Opinion

The Doomsday Equation and 50 years beyond: new perspectives on the human-water system

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In 1960, von Foerster et al. humorously predicted an abrupt transition in human population growth to occur in the mid-21st century. Their so-called 'Doomsday' emerged from either progressive degradation of a finite resource or faster-than-exponential growth of an increasingly resource-use efficient population, though what constitutes this resource was not made explicit. At present, few dispute the claim that water is the most fundamental resource to sustainable human population growth. Multiple lines of evidence demonstrate that the global water system exhibits nontrivial dynamics linked to similar patterns in population growth. Projections of the global water system range from a finite carrying capacity regulated by accessible freshwater, or 'peak renewable water,' to punctuated evolution with new supplies and improved efficiency gained from technological and social innovation. These projections can be captured, to first order, by a single delay differential equation with human–water interactions parameterized as a delay kernel that links present water supply to the population history and its impacts on water resources. This kernel is a macroscopic representation of social, environmental, and technological factors operating in the human-water system; however, the mathematical form remains unconstrained by available data. A related model of log-periodic, power-law growth confirms that global water use evolves through repeated periods of rapid growth and stagnation, a pattern remarkably consistent with historical anecdotes. Together, these models suggest a possible regime shift leading to a new phase of water innovation in the mid-21st century that arises from delayed feedback between population growth and development of water resources.

How to cite this article:
WIREs Water 2015. doi: 10.1002/wat2.1080

INTRODUCTION

From the 17th century today, the focus of the sustainability debate has evolved from the global human carrying capacity to the modern challenge of balanced social and ecological objectives given Earth's finite resource base.[1–7] Along the way, it was recognized that feedback between Earth's resources and human inhabitants portends a wide range of consequences for the sustainability of future human population growth. A key point that emerged concerns whether a large population uses available resources more efficiently, through advanced social and technological innovation, or less efficiently, through progressive resource degradation.

In 1960, von Foerster et al.[2] invigorated this debate in a quantitative analysis that demonstrated how human-resource feedback inevitably leads to a regime change in global human population growth, regardless of how the resource-use efficiency changes over time. They opposed 'pessimistic' and 'optimistic' views that hypothesized a respective decreased or increased growth rate as the population grows. The

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Conflict of interest: The authors have declared no conflicts of interest for this article.

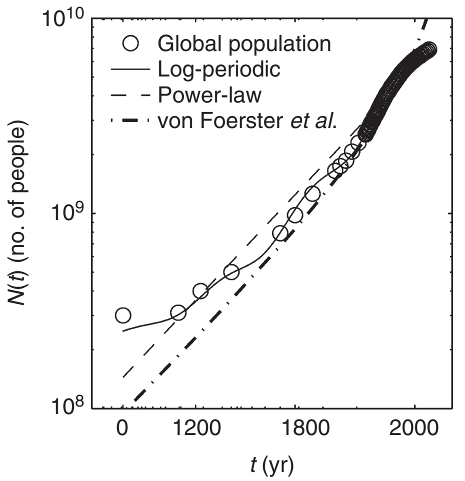

FIGURE 1 | Power-law growth in global human population.[7] The solid line is a log-periodic fit, described in Equation (7), with parameters $a = 1.98 \cdot 10^8$, $b = 1.66 \cdot 10^{12}$, $t_c = 2062.7$, $c = 1.82 \cdot 10^{11}$, $\beta = -1.37$, $\omega = 5.82$, and $\phi = 6.17$. The dashed line is a power-law fit, $N(t) = k(t_c - t)^{-1/\delta}$ with $k = 4.2 \cdot 10^{11}$, $t_c = 2062.7$, and $\delta = 0.957$. The dot-dashed line is the original power-law fit by von Foerster et al.[2] with $k = 1.8 \cdot 10^{11}$, $t_c = 2026.9$, and $\delta = 1.01$.

pessimistic view coincides with the classic logistic curve, whereby the per capita growth rate decreases linearly with population, N, and N approaches a constant carrying capacity, K, inherent to any closed system. That is, a large N uses available resources less efficiently. Conversely, the optimistic view reasoned,[2]

> it is not absurd to assume that an increase in [individuals] may produce a more versatile and effective coalition and thus not only may render environmental hazards less effective but also may improve the living conditions beyond those found in a 'natural setting.'

