AGU100 ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2019EF001185

Key Points:
- Socio-hydrological systems exhibit power law growth with punctuated equilibria
- Global per capita water use increased, indicating positive human-water feedbacks
- Past water use has delayed effects on future water infrastructure decisions

Correspondence to:
A. J. Parolari,
anthony.parolari@marquette.edu

Citation:
Parolari, A. J., & Manoli, G. (2019). Power law growth and delayed feedbacks in socio-hydrological systems. *Earth's Future*, *7*, 1220–1231. https://doi.org/10.1029/2019EF001185

Received 18 FEB 2019
Accepted 6 OCT 2019
Accepted article online 11 NOV 2019
Published online 15 NOV 2019

Power Law Growth and Delayed Feedbacks in Socio-Hydrological Systems

Anthony J. Parolari[1] and Gabriele Manoli[2,3]

[1]Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI, USA, [2]Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland, [3]Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK

Abstract Water infrastructure dynamics result from coupled social and physical hydrological processes embedded in "socio-hydrological systems" (SHSs). Freshwater fuels socioeconomic activity, which in turn exerts pressure on water resources through increased water demand and water quality degradation. Many factors emphasize the need for quantitative tools to predict the future of these systems, including SHS failures due to growing water scarcity from population growth and climate change. However, unfolding the interactions between social and hydrological factors continues to resist theoretical treatment, impeding progress toward a predictive framework. To resolve this issue, we propose and evaluate time delays as surrogates for the social dynamics in SHS models. This approach permits the development of models that describe SHS dynamics in terms of observable, physical, hydrological state variables. We apply this approach to two case studies: (a) reservoir storage capacity growth in the world and the U.S. Water Resources Regions and (b) global water withdrawals. Substantial variability was identified in empirical estimates of growth rates and time delays. Reservoir construction typically follows a saturating, logistic curve with periodic, punctuated equilibria, separated by delays ranging from 5 to 20 years both globally and regionally. In contrast, global water withdrawal data display faster-than-exponential growth, characteristic of a positive feedback through which water use drives further water development. Historical analysis suggests that growth trends in water resources systems are superimposed by recurring periods of innovation and inactivity which are indicative of slow memory dissipation and delayed effects of past water use on current water infrastructure decisions.

1. Introduction

Human water use rivals natural processes in freshwater hydrological systems, thereby embedding socioeconomic processes into the water cycle, that is, the so-called "hydro-social cycle" (Linton & Budds, 2014). Major human hydrological processes include surface and groundwater withdrawals and surface water storage in reservoirs to support social and economic enterprises, primarily agriculture. The global scale of human-imposed hydrologic change is immense, encompassing 54% of accessible runoff and 26% of terrestrial evapotranspiration and approaching the proposed planetary boundary for freshwater consumptive use (Postel et al., 1996; Rockström et al., 2014). Therefore, an urgent challenge toward water security is to quantify the interactions between the social and economic drivers of water consumption and physical hydrological processes (Sivapalan et al., 2012, 2014; Thompson et al., 2013).

One source of uncertainty in the modeling of socio-hydrological systems is the direction and magnitude of the feedbacks between the socioeconomic and physical system components. This limitation derives from a fundamental lack of knowledge regarding the governing state variables and, in particular, the sensitivity of social dynamics to changes in the hydrological states and fluxes (Liu et al., 2007; Parolari et al., 2015; Thompson et al., 2013; Viglione et al., 2014). Both positive and negative feedbacks between social and hydrologic systems are likely. Water resources development improves sanitation and health, water supply reliability by dampening hydro-climatic variability, and industrial and agricultural output (Gleick, 2003; Montgomery & Elimelech, 2007; Vörösmarty et al., 2010). Each of these factors can spur further population, urban, agricultural, or economic growth, increasing the demand for further water development. On the other hand, human water appropriation degrades ecosystem services and negatively impacts in-stream or downstream uses, which may decrease water demand and withdrawals (Gleick & Palaniappan, 2010; Kandasamy et al., 2014). Finally, socioeconomic systems can either amplify or attenuate perturbations resulting from hydro-climatic variability (i.e., drought and floods; Viglione et al., 2014; Vörösmarty et al., 2010). Constraints on the aggregate balance of such positive and negative socio-hydrological feedbacks and their change over time are needed to characterize both near-term growth regimes and future stability scenarios of water resources systems.

In this paper, we quantify socio-hydrological feedbacks by characterizing the temporal dynamics of water resources systems at the scale of regional watersheds, individual countries, and the globe. We apply methods from nonlinear dynamics to identify positive and negative feedbacks and other nonlinear behavior in these systems. We study the temporal evolution of two water resources systems: (a) reservoir storage capacity across the globe and in regional-scale watersheds across the United States and (b) global water withdrawals. Nontrivial dynamics characteristics of strongly coupled systems with memory are identified, and the implications of these patterns for socio-hydrological feedbacks and quantitative predictions are discussed.

2. Methodology

The methodology is described below. In section 2.1, the concept of time delays and their use in characterizing socio-hydrological feedbacks is introduced. In sections 2.2 and 2.3, the models used to analyze the data are described. And, finally, in section 2.4, the data used in the analysis are described.

2.1. Socio-Hydrological Feedbacks as Time Delays in Water Resources Systems

Time delays are common features of high-dimensional dynamical systems, with examples in electrical engineering and control theory, multitrophic ecosystem dynamics, and virus replication (Culshaw & Ruan, 2000; Levin et al., 1977; Reddy et al., 2000), as well as in a variety of coupled human-natural systems (Bain et al., 2012; Liu et al., 2007; Manoli et al., 2016; Parolari et al., 2015). Delays may result from temporal or spatial heterogeneity in process rates or system states and imply the existence of coupled subsystems with finite process times. A classic example in population ecology is the finite times required for individuals to reach maturity and for gestation, which effectively decouples the instantaneous population growth rate and population density (Murray, 2002).

Water resources systems in a socio-hydrological context display similar attributes. First, the time between initial project conception, when the need for expanded supply capacity is initially perceived, and construction, when the additional system capacity is available for use, can span several years to decades. Further, because large water resources projects often operate for several decades, the system may carry a legacy of historical management concepts or under or overutilized capacity. For example, initial investigations at Black and Boulder Canyons began in 1902, while Hoover Dam entered operation in 1936 and is still in use today over 80 years later (Simonds, 1995). Second, the emergence of perceived water resources challenges and environmental ethic over time can link present water resources management decisions to decades of past degradation. After 90 years of expansion in the Murrumbidgee River basin, irrigated area, agricultural production, and population substantially declined after widespread environmental degradation, perception of these impacts, and subsequent remediation (Kandasamy et al., 2014). Such memory-generating processes underlie the temporal expansion and contraction of water resources systems and reflect the social, economic, and political subsystems that respond to hydro-climate and water availability and govern water demand and the feasibility of meeting that demand.

Delays in time-series observations of water resources systems can provide foresight into the future evolution of socio-hydrological systems. The presence of time delays implies that the present rate of growth in the system is not independent of the past, and therefore, estimation of these time lags may reveal the time scales of memory dissipation in the socio-hydrological system. In addition, delays can destabilize otherwise stable systems and induce oscillations (Kuang, 1993; Yukalov et al., 2009).

