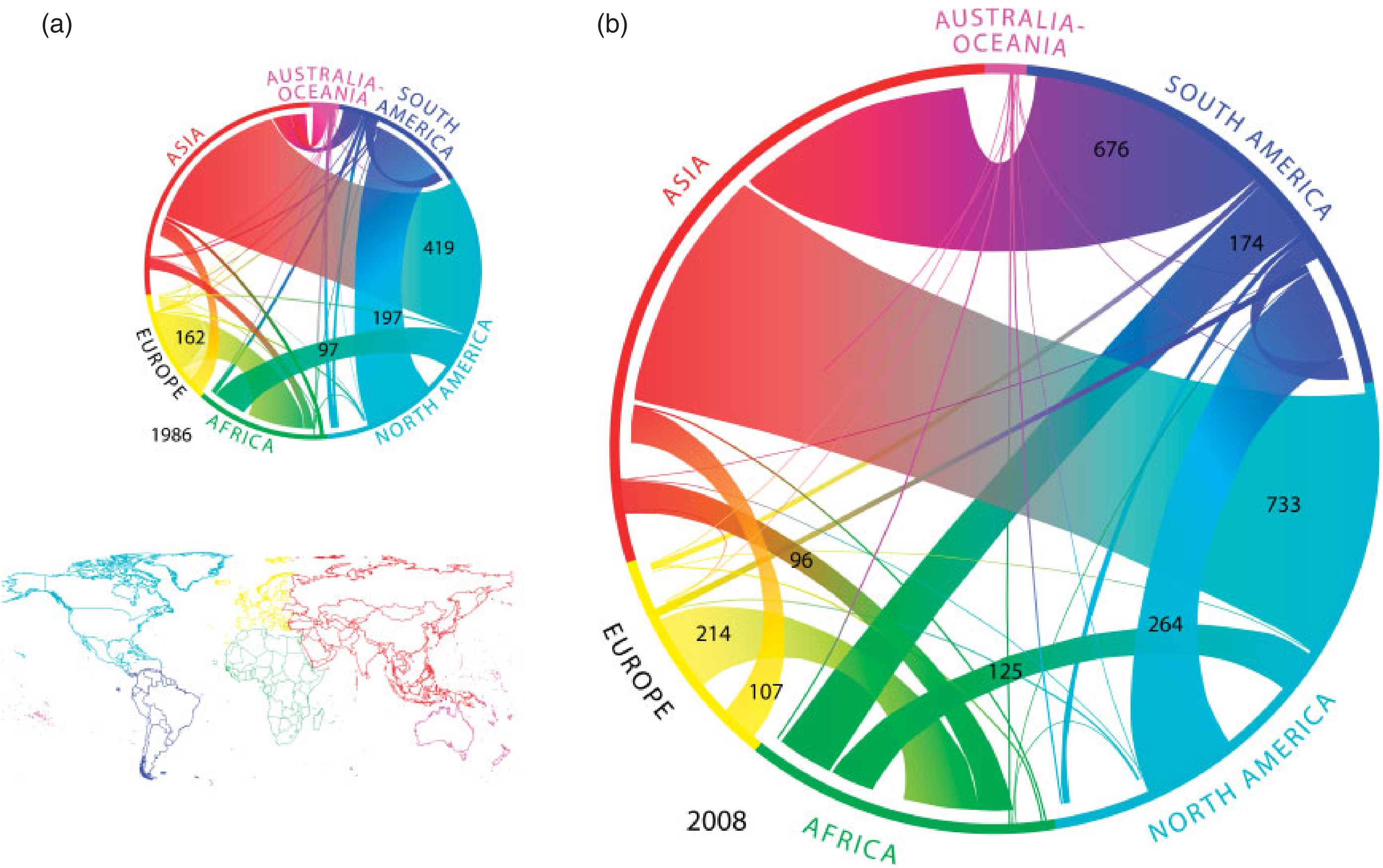

Figure 2. Water saved by global food trade in (a) 1986 and (b) 2008. Each circle displays regional water saved and is scaled by volume saved; 2.3 times more water was saved in 2008. The color of each region is provided in the map legend and import direction is indicated with white band. Numbers indicate km^3 water and negative flows are not displayed.

adverse environmental outcomes and the combined structure of land, labor, energy, ecological, and water constraints are taken into account. It is clear that in order to understand why trade saves water at the global scale, but not for certain regional and local trade links, it is essential to consider the social factors underlying agricultural production and trade [*Konar et al*., 2013].