They approached this possibility by assuming that in an open system, K increases with N according to a power law, $K = rN^{\delta}$ with $\delta > 0$. In the resulting solution, $N(t) \propto (t_c - t)^{-1/\delta}$, which grows at a faster-than-exponential rate and 'explodes' to infinity at a finite critical time t_c.[2,8]

Population records confirm that the human population on Earth has been growing at a faster-than-exponential rate (Figure 1) and a 'Doomsday' singularity is anticipated to occur within the next 50 years.[2,7,8] While such a singularity is associated with infinite N and K, this is unlikely to occur on a finite-sized planet. Prediction of the singularity merely fingerprints a regime shift where the dynamics describing N for $t > t_c$ differ from those for $t \ll t_c$, as may occur if N dramatically declines.

Given faster-than-exponential population growth and a finite supply of freshwater, the future and sustainability of the global water supply remain elusive. The evolution of water systems has been suggested to follow a wide range of temporal patterns, including saturation to peak renewable water, overshoot of nonrenewable water, and punctuated evolution with successive regimes shifts.[6,9] Further, models of the global coupled human-water system indicate that a mid-century regime shift in population growth may be driven by global water scarcity.[7,10] Following von Foerster et al., recent analyses have proposed a link between resource availability and population history to explain nontrivial consumer-resource dynamics such as punctuated evolution and faster-than-exponential growth.[3,8,11–13] We are of the opinion that a similar quantitative approach that accounts for the interaction between water use and population history can assist in delineating future trajectories of coupled human-water systems and may uncover new alternatives as more data become available. Below, we explore theoretical, empirical, and anecdotal avenues to characterize the global human-water system dynamics in this context.

PAST AND FUTURE EVOLUTION OF THE GLOBAL HUMAN-WATER SYSTEM

The following discussion considers the merits of three methods to analyze the history and predict the future of the global human-water system: quantitative theory, data analysis, and conceptual (or anecdotal) models. First, a model of coupled population-resource dynamics is introduced and shown to reproduce the typical dynamics of water supply systems. Second, statistical models are applied to global population and water withdrawal estimates for the 20th century to infer the nature of observed human-water system dynamics. Finally, anecdotal evidence is combined with the model and the data to foreshadow possible futures for the human-water system.

Minimalist Models of Coupled Human-Water System Dynamics

The familiar starting point for population dynamics is the logistic equation,

$$\frac{dN}{dt} = rN(K - N), \tag{1}$$

where N is the number of individuals at time t, r is the growth rate, and K is the carrying capacity. For small N, the population grows exponentially at a rate rK in the absence of resource limitation. As N grows, resource limitation develops, the growth rate decreases to 0, and N levels off at K. The assumption of a constant $K>0$ is equivalent to a per capita growth rate that declines linearly with N (i.e., $\frac{1}{N}\frac{dN}{dt} \propto -rN$).

Alternative hypotheses of environmental degradation or improved resourcefulness on a densely populated planet can be introduced into Equation (1) using a dynamic carrying capacity $K[N(t)]$. One modification assumes a linear response,[3]

$$K\left[N(t)\right] = A + BN(t), \tag{2}$$

where the sign of B signifies whether increased N has an adverse or positive effect on K and A reflects a background carrying capacity in the absence of human activity. Equation (1) with Equation (2) is a one-dimensional ordinary differential equation (ODE) whose general solution is a logistic curve for all values of B,

$$N(t) = \frac{N_0 \exp(Art)}{1 - \frac{(B-1)}{A} N_0 \left[\exp(Art) - 1\right]}, \tag{3}$$

where N_0 is an initial population set at a reference time $t=0$.

The dynamics of Equation (3) depend on the parameter B,[3] or the sensitivity of K to N (i.e., $\frac{\partial K}{\partial N} = B$). When $B<1$, growth is logistic with time-dependent K and for the special case $B=0$, the standard logistic equation with constant $K=A$ is recovered. When $B=1$, growth is exponential with rate rA. When $B>1$, growth is faster-than-exponential with a finite-time singularity at the critical time,

$$t_c = \frac{1}{rA} \ln\left[\frac{A}{(B-1)N_0} + 1\right]. \tag{4}$$

This t_c is obtained by noting that the denominator of Equation (3) reaches 0 when $N \to \infty$.