2.2. Punctuated Equilibria in Reservoir Storage Capacity Expansion

Socio-hydrological dynamics can be characterized as an extension of the logistic equation that accounts for the possible positive or negative feedbacks operating within the system. In this framework, human water feedbacks are embedded in a time-varying carrying capacity, $K(t)$, interpreted as the maximum water availability when all water resources are developed, given current technology and social attitudes. The carrying capacity may decrease (destructive, negative feedback) or increase (innovative, positive feedback) as the socioeconomic system grows and either degrades the environment or learns to use available water

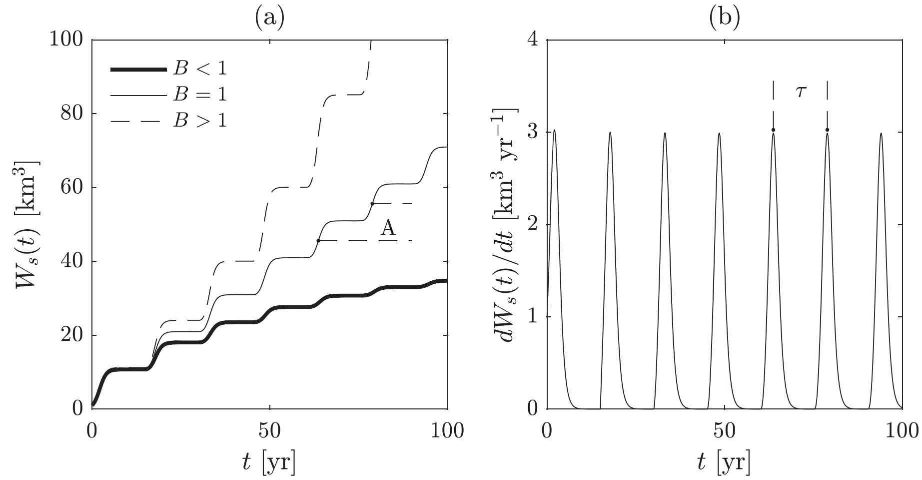

Figure 1. Example water storage capacity trajectories predicted by equation (1): (a) $W_s(t)$ for logistic, exponential, and faster-than-exponential growth patterns and (b) corresponding time-rate of change $\mathrm{d}Ws(t)/\mathrm{d}t$ for exponential growth. Model parameters are $r = 0.1$ km^{-3} year^{-1}, $A = 10$ km^3, and $\tau = 15$ years.

resources more efficiently (Parolari et al., 2015; Von Foerster et al., 1960). The direction and magnitude of these feedbacks may change over time (Kandasamy et al., 2014; Liu et al., 2007; Simonds, 1995; Thompson et al., 2013).

Incorporating this range of possible feedback types, a general time-delayed logistic-type equation for water resources systems can be written as

$$\frac{\mathrm{d}W(t)}{\mathrm{d}t} = rW(t)\left[K(t') - W(t)\right], \tag{1}$$

where $W(t)$ is the water resources system capacity at time t and r is the implicit growth rate of the system capacity. Below, water resources system capacity will be defined as either water storage, W_s, or water withdrawal, W_w. The carrying capacity is defined as

$$K(t') = A + \int_{t-\tau}^{t} B(t')W(t')\mathrm{d}t'. \tag{2}$$

The total carrying capacity combines the carrying capacity in the absence of human activity, A, and a history of the water system capacity weighted by the time-delay kernel $B(t')$. The mathematical form and parameters describing $B(t')$ encode the key positive and negative feedbacks, and their change over time, between the social and hydrological systems.

Equation (1) with equation (2) is a delayed logistic equation with a time-distributed delay, a nonlinear, integro-differential equation that is infinite dimensional and generates a wide range of dynamical behavior (Kuang, 1993; Yukalov et al., 2009). This behavior includes saturating, exponential, and faster-than-exponential growth; decaying and sustained oscillations; and punctuated equilibria (Yukalov et al., 2009). The dynamical regimes of this system can be illustrated for a constant, single-time delay $B(t') = B\delta(t-\tau)$, where δ is the Dirac-delta function that is unity at $t-\tau$ and zero otherwise. When $B = 1$, growth is exponential, and the jump size is A. When $B < 1$, growth is sigmoidal, and the jump size decreases over time at a rate dependent on B. Finally, when $B > 1$, growth is faster than exponential, and the jump size increases over time, again as a function of B. For all values of B, the time between jumps is equal to τ. These regimes are illustrated in Figure 1.

2.3. Punctuated Equilibria in Global Water Withdrawals

To capture the long-term history of global water withdrawals, we employ another growth curve related to equation (1) and previously proposed to describe the evolution of global water use (Parolari et al., 2015) and other complex systems (Sornette, 2002). In general, resource distribution networks driven by socioeconomic systems draw many parallels with metabolic engines, like those that power individual organisms. Resource consumption in both biological and social systems is known to scale predictably with size according to a power law relationship (Bettencourt et al., 2007). For water resources systems, this leads to the following hypothesis for the relationship between capacity and population

$$W(t) = W_0 N(t)^{\beta}, \tag{3}$$

where W_0 is the initial water system capacity, $N(t)$ is the service population at time t, and β is the scaling exponent.

At the global scale, population growth is generally described by a logistic model with carrying capacity K_N. Von Foerster et al. (1960) assumed that $K_N(t) \sim N(t)^{\sigma}$ with $\sigma > 1$ and provided the general solution $N \sim (t - t_c)^{-1/\sigma}$. This model suggests faster-than-exponential population growth and a finite-time singularity at time t_c=2,026 (i.e., the "doomsday") when a regime shift in global population dynamics is predicted to occur (Kaack & Katul, 2013). Hence, from equation (3), it follows that growth in human water use can also be described by a power law, $W \sim (t - t_c)^{\beta^*}$, where t_c is the critical time at which the solution diverges and $\beta^* = -\beta/\sigma$ is the scaling exponent. This type of growth is the solution to a variant of equation (1) with a carrying capacity that scales according to $K \sim W^{1/\beta^*}$ and no logistic-type negative feedback. This form of the carrying capacity assumes that expansion in water use spurs further technological innovation permitting freshwater harvesting, thereby eliminating any carrying capacity limitations on water withdrawals (i.e., a positive feedback).

Punctuated equilibria, which were generated above by the delayed carrying capacity in equation (1), can be introduced to equation (3) by a periodic modulation of the underlying power law growth curve (Johansen & Sornette, 2001; Parolari et al., 2015; Sornette, 2002; Sornette & Sammis, 1995) according to

$$W(t) = a + b(t_c - t)^{\beta^*} + c(t_c - t)^{\beta^*} \cdot cos\left[\omega \cdot ln\left(t_c - t\right) + \phi\right]. \tag{4}$$

Equation (4) replicates the power law growth and punctuated equilibria of equation (1) and reproduces the decrease in interval durations often observed in innovative systems (Bettencourt et al., 2007; Johansen & Sornette, 2001), in contrast to the constant interval duration predicted by equation (1). This model has seven parameters: a, b, c, t_c, β^*, ω, and ϕ. The leading power law term controls growth over time (b and β); the term in the curly brackets characterizes oscillations around this prevailing growth rate (c, ω, and ϕ); and t_c is the critical time at the finite-time singularity (Johansen & Sornette, 2001; Von Foerster et al., 1960). The log-periodic oscillations in equation (4) are analogous to the delay effect in equation (1) and may be related to faster-than-exponential growth behavior in other population dynamics models but incorporating discrete scale invariance (in time) and the complex power law exponent (Saleur et al., 1996; Sornette, 2002).