3.2. Efficiency Paradox

Efficiency of resource use has been considered an unassailable "gospel." A range of practices and technologies to increase irrigation efficiency and save water have proven successful at the farm scale. Yet efficiency presents a paradox when assessed at larger scales because the "wasted" water upstream often becomes downstream supply. Without norms governing how the saved water must be reallocated—either by leaving it in the watercourse or protecting downstream water users, efficiency may only increase total irrigation use, worsen inequity, and deprive ecosystems of much-needed flows. The efficiency effect of increasing resource use—identified by William Stanley Jevons in *The Coal Question* (1865)—is especially evident across sectors where improvements in one sector produce externalities in another. An illustrative example is the coupled use of water and energy in Mexico, where efficient and subsidized electricity supplied to pump groundwater for irrigation had the unintended effect of increasing pumping by 4.9 $km^3\ yr^{-1}$ (25% of agricultural groundwater pumping), speeding up aquifer depletion [*Scott*, 2011].

3.3. Peak-Water Paradox

Water use is often assumed to increase with economic growth in demand projections. Yet many parts of the world are experiencing decreasing human water use despite sustained economic growth. In the Murrumbidgee Basin in Australia, construction of a series of dams initiated in the 1920s spurred an expansion of irrigated farming, accompanied by growth in population and agricultural exports. By 1980, abstractions from streams were almost 100% of the natural flows during low-flow periods. But by 2000, a prolonged drought, increased environmental consciousness, and diminution of agriculture as a fraction of the national economy resulted in a sharp reversal of this trend [*Kandasamy et al*., 2013], with irrigation rights being bought back and reallocated to the environment (see Figure 3). Such a change in the structure and dynamics of water abstraction in the Murrumbidgee Basin can be explained only if one considers the changing norms governing the relative value placed on water used in agriculture versus in-stream water [*Gleick and Palaniappan*, 2010].

Current approaches are unable to explain and predict outcomes in the above paradoxes, resulting in unsustainable water resource management outcomes. Unfortunately, these paradoxes are not unique to a single case study site and occur in a range of locations. In each case, however, once the analysis frameworks are broadened (as in Figure 2), they can be understood as emergent dynamics resulting from two-way feedbacks between coupled human and water systems, thus highlighting the need to study human-water systems in a more general way to improve our explanatory and scenario development capabilities.

4. Socio-hydrology as Use-Inspired Science

There is a long history of scholarship on the role of water in social and environmental changes [*Maass et al*., 1962; *Wescoat*, 2000; *Tainter*, 2006]. The complexity of the waterscape today—in which human actions are often varied, distributed, and informal—requires new understanding as these actions manifest in often unpredictable ways. Socio-hydrology builds upon previous work by incorporating impacts of decentralized human agents and institutions to water flows and storages, as well as their feedbacks. Additionally, socio-hydrology as proposed here is explicitly problem inspired, constructing novel hypotheses to address water sustainability challenges.

Human-water dynamics are complex and require new understanding. We propose socio-hydrology as a use-inspired scientific discipline that entails study of real-world systems across gradients of climate, socioeconomic status, ecological degradation, and human management. This effort will require contributions of experts across a range of perspectives—from hydrologists to natural and social scientists to humanists—to be successful. It is only through such joint efforts we can generate viable solutions to the water sustainability challenges of the Anthropocene.