Lags between social and ecological dynamics imply that K may not respond to N instantaneously, as assumed in Equation (2). A further generalization represents this response as a time-delay kernel, $B(t)$, that links the current K to a parameterized time-history of N,

$$K\left[N(t)\right] = A + \int_{t-\tau}^{t} B\left(t'\right) N\left(t'\right) dt', \tag{5}$$

where the period τ represents the range of population history embedded in the current K. Equation (1) with Equation (5) constitutes a delay differential equation (DDE), where the rate of change of N in time depends on the history of N. The kernel $B(t)$ embeds the effects of past resource use on current resource availability and, in theory, can account for an infinite number of timescales associated with the consumption and regeneration of essential resources. This DDE encapsulates previously observed and hypothesized dynamics of the human-water system (or generic consumer-resource systems), including finite-time singularity (or death), sustained or decaying oscillations, punctuated evolution, exponential or logistic-type growth, and bistability.[11]

To demonstrate the application of the DDE to coupled human-water system dynamics, the kernel $B(t) = B\delta(t-\tau)$ is chosen, where $\delta(0)=1$ and 0 otherwise.[11] That is, the carrying capacity depends only on the population τ years in the past. With this assumption, a single DDE for the population is written as,

$$\frac{dN(t)}{dt} = rN(t)\left[A + BN(t-\tau) - N(t)\right], \tag{6}$$

from which $K(t)$ can be directly computed as the first two terms in the brackets. Two examples of human-water system dynamics generated by Equation (6) are shown in Figure 2—punctuated evolution to peak renewable water and overshoot of nonrenewable water. Punctuated evolution occurs when the population is innovative and increasingly efficient and grows faster than the carrying capacity (i.e., $0<B<1$). On the other hand, overshoot occurs when the population is destructive and increasingly inefficient (i.e., $-1<B<0$). Overshoot also requires that the natural carrying capacity is initially large relative to the population (i.e., $A>|B|N(t=0)$). These examples support our opinion that the aforementioned concepts and associated projections such as saturation to peak renewable water, overshoot of nonrenewable water, and punctuated evolution with successive regime shifts are tied to $B(t)$.

Other studies expanded on this minimalist framework to explicitly represent the underlying physical processes that link socioeconomic dynamics to the earth system. The simplest of these models are also exploratory and couple human population dynamics to one or more biosphere resources, such as biomass.[14,15] These models are similar to Equation (2), except that the $K(t)$ emerges from the coupled human-resource dynamics rather than being imposed as a function of $N(t)$. Theoretically, such multidimensional ODE models can be extended to include any number of natural resources. Indeed, more complex approaches fully integrate population, economic, and resource dynamics within global models that account for multiscale dynamics of the global coupled water–carbon cycle (e.g., 'Integrated Assessment' models[16]). While these models may support more accurate forecasts, the large number of required