2.4. Data Analysis

The models above (equations (1)–(4)) are applied to analyze data sets describing the dynamics of reservoirs within the United States and across the globe and the dynamics of global water withdrawals. Dam locations, construction dates, and storage volumes (W_s) were obtained from Global Reservoir and Dam database (Lehner et al., 2011, 2011) and the U.S. National Inventory of Dams (United States Army Corps of Engineers, 2018). To construct the time series, dams were aggregated considering (i) the entire world, (ii) selected countries with different histories and socioeconomic conditions (i.e., United States, China, India, Brazil, United Kingdom, and sub-Saharan Africa), and (iii) the 18 water resources regions (i.e., HUC2 watersheds) defined for the conterminous United States (https://water.usgs.gov/GIS/huc). Hawaii, Alaska, and Puerto Rico were not included in the analysis. Dates corresponding to rapid system growth were identified through the following steps. First, each time series was interpolated by Piecewise Cubic Hermite Interpolating Polynomial (pchip, MATLAB). From the interpolation, the derivative was calculated numerically. Growth periods were selected as maxima in the derivative, corresponding to inflection points in the time series (and the time of maximum growth in the logistic curve). Interval durations were estimated as the times between growth periods and jump sizes were estimated as storage capacity added between growth periods. To isolate substantial growth periods, a minimum jump size threshold was applied. Per capita water storage capacity was calculated using population estimates by the UN World Population Prospects (United Nations, 2019).

Global water withdrawals (W_w) for the twentieth century were obtained from Gleick (2003). Equation (4) was fit to W_w estimates, and the prediction was extended from the present into the past to the Year 3000 BCE (Parolari et al., 2015), based on previously published population and subsistence agriculture per capita water use estimates (Cohen, 1995; Kaack & Katul, 2013). The global water withdrawal rate in 3000 BCE

10.1029/2019EF001185

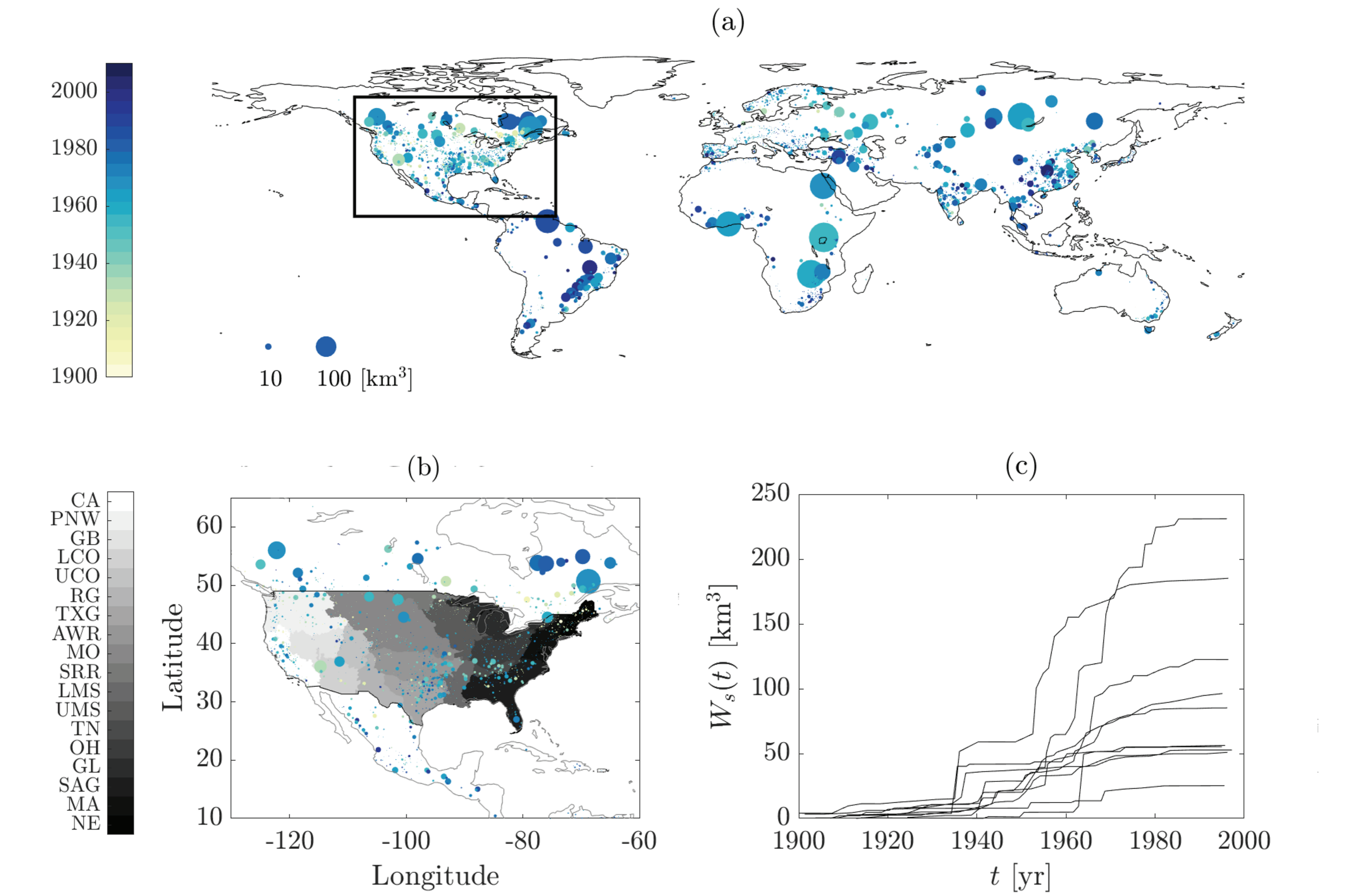

Figure 2. Distribution of dams in (a) the world and (b) the United States. Colors indicate the year of construction, and the marker size indicates the storage capacity W_s. The U.S. hydrologic regions (HUC) are illustrated in (b). Time series of twentieth century reservoir storage capacity expansion in 10 water resources regions of the United States (Graf, 1999) are illustrated in (c).

was estimated assuming a global population of 56.5 million people (Kaack & Katul, 2013) and an average per capita water use of 50 L/day (Cohen, 1995). Equation (4) was fit to the data using nonlinear regression (nlinfit, MATLAB).