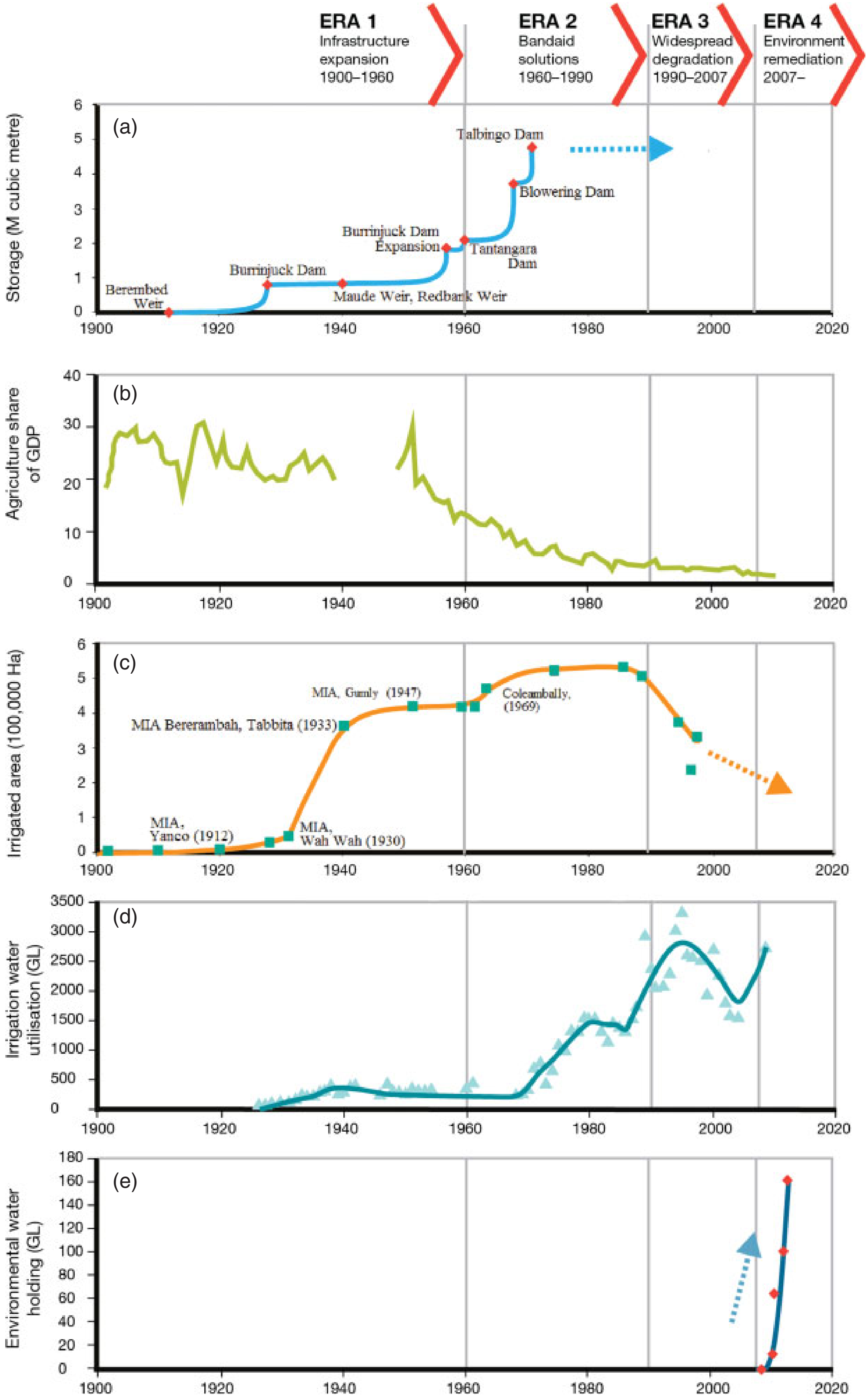

Figure 3. Pendulum swing in the Murrumbidgee Basin. Time series of (a) storage, (b) agriculture's share of gross domestic product, (c) irrigated area, (d) irrigation water use, and (e) environmental water holding. Source: Kandasamy *et al.*, 2013.

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