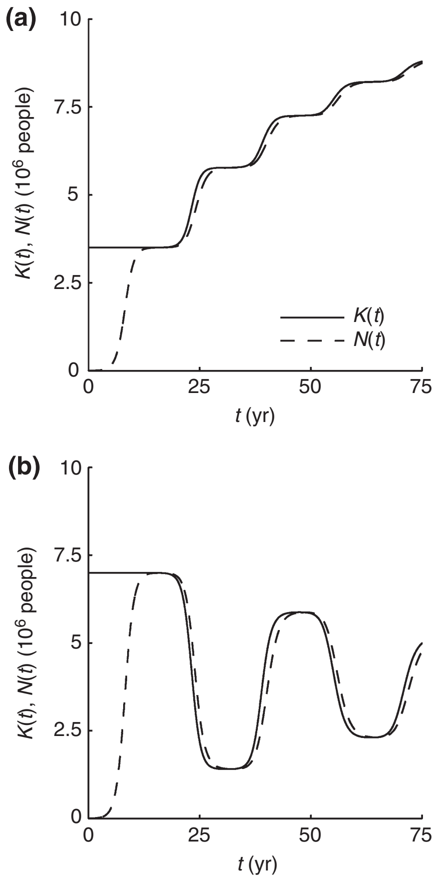

FIGURE 2 | Conceptual models of renewable (a) and nonrenewable (b) water use. In these examples, the delay kernel from Yukalov et al.[11] is adopted, which can be written as $B(t)=B\,\delta\,(t-\tau)$, where $\delta(0)=1$ and 0 otherwise. In (a) $B=0.65$ and in (b) $B=-0.8$. Common parameters are $A=3.5\cdot 10^6$, $\tau=15$, $N_0=10^3$, and $r=1$. (a) Punctuated evolution to peak renewable water: Coupled human-water systems with a carrying capacity that grows slower than the population (i.e., $0<B<1$) evolve in a punctuated manner. N and K grow through successive logistic phases that reach incrementally larger plateaus, eventually reaching an asymptote $N=K$. At the carrying capacity, water is produced at the maximum sustainable rate, which may be governed by natural renewal rates or ecological considerations.[6] (b) Overshoot of nonrenewable water: Coupled human-water systems with a carrying capacity that is initially large (i.e., $A>|B|N_0$) and decays slower than the population (i.e., $-1<B<0$) evolves in a punctuated manner between oscillating levels. These dynamics are characteristic of nonrenewable water extraction, such as groundwater use, where the production rate initially exceeds the natural recharge rate. As aquifers are depleted or contaminated, production costs increase and supply decreases back toward the sustainable extraction rate. Such oscillatory dynamics are common in consumer-resource systems.[6,14,15]

parameters often impedes detailed understanding of the underlying human–environment feedbacks. The DDE offers a minimal representation of coupled human and natural systems with few parameters, but a diverse set of possible dynamics.

Inferring Human-Water System Dynamics from Global Water Withdrawals

In what follows, global water withdrawal data are analyzed to delineate the governing dynamics of the observed human-water system. Two models are fit to the data and described below: a DDE following the approach introduced above and a separately defined function that is independent of any assumption on $B(t)$. We use estimates of global water withdrawals, $W(t)$,[17,18] to characterize the water system and note that this quantity is different from $K(t)$. Further, the data are estimates of water withdrawn from streams, rivers, and aquifers and do not include terrestrial evapotranspiration appropriated to agriculture, which may be up to four times the withdrawal rate.[19] Nevertheless, the temporal pattern of $W(t)$ is expected to provide some insight into how population and water use covary.

Without *a priori* knowledge of $B(t)$ or the water-use efficiency of human population growth, a first-order model can be constructed with the single-value delay used above and the assumption of a constant per capita water use, w, such that $W(t)=wN(t)$. Combining this expression with Equation (6) gives a DDE for $W(t)$,

$$\frac{\mathrm{d}W(t)}{\mathrm{d}t}=\frac{r}{w}W(t)\left[Aw+BW(t-\tau)-W(t)\right], \quad (7)$$

where the parameters have the same definitions as before. Equation (7) can accommodate logistic growth (i.e., $\tau=0$, referred to as the 'logistic' model below) and punctuated evolution with possible finite-time singularity (i.e., $\tau>0$, referred to as the 'delay' model below).

Alternatively, the form of $W(t)$ can be assumed without explicit assumptions for $B(t)$ and $w(t)$. For this approach, we fit a log-periodic power-law growth model (referred to as the 'log-periodic' model below) that describes a type of faster-than-exponential growth with a finite-time singularity at t_c previously found in the human population, economic indices, and turbulence,[8,20]

$$W(t)=a+b\left(t_c-t\right)^{\beta}+c\left(t_c-t\right)^{\beta}\times\cos\left[\omega\ln\left(t_c-t\right)+\phi\right]. \quad (8)$$

This model has seven parameters: a, b, c, t_c, β, ω, and ϕ. The parameter a is the water withdrawal rate in the limit $t\to-\infty$; the second term controls how withdrawals grow over time (b and β); the third term characterizes oscillations around this prevailing growth rate (c and β); and t_c is again the critical time. The log-periodic oscillations in Equation (8) are analogous to the delay effect in Equation (7) and others have