3. Results and Discussion

3.1. Reservoir Storage Capacity Growth in the World and the United States

The distribution of reservoir construction date and volume across the world and in the United States is illustrated in Figures 2a and 2b. Punctuated equilibria in water resources systems expansion, like those predicted from equation (1), are clearly shown in time series of reservoir storage capacity (Graf, 1999; Figure 2c). To quantify the rate and magnitude of water resources systems expansion, the time intervals between expansion periods, analogous to τ, and the magnitudes of storage capacity expansion, analogous to A, were estimated at the regional, national, and global scales.

Interval durations between expansion periods represent the time lag between the initial public perception of a water scarcity crisis and the implementation of a solution or, alternatively, the time needed to accumulate sufficient social and financial capital to execute a series of projects. Across nations and watersheds, interval durations are clustered within a relatively narrow range, approximately 5 to 20 years, but may be as long as 70 years (Figures 3a and 3b). China and the United Kingdom exhibit longer average interval times compared to the United States, India, and Brazil. The similarity between China and the United Kingdom is notable given their substantial differences in population and geography. Across the U.S. regional watersheds, relatively large outliers are found in the Lower Colorado, New England, Souris-Red-Rainy, and Upper Mississippi regions; whereas relatively small outliers are found in the Arkansas-White-Red, South Atlantic-Gulf, and

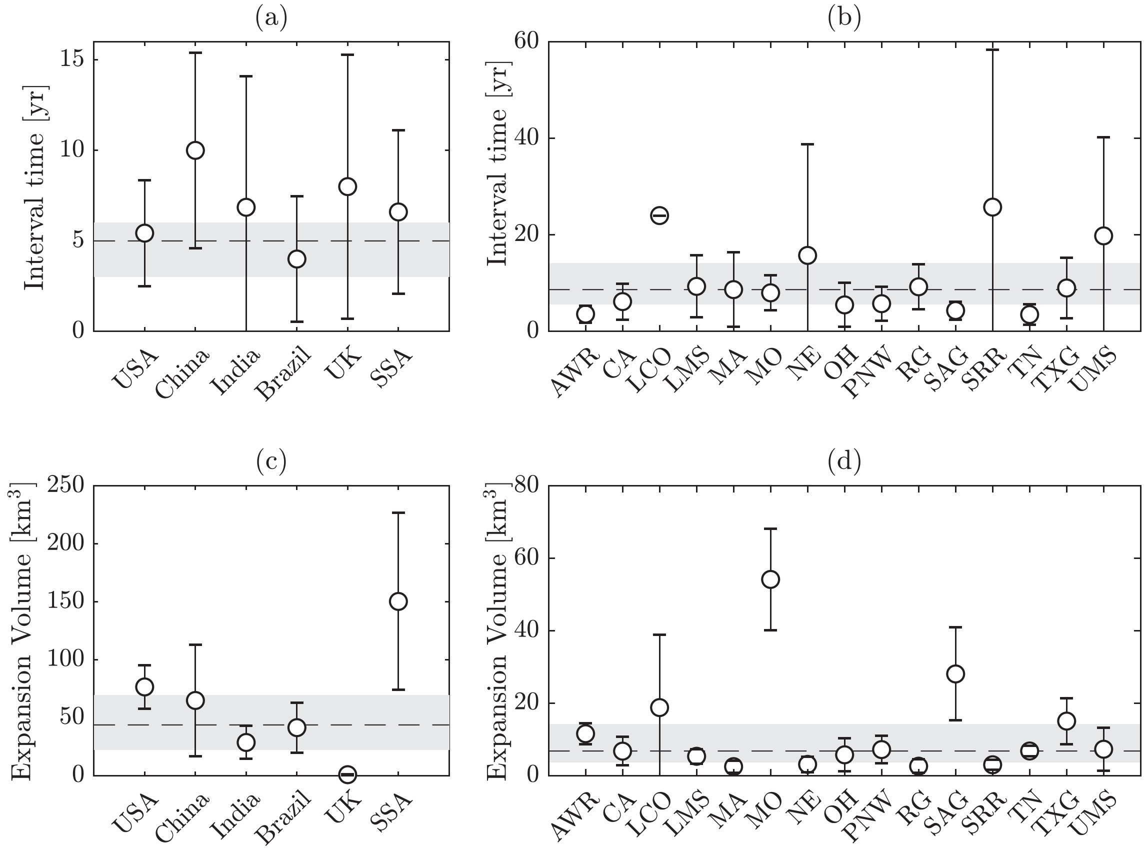

Figure 3. Estimates of interval duration between storage expansion (a,b) and volume added during expansion (c,d) for twentieth century reservoir storage capacity development in (a,c) United States, China, India, Brazil, United Kingdom, and sub-Saharan Africa and (b,d) the 15 water resources regions of the United States. Circles indicate mean values, while error bars indicate ±1 standard deviation for each country or region. The dashed line indicates the median, and the colored regions indicates the 25% and 75% quantiles across the 5 countries and the 15 water resources regions. Region abbreviations are AWR (Arkansas-White-Red) CA (California), LCO (Lower Colorado), LMS (Lower Mississippi), MA (Mid-Atlantic), MO (Missouri), NE (New England), OH (Ohio), PNW (Pacific Northwest), RG (Rio Grande), SAG (South Atlantic Gulf), SRR (Souris-Red-Rainy), TN (Tennessee), TXG (Texas Gulf), and UMS (Upper Mississippi).

Tennessee regions. Variability in interval times between regions and countries may indicate variability in economic or political drivers that determine when a new reservoir can be constructed.

Expansion volumes represent the increase in capacity at each innovation period and may be related to storage cost or surface water availability (Graf, 1999). Across countries, average expansion volumes range from 0.6 (United Kingdom) to 150 (sub-Saharan Africa) km^3 (Figure 3c). Sub-Saharan Africa had the largest average expansion volume, owing to a small number of large reservoirs (see Figure 2). The average expansion volume across all U.S. regional watersheds was 13 km^3 (Figure 3d), approximately equal to the volume of the Roosevelt Reservoir behind Grand Coulee dam. In general, expansion volumes are consistent with total reservoir storage within each region, as reported by Graf (1999). For example, the Missouri and South Atlantic-Gulf regions experienced much larger expansion volumes than the other regions. These are the two regions with the largest area, number of dams, and storage volume (Graf, 1999). This may indicate higher surface water availability and, therefore, socio-hydrological regimes that rely heavily on surface water.

Empirical interval durations and expansion volumes varied over time (Figure 4). At the country level, no clear trends were identified, while in the U.S. regions, expansion volumes exhibited a peak in the middle of the twentieth century, whereas interval durations decreased consistently. Implications of such temporal variability on system stability can be characterized by further analysis of equation (1) with $B(t-s) = B\delta(t-\tau)$. Stability of the steady state $W_\infty = K$ depends on the parameters τ and B. When $B < 0$, the system loses stability as τ increases through two successive dynamical regimes: a stable limit cycle and oscillations to finite-time death (Yukalov et al., 2009). Further, the steady state may be destabilized by increasing expansion volumes over time. In this case, the system shifts to faster-than-exponential growth, revealing a finite-time

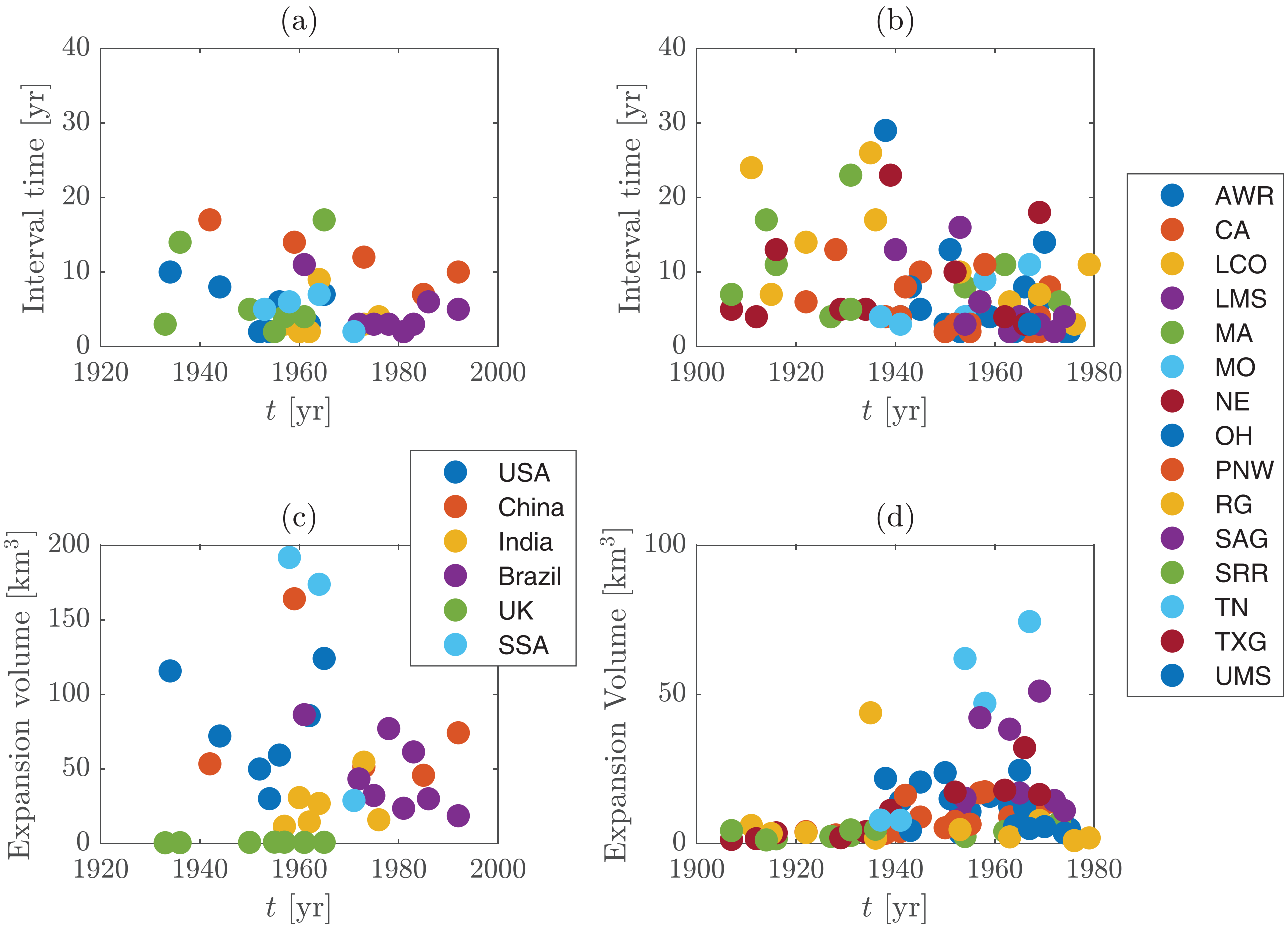

Figure 4. Trajectories of interval duration between storage expansion (a,b) and volume added during expansion (c,d) over time for twentieth century reservoir storage capacity development in (a,c) United States, China, India, Brazil, United Kingdom, and sub-Saharan Africa and (b,d) the 15 water resources regions of the United States.

singularity that fingerprints the existence of a future regime shift. Therefore, the risk of destabilization is larger in more rapidly growing systems and systems with longer delays. Both interval durations and expansion volumes have decreased over time in recent years, indicating a stabilizing behavior in the coupled socio-hydrological dynamics of reservoir storage capacity growth in the United States (Figure 5a). A similar saturation trend was found at the global scale and for sub-Saharan Africa, while countries such as Brazil and China were still in a growth phase.

The observed sigmoidal growth in reservoir capacity expansion is consistent with many social, economic, and physical factors that have contributed to a decreased rate of expansion in recent history. As reservoirs are constructed, there is necessarily a decrease in the number of undammed rivers and available dam sites. Second, growing public perception of the negative ecological impacts of dams, including sediment and pollutant trapping and impeded fish migration, caused decreased public support for reservoir construction and even strong campaigns for dam removal (Doyle et al., 2008). Finally, the advent of new technologies to increase water system resilience, such as water reuse, groundwater storage, and desalination, as well as green energy substitutions for hydropower, has provided alternatives to the traditional reservoir solution.

3.2. Scaling of Water Resources System Capacity With Population

Per capita water storage and water withdrawals showed varying trends across countries and the world (Figure 5). Globally, per capita water storage and water withdrawals increased until the 1980s and then decreased. A similar trend occurred in the United States, while in sub-Saharan Africa, the decline began in the 1960s. This trend indicates that the rate of population growth is now faster than the rate of water resources system capacity growth. In contrast, reservoir storage capacity in countries such as China and Brazil continues to grow in both absolute (Figure 5a) and per capita (Figure 5b) terms. Sub-Saharan Africa

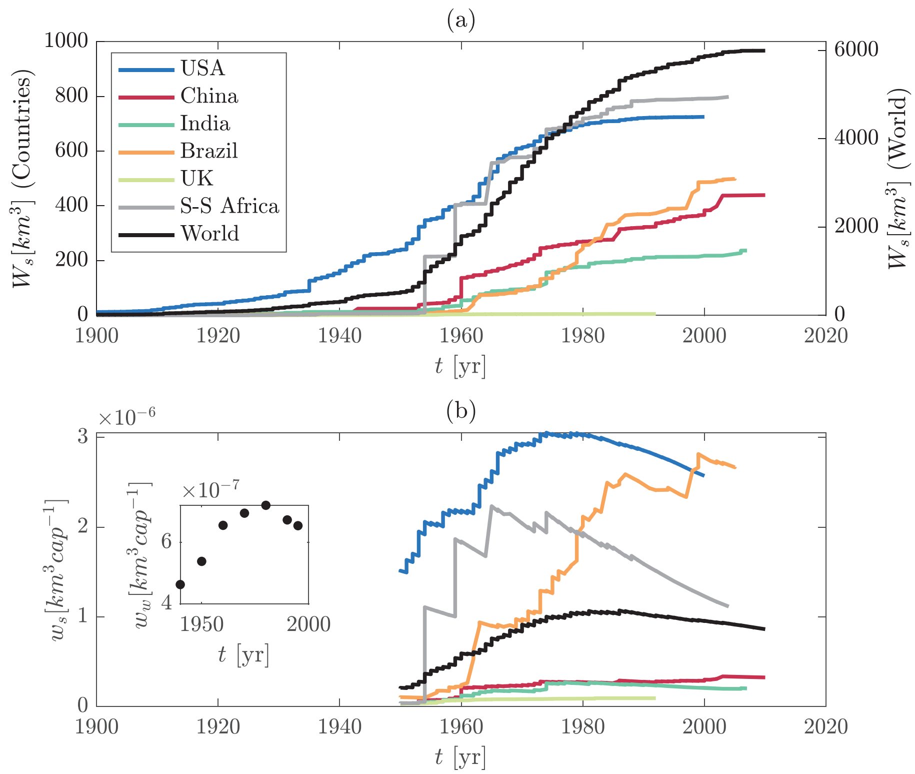

Figure 5. Historical evolution of (a) reservoir storage capacity and (b) per capita reservoir storage capacity in the United States, China, India, Brazil, United Kingdom, and sub-Saharan Africa, and the world. Estimates of per capita global water withdrawals(Gleick, 2003) are also shown (inset in (b)).