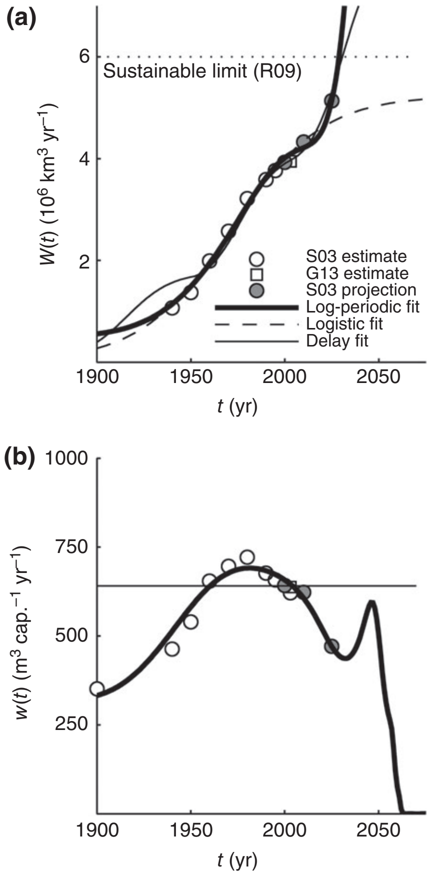

FIGURE 3 | The 20th century global water withdrawals (a) and per capita water demand (b) with corresponding log-periodic, delay, and logistic model fits. Parameters for the log-periodic fit are $a = 0$, $b = 5.65 \cdot 10^7$, $t_c = 2092.5$, $c = 1.58 \cdot 10^7$, $\beta = -2.13$, $\omega = 6.23$, and $\phi = 2.02$. Parameters for the delay model are $Aw = 1072$, $B = 1.77$, $\tau = 50$, $r/w = 4.59 \cdot 10^{-5}$, $W(t = 0) = 394$, $w = 6.58 \cdot 10^{-7}$. Parameters for the logistic model are $Aw = 2902$, $B = 0.45$, $r/w = 1.41 \cdot 10^{-5}$, $W(t = 0) = 273$, $w = 6.58 \cdot 10^{-7}$. In (b), $w(t)$ for the log-periodic model is calculated with population obtained from the log-periodic fit in Figure 1 and the horizontal line corresponds to the constant w assumed for the delay and logistic models. Other references are: Refs Rockstrom et al. 2009 (R09),[5] Shiklomanov 2003 (S03),[17] Gleick 2013 (G13).[18]

noted that Equation (8) is related to von Foerster's original continuous power-law solution, but with discrete scale invariance and a complex power-law exponent.[20] The ability of the DDE to reproduce log-periodic, power-law growth with a time-varying $B(t)$ is an open question to be explored in future work.

Twentieth century trends in global water withdrawals reveal their own bounds for future optimism. Withdrawals to-date are consistent with both logistic or punctuated evolution to peak renewable water, whereas early 21st century projections suggest a punctuated evolution at a faster-than-exponential rate [Figure 3(a)]. These divergent modes of water withdrawal growth bracket the possible futures of the global human-water system; however, with less than 100 years of estimates, it is difficult to discern which hypothesis best describes the trends.

Under the prospect of a population rapidly approaching a mid-century Doomsday, the water withdrawal data raise questions regarding the capacity of the global water system to quench an ever-greater number of people. The log-periodic and delay models describe an optimistic scenario of ongoing rapid improvements in global water supply. However, this scenario predicts that global water withdrawals will exceed the sustainable limit[a] around the year 2029, which interestingly agrees with the original Doomsday prediction $t_c = 2026 \pm 5$. Extrapolating further into the future, the power-law model reaches its own singularity in the year 2093, 30 years beyond the most optimistic estimate for the human population itself,[7] whereas the delay model continues to grow indefinitely. Alternatively, a pessimistic Malthusian scenario is described by the logistic model and cannot be discarded from the data alone. The logistic model approaches an asymptotic value of approximately $5200\,\mathrm{km}^3\,\mathrm{yr}^{-1}$, comparable to the sustainable limit of $6000\,\mathrm{km}^3\,\mathrm{yr}^{-1}$.

Regardless of the future trajectory in total water withdrawals, faster-than-exponential population growth implies that the per capita water demand, $w(t)$, must decrease rapidly in the near future, eventually reaching 0 at the population singularity [Figure 3(b)]. Given that the minimum per capita demand on a cultivated planet is on the order of a few hundred cubic meters per person per year,[21] this situation is clearly unsustainable. No matter how quickly water supply can be improved in the future, the earth system will be challenged to meet the water demands of an 'infinite' number of people.

A History of Punctuated Change in Water Systems

Looking toward the distant past, the log-periodic model resembles a punctuated evolution of water withdrawals with several instances of rapid growth over the last five millennia (Figure 4).[b] The first of these is predicted between 1500 BC and 0 AD, which is roughly coincident with the advent of hydrologic infrastructure in Northern Africa, the Mideast, and Western Asia.[22] During this time, water use estimates are consistent with domestic water demand prior to the widespread expansion of hydrologic engineering and irrigation practices, which likely ranged between 10 and $50\,\mathrm{m}^3$ per person per year.[21] This initial water system revolution is followed into the present by three periods of increasingly rapid and frequent

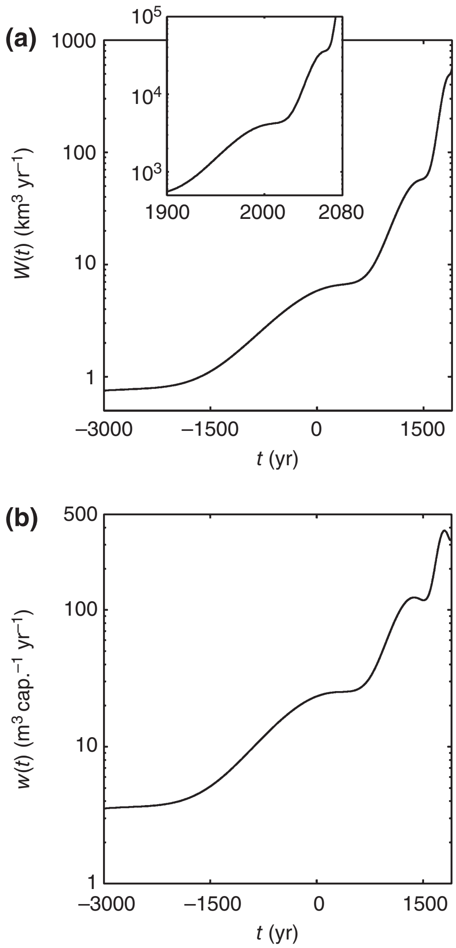

FIGURE 4 | Historical predictions of global water withdrawals (a) and per capita water demand (b) from the log-periodic model. The inset in (a) shows the observed 20th century expansion and the predicted mid-21st century expansion. In (b), population is obtained from the log-periodic fit in Figure 1.

expansion approximately 600–1400, 1500–1800, and 1900–2000. The next phase of global water change is predicted to occur in the middle of this century, between the years 2020 and 2060.

Such punctuated evolution of human-water systems draws many parallels to energy harvest regimes in human and animal societies. Tainter et al. presented evidence for a trajectory of consumer-resource evolution with two serial stages of rapid innovation.[23] The first involves concentration of a high quality energy source, such as the preindustrial shift from solar energy embedded in crops and lumber to that embedded in coal. As the concentrated energy source becomes increasingly rare and expensive, a second transformation involves a shift to a lower quality, but abundant energy source, such as the present emergence of renewable solar and wind energy production. Exploitation of low quality, distributed resources requires capital to overcome initial economic or political impediments and to support a high degree of social organization and information flow.

Consistent with the previous modeling exercise and with the evidence provided by Tainter et al.,[23] the history of human appropriation of the hydrologic cycle displays characteristics of both revolutionary stages. For most of human history, population growth was sustained by foraging and rainfed agriculture, modes of water use exclusively reliant on local water availability subject to natural hydroclimate variability. The first hydrological revolution began 5000 years ago,[22] when reservoir construction allowed for irrigated agriculture and increased productivity through reduced hydrologic variability and concentration of freshwater resources on land. Exploitation of concentrated, high quality freshwater resources, including groundwater depletion, rapidly proliferated during the industrial revolution and continues today. During the 20th century, the most recent growth period of the log-periodic model, global water withdrawals expanded nearly 600% and now account for 35% of accessible runoff.[17,19]

Several recent trends indicate that a new water epoch may be on the horizon. In some regions, accessible freshwater is scarce, freshwater extraction and recovery costs are increasing, and dependence on advanced social organization to produce low quality resources is evident. Many of the world's rivers, including the Colorado, Yellow, Nile, and Jordan, are overappropriated or nearly so,[6] once vast groundwater aquifers are now depleted,[24,25] and changes in rainfall patterns now manifest will challenge freshwater management.[26] Further, the cost of water security is increasing, through large dam construction, interbasin water transfers, and water treatment and reuse.[27] These changes underscore the increased cost of the existing water system, a possible signal of its impending replacement.[23]

The future water system may be foreshadowed by the recent development of low quality, spatially distributed water resources. For example, in the arid southwest United States, transboundary water agreements have allowed redistribution of Colorado River flow and Sierra Nevada snowpack across a wider geographic range. Even more so, virtual water trade now facilitates global water redistribution.[10] And, finally, desalination capacity, while still a small fraction of total water withdrawals, is taking root in water-scarce regions, despite its large expense.[28] These water supply improvements are characteristic of a water system built on distributed, but abundant sources that will require economic and political will and a high degree of cooperation among producers and consumers.