exhibited a unique trajectory driven by a few large projects, such as Lake Kariba on the Zambezi River and Lake Volta on the Volta River. In addition, rapid population growth is evident in the downward trajectory in per capita storage for sub-Saharan Africa.

The power law exponent, β, of equation (3) captures the coupling between population and water resources systems dynamics. Water withdrawals at the global scale follow a superlinear scaling with global population ($\beta = 1.46$; see Figure 6). This scaling relationship indicates innovative, positive feedback between water use and population that yields increasing returns. That is, increased water use facilitates further increases in water use. Consequently, global water withdrawals appear to have grown at a faster-than-exponential rate ($\beta^* = -2.13$) for the past five millennia (Figure 7a). Faster-than-exponential growth emerges when the rate of growth is proportional to the system state raised to a power greater than one (superlinear growth), indicating that the growth rate increases with the system capacity and the two are engaged in a positive feedback.

In contrast, the global water storage capacity grew superlinearly until the 1970s, but the growth rate transitioned to sublinear conditions during the 1980s, causing a stabilization over more recent decades (Figure 6). This stabilization, together with the growth in global population, has caused a decline in global per capita water storage (Figure 5b). The storage capacity of reservoirs represents a buffer to external perturbations, ensuring the resilience of socioeconomic systems to adverse climatic fluctuations (e.g., extreme drought events). Hence, a decrease in storage capacity associated with the observed power law growth in water consumption implies that society is becoming increasingly reliant on water resources fluctuations and less resilient to climate variability. In the context of future population growth and climate change (Lehner et al., 2017), these results highlight the need to identify and design solutions for more resilient socio-hydrological systems.

The observed saturation of storage expansion is consistent with the observed increase in the volume and number of connections of the global virtual water trade associated with the global trade of food and other commodities (Dalin et al., 2012). This suggests a shift from real to virtual water use. Such a reliance on

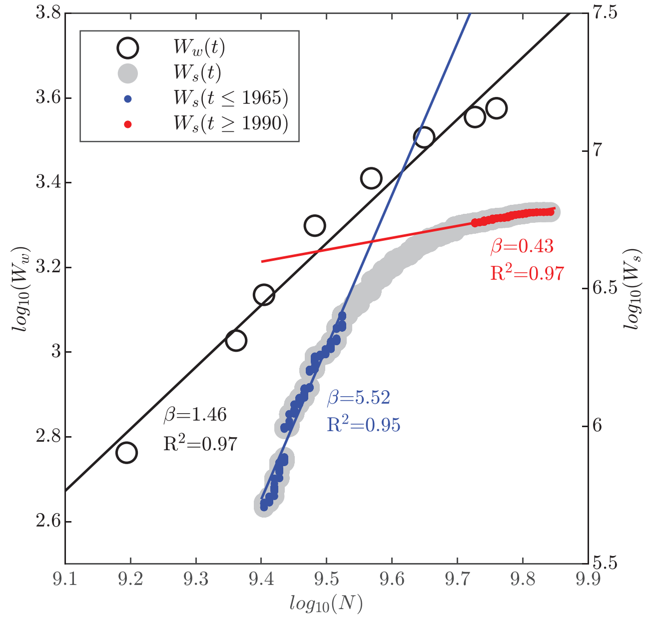

Figure 6. Scaling of global water withdrawals (W_w) and global storage capacity (W_s) with population (N). Symbols represent observations, and lines represent linear regressions. W_s data are fitted for two separate periods, before 1965 and after 1990, corresponding to rapid and saturating storage expansion, respectively.

international trade may enhance global water resource use efficiency (Dalin et al., 2012) but may also reduce the ability to cope with water scarcity at the local or regional level. These impacts, however, can be mitigated by the structure, design, and management of local water resources networks (Mamede et al., 2012).

3.3. A Historical Perspective on Global Scale Water Crisis and Innovation

The log-periodic, power law growth model (equation (4)) aligns with commonly held anecdotes regarding historical population growth, technological advances, and water resources development at the global scale (Vuorinen et al., 2007). Five periods of alternating water resources innovation and crisis were identified in the model-data-history synthesis illustrated in Figure 7: (1) Local Agricultural Revolution to the Roman Empire (3000 BCE to 450 CE), (2) Expansion of urban areas and regional water distribution systems (450 to 1500 CE), (3) Industrial Revolution (1500 to 1870 CE), (4) Global Agricultural (or "Green") Revolution (1870 to 2010 CE), and 5) Rapid global industrial expansion (2010 CE to the present). Each of these innovation periods is punctuated by a period of crisis, during which no growth occurs. The length of innovation and crisis periods become increasingly shorter, and the innovation jumps larger, over time. In systems with faster-than-exponential growth, "continuous growth necessitates an accelerating treadmill of dynamical cycles of innovation" (Bettencourt et al., 2007) and, therefore, may be unsustainable given a finite water resource availability.

Per capita water use indicates the water-use intensity of social and economic structures prevalent during each historical regime, and the prediction suggests that this intensity increased markedly throughout history. During the Local Agricultural Revolution and the first urbanization, that is, over 4,000 years of history, per capita water use remained below approximately 50 m^3 per person per year, consistent with prior estimates for subsistence agriculture with irrigation (Cohen, 1995). Owing to drastic changes in socioeconomic activity and living standards, this water-use intensity has risen to over 700 m^3 per person per year today. Despite recent improvements in water-use efficiency (Gleick, 2003; see Figure 5), this expanded historical context demonstrates that these local changes are superimposed over a long-range rise in human water use over the entire modern history (Parolari et al., 2015). That is, the massive scale of today's global water resources system resulted from both the addition of six billion people and an over tenfold increase in the water-use intensity of human activity. This result depends on the power law growth model fits to both population and water use. However, it is robust as long as the growth rate of water use is greater than that of population, which is clearly demonstrated in Figure 6. Further, we note the ability of the power law growth

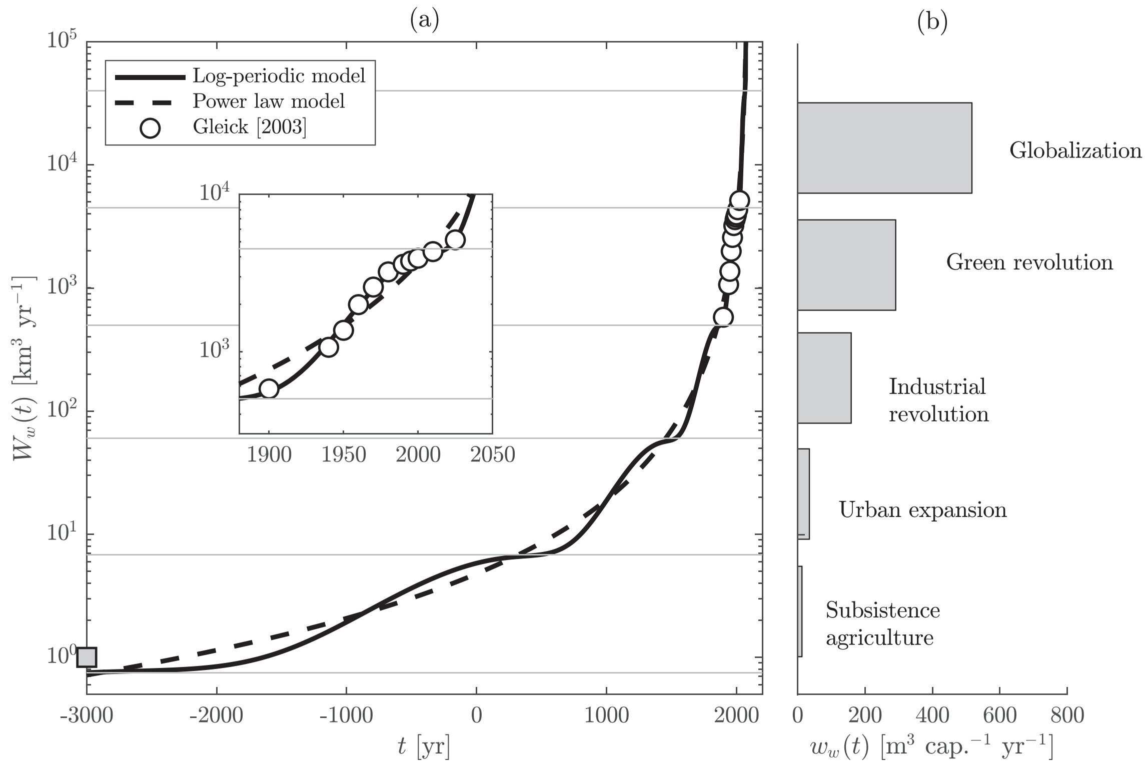

Figure 7. Modeled historical evolution of (a) global water withdrawals and (b) per capita water use as informed by the power law growth model (Parolari et al., 2015) and anecdotal evidence. The dashed curve is the power law growth curve without log-periodic oscillations, the bold curve is generated from equation 4, the white circles are empirical global water withdrawal estimates, and the gray symbol (square) at $t = 3000$ BCE indicates an estimate of global water use prior to the Local Agricultural Revolution, corresponding to societies supported by subsistence agriculture with no irrigation. For equation (4), the estimated parameters are $a = 0$, $b = 5.65 \times 10^7$, $t_c = 2,092.5$, $c = 1.58 \times 10^7$, $\beta = -2.13$, $\omega = 6.23$, and $\phi = 2.02$. The inset shows the Gleick (2003) data from the most recent century.

model to backcast global water use several millennia, whereas exponential and logistic growth models are unable to do so (Parolari et al., 2015).

4. Conclusions

Our analysis of the long-term evolution of water resources infrastructure systems provides analytical foresight into the dynamics of socio-hydrological systems. Using data and models, nontrivial dynamics were identified, including punctuated equilibria superimposed over sigmoidal growth in the temporal evolution of reservoir storage capacity and faster-than-exponential growth with periodic oscillations in global water use over the past five millennia. From a theoretical viewpoint, delay differential equations were found to generate realistic dynamics consistent with observations, suggesting a useful framework for low-dimensional quantitative analysis of socio-hydrological systems. These results can be used to inform the development of model structures that couple population, water resources infrastructure, and hydrologic processes.

Reservoir storage capacity innovations and their characteristic time scales are indicative of the action of socio-hydrological feedbacks emergent at global, national, and regional scales. Estimated delays in reservoir storage capacity growth suggest a strong coupling between reservoir construction and the balance of water storage supply and demand at intervals 5 to 20 years in the past. These values are considered a first-order estimate of the lag between the initial public perception of a water scarcity crisis and the implementation of a solution or, alternatively, the time needed to accumulate sufficient social and financial capital to execute a series of projects. When placed in the context of the analytical results (Kuang, 1993; Yukalov et al., 2009), the presence of such lags suggests that water resources systems can be destabilized if the interval duration exceeds a critical threshold, leading to oscillations or rapid disruption. Because the delay couples the present growth rate to the state history, this implies that long delays (i.e., memory is dissipated at a slower rate) decrease the system capacity to respond to change. The need for updated water resources systems management practices that focus on resilience, through changes in design longevity and adaptability, is thus highlighted.

The possibility of faster-than-exponential, power law growth of water use at the global scale diagnoses a positive socio-hydrological feedback powered by water use. Since the initial agricultural revolution, human appropriation of water has permitted the development of social and economic structures upon which technology was advanced toward further increased rates of water resources development. Log-periodic oscillations superimposed over this underlying power law growth trend suggest periods of rapid water resources development were interspersed by periods of relative stagnation or crisis. These periods are characteristic of negative socio-hydrological feedback and are overcome at regular intervals by social and technological change that reinvigorates the positive feedback. The presence of power law growth and punctuated equilibria at a range of scales suggests that this modeling framework may be robust across different scales of analysis.

There remains a wide range of open questions to close the gap between the macroscopic approaches employed here and a detailed characterization of the state variables and feedbacks in coupled socio-hydrological systems, of which two are emphasized here. First, quantitative analyses will require a holistic view of water resources than what was achieved here, integrating reservoir storage, groundwater storage, desalination capacity, and virtual water. Second, social, economic, and political regimes respond to hydro-climatic change factors, such as drought and flood, both over spatial and temporal gradients. Therefore, attention is needed to classify the internal dynamics of socio-hydrological systems separately from their external, stochastic drivers. A complete quantitative theory of socio-hydrological systems promises to illuminate opportunities for social, economic, and engineering advances toward future water security.

Acknowledgments
G. M. was supported by "The Branco Weiss Fellowship - Society in Science" administered by ETH Zurich. A. J. P. was supported by the United States Department of Energy through the Office of Biological and Environmental Research, Terrestrial Ecosystem Science program (DE-SC0006967) and the Marquette University Opus College of Engineering. We thank Gabriel Katul and Amilcare Porporato for their constructive comments on an early version of this manuscript. The Global Reservoir and Dam database can be retrieved online (at https://sedac.ciesin.columbia.edu/data/set/grand-v1-reservoirs-rev01), the U.S. National Inventory of Dams can be retrieved online (at https://nid.sec.usace.army.mil/), and the United Nations World Population Prospects can be retrieved online (at https://population.un.org/wpp/).