CONCLUSION

Theoretical, empirical, and anecdotal evidence suggest that global human-water system dynamics appear to be governed by faster-than-exponential power-law growth in both population and water supply, with punctuated equilibria marking successive periods of rapid change and stagnation. Faster-than-exponential growth fingerprints a positive feedback between population and water supply that implies that water-use efficiency is increasing over time. However, population is growing faster than the water supply. Hence, we are of the opinion that such an imbalance between water supply and demand can lead to a possible finite-time singularity mathematically characterized by an infinite number of people competing for a finite supply of water.

In addition to revealing punctuated, power-law growth in the global human-water system, the analyses presented here suggest opportunities to improve quantitative understanding of coupled human-water systems. The proposed DDE [e.g., Equation (6)] captures punctuated evolution to peak renewable water as well as the hypothesized overshoot of nonrenewable water and promises to be a useful tool to explore human-water feedbacks. However, a relatively sparse amount of work has investigated the mathematical form of the delay kernel $B(t)$,[11,12] which represents the link between human activity and water resource availability in this model.

One path forward is a better integration of models and data with a specific focus on constraints for $B(t)$, which can be considered a macroscopic function that integrates the social, environmental, and technological factors that drive human–water interactions. To illustrate this point more clearly, note that the water-based carrying capacity can be conceptualized as the ratio of the renewable freshwater supply, $Q_r(t)$, to the per capita water demand, $w(t) = W(t)/N(t)$,

$$K(t) = \frac{Q_r(t)}{w(t)} = \frac{Q_r(t)}{W(t)/N(t)} = A + \int B(t')\,N(t')\,\mathrm{d}t'. \tag{9}$$

Therefore, $B(t)$ encapsulates information on the development of freshwater resources and changes in per capita demand. Also, this relation shows that data on $Q_r(t)$, $W(t)$, and $N(t)$ are necessary to adequately constrain $B(t)$. While some studies have attempted to define the limits to freshwater availability,[5] $Q_r(t)$ and its relation to $W(t)$ are yet unknown. Indeed, independent analysis of $W(t)$ and $N(t)$ resulted in a nonmonotonic $w(t)$ during the 20th century (Figure 3), reaching a peak in 1980. Assuming $Q_r(t)$ constant, this is circumstantial evidence that $B(t)$ is neither constant [as assumed in Equations (6) and (7)] nor monotonic. Progress toward quantitative modeling of human-water system dynamics therefore compels a deeper understanding of the history of human interactions with the water cycle, as quantified by $B(t)$.

Viewing the global human–water interaction as a dynamical system with internal innovative and destructive forces offers a new methodology to weigh the optimistic and pessimistic attitudes hypothesized by von Foerster et al.[2] While the optimist may argue that water conservation measures, improved agricultural water-use efficiency, and desalination will meet the demands of a growing and increasingly affluent population, the pessimist responds with the gradual approach to sustainable levels of freshwater use. Nevertheless, the appearance of power-law growth in both population and water withdrawals hints at a regime shift in coupled human-water dynamics before the end of this century. Renewable limits to freshwater supply therefore represent one barrier standing between today and Doomsday.

NOTES

[a] Peak ecological water withdrawal is estimated from Rockstrom et al.[5] assuming that the ratio of water withdrawals to consumptive use remains constant at approximately 1.5.

[b] Note that the logistic and delay models predict water withdrawals below the minimum requirement for drinking water (approximately 1 m^3 per person per year[21]) around the year 1750 (data not shown).

ACKNOWLEDGMENTS

The authors acknowledge support from the US National Science Foundation (AGS-1102227, CBET-1033467, EAR-1344703, EAR-1331846, EAR-1316258, and FESD-1338694), the US Department of Agriculture through the Agriculture and Food Research Initiative (2011-67003-30222), and the US Department of Energy through the Office of Biological and Environmental Research Terrestrial Carbon Processes program (DE-SC0006967 and DE-SC0011461).

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