References

Bain, D. J., Green, M. B., Campbell, J. L., Chamblee, J. F., Chaoka, S., Fraterrigo, J. M., et al. (2012). Legacy effects in material flux: Structural catchment changes predate long-term studies. *Bioscience*, *62*(6), 575–584.

Bettencourt, L. M., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the national academy of sciences*, *104*(17), 7301–7306.

Cohen, J. E. (1995). How many people can the Earth support? *The Sciences*, *35*(6), 18–23.

Culshaw, R. V., & Ruan, S. (2000). A delay-differential equation model of HIV infection of CD4+ T-cells. *Mathematical Biosciences*, *165*(1), 27–39.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., & Rodriguez-Iturbe, I. (2012). Evolution of the global virtual water trade network. *PNAS; Proceedings of the National Academy of Sciences*, *109*(16), 5989–5994.

Doyle, M. W., Stanley, E. H., Havlick, D. G., Kaiser, M. J., Steinbach, G., Graf, W. L., et al. (2008). Aging infrastructure and ecosystem restoration. *Science*, *319*(5861), 286–287.

Gleick, P. H. (2003). Water use. *Annual Review of Environment and Resources*, *28*(1), 275–314.

Gleick, P. H., & Palaniappan, M. (2010). Peak water limits to freshwater withdrawal and use. *Proceedings of the National Academy of Sciences*, *107*(25), 11,155–11,162.

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research*, *35*(4), 1305–1311. https://doi.org/10.1029/1999WR900016

Johansen, A., & Sornette, D. (2001). Finite-time singularity in the dynamics of the world population, economic and financial indices. *Physica A: Statistical Mechanics and its Applications*, *294*(3), 465–502.

Kaack, L. H., & Katul, G. G. (2013). Fifty years to prove Malthus right. *Proceedings of the National Academy of Sciences*, *110*(11), 4161–4162.

Kandasamy, J., Sounthararajah, D., Sivabalan, P., Chanan, A., Vigneswaran, S., & Sivapalan, M. (2014). Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: A case study from Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences*, *18*, 1027–1041.

Kuang, Y. (1993). *Delay differential equations: With applications in population dynamics* (Vol. 191). Boston: Academic Press.

Lehner, F., Coats, S., Stocker, T. F., Pendergrass, A. G., Sanderson, B. M., Raible, C. C., & Smerdon, J. E. (2017). Projected drought risk in 1.5°C and 2°C warmer climates. *Geophysical Research Letters*, *44*, 7419–7428. https://doi.org/10.1002/2017GL074117

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., et al. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494–502.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., et al. (2011). Global reservoir and dam database, version 1 (grandv1): Reservoirs, revision 01. https://sedac.ciesin.columbia.edu/data/set/grand-v1-reservoirs-rev01, Accessed: 25 September 2019.

Levin, B. R., Stewart, F. M., & Chao, L. (1977). Resource-limited growth, competition, and predation: A model and experimental studies with bacteria and bacteriophage. *The American Naturalist*, *111*(977), 3–24.

Linton, J., & Budds, J. (2014). The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum*, *57*, 170–180.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., et al. (2007). Complexity of coupled human and natural systems. *Science*, *317*(5844), 1513–1516.

Mamede, G. L., Araújo, N. A. M., Schneider, C. M., de+Araújo, J. C., & Herrmann, H. J. (2012). Overspill avalanching in a dense reservoir network. *PNAS; Proceedings of the National Academy of Sciences*, *109*(19), 7191–7195.

Manoli, G., Katul, G. G., & Marani, M. (2016). Delay-induced rebounds in CO_2 emissions and critical time-scales to meet global warming targets. *Earth's Future*, *4*, 636–643. https://doi.org/10.1002/2016EF000431

Montgomery, M. A., & Elimelech, M. (2007). Water and sanitation in developing countries: Including health in the equation.
Murray, J. (2002). Mathematical biology: I. An introduction.
Parolari, A. J., Katul, G. G., & Porporato, A. (2015). The doomsday equation and 50 years beyond: New perspectives on the human-water system. *Wiley Interdisciplinary Reviews: Water*, *2*(4), 407–414.
Postel, S. L., Daily, G. C., & Ehrlich, P. R. (1996). Human appropriation of renewable fresh water. *Science*, *271*, 785–788.
Reddy, D. R., Sen, A., & Johnston, G. L. (2000). Experimental evidence of time-delay-induced death in coupled limit-cycle oscillators. *Physical Review Letters*, *85*(16), 3381.
Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jägerskog, A., et al. (2014). The unfolding water drama in the anthropocene: Towards a resilience-based perspective on water for global sustainability. *Ecohydrology*, *7*(5), 1249–1261.
Saleur, H., Sammis, C. G., & Sornette, D. (1996). Discrete scale invariance, complex fractal dimensions, and log-periodic fluctuations in seismicity. *Journal of Geophysical Research*, *101*(B8), 17,661–17,677.
Simonds, W. J. (1995). The Boulder Canyon Project: Hoover Dam. Bureau of Reclamation History Program.
Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C., et al. (2014). Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future*, *2*, 225–230. https://doi.org/10.1002/2013EF000164
Sivapalan, M., Savenije, H. H., & Blöschl, G. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes*, *26*(8), 1270–1276.
Sornette, D. (2002). Predictability of catastrophic events: Material rupture, earthquakes, turbulence, financial crashes, and human birth. *Proceedings of the National Academy of Sciences*, *99*(suppl 1), 2522–2529.
Sornette, D., & Sammis, C. G. (1995). Complex critical exponents from renormalization group theory of earthquakes: Implications for earthquake predictions. *Journal de Physique I*, *5*(5), 607–619.
Thompson, S., Sivapalan, M., Harman, C., Srinivasan, V., Hipsey, M., Reed, P., et al. (2013). Developing predictive insight into changing water systems: Use-inspired hydrologic science for the Anthropocene. *Hydrology and Earth System Sciences*, *17*(12), 5013–5039.
United Nations (2019). World population prospects 2019. https://population.un.org/wpp/, Accessed: 13 September 2019.
United States Army Corps of Engineers (2018). National inventory of dams. https://nid.sec.usace.army.mil/, Accessed: 25 September 2019.
Viglione, A., Di Baldassarre, G., Brandimarte, L., Kuil, L., Carr, G., Salinas, J. L., et al. (2014). Insights from socio-hydrology modelling on dealing with flood risk–roles of collective memory, risk-taking attitude and trust. *Journal of Hydrology*, *518*, 71–82.
Von Foerster, H., Mora, P. M., & Amiot, L. W. (1960). Doomsday: Friday, 13 November, AD 2026. *Science*, *132*(3436), 1291–1295.
Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., et al. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555.
Vuorinen, H., Juuti, P., & Katko, T. (2007). History of water and health from ancient civilizations to modern times. *Water Science and Technology: Water Supply*, *7*(1), 49–57.
Yukalov, V. I., Yukalova, E., & Sornette, D. (2009). Punctuated evolution due to delayed carrying capacity. *Physica D: Nonlinear Phenomena*, *238*(17), 1752–1767.