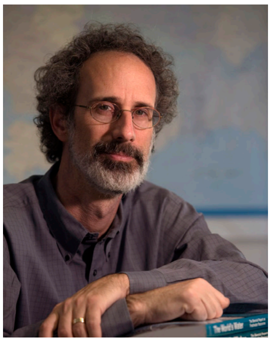

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THE CONCEPT OF PEAK WATER*

The new concept of 'peak water' is described here in the context of global and local water challenges. Three different definitions are provided: 'peak renewable,' 'peak non-renewable,' and 'peak ecological' water, with specific examples of each and their role in characterizing water problems and solutions. Regions around the world are increasingly experiencing peak water constraints, as evidenced by a growing competition for water, increasing ecological degradation associated with human extraction of water from surface and ground water systems and political controversies around water. Understanding the links between human demands for water and peak water constraints can help water managers and planners move towards more sustainable water management and use by moving away from peak limits, by cutting non-renewable water use to more sustainable levels and by restoring aquatic ecosystems as a way to reduce ecological damage from exceeding 'peak ecological water'.

Key words: peak water, peak ecological water, peak renewable water, peak non-renewable water, fresh water resources, climate change

Purpose of the article

In the past few years, resource challenges around water, energy and food have led to new debates over definitions and concepts about sustainable resource management and use. Energy experts have long debated the timing of the point of maximum production of petroleum, or 'peak oil' (Bardi, 2009; Kerr, 2007; Duncan, 2003; Bentley, 2002). More recently, there has been a growing discussion of whether we are also approaching a comparable point for water resources, where natural limits will constrain growing populations and hinder economic expansion (Gleick and Palaniappan, 2010). In this article, we present and review the concept of 'peak water,' evaluate the similarities and differences between water and oil, and offer some thoughts about the applicability of this concept to hydrologic and water-management challenges. Brief recommendations are made for avoiding these peak constraints.

Humanity faces serious water challenges. These include the failure to meet basic human needs for safe water and sanitation, growing water contamination, the consequences of extreme events such as floods and droughts, disruptions in aquatic ecosystems, increasing concerns about water shortages and scarcity and the new risks to water resources and systems from climatic changes. Considering the total volume of water on Earth, however, the concept of 'running out' of water on a global scale is of little practical utility. There are huge volumes of water – many thousands of times the volumes that humans appropriate for all purposes. The world's fresh water stocks (< 3 per cent of all water) are estimated at around 35 million km^3. Much of this fresh water is locked up in the icecaps of Antarctica and Greenland, permanent snow cover in mountains or high latitudes, or deep ground

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* This is a condensed and modified version of an article that appeared in the Proceedings of the National Academy of Sciences, Gleick, P.H. and M. Palaniappan. 2010. Peak Water: Conceptual and Practical Limits to Freshwater Withdrawal and Use. Proceedings of the National Academy of Sciences (PNAS), Vol. 107, No. 25, pp. 11155–11162 Washington, D.C. June 22, 2010.

water. Only small fractions are available to humans as 'green' or 'blue' water in river flows, accessible surface lakes and ground water, soil moisture, or rainfall (Shiklomanov, 2000; CSD, 1997; Falkenmark et al., 1989). Table 1 shows the distribution of the main components of the world's water. In the early 2000s, total global withdrawals of water were approximately 3700 km^3 per year (excluding water used directly as rainfall or soil moisture), a tiny fraction of the estimated stocks of fresh water.

A more accurate way to evaluate human uses of water, however, would look at specific, often localised, stocks and flows of water and the impact of human appropriations of rainfall, surface and ground water stocks and soil moisture. An early effort to evaluate these uses estimated that substantially more water in the form of rain and soil moisture –perhaps 11,300 km^3/y – is appropriated for human-dominated land uses, such as cultivated land, landscaping and to provide forage for grazing animals. Overall, that assessment concluded that humans already use, in one form or another, more than 50 per cent of all renewable and 'accessible' fresh water flows, including a fairly large fraction of water that is used in-stream for the dilution of human and industrial wastes (Postel et al., 1996). It is important to note, however, that these uses are of the 'renewable' flows of water (described in more detail below). In theory, the use of renewable flows can continue indefinitely without any effect on future availability. In practice, however, while many flows of water are renewable, some uses of water will degrade the quality or reduce quantities to a point that constrains the kinds of use possible. In this context, the three concepts of 'peak water' presented here may be especially useful.

Peak resource production

The theory of peak resource production originated in the 1950s with the work of geologist M. King Hubbert and colleagues who suggested that the rate of oil production would likely be characterised by several phases that follow a bell-shaped curve (Hubbert, 1956). The first phase is the discovery and rapid increase in growth in the rate of exploitation of oil as demand rises, production becomes more efficient, and costs fall. Second, as stocks of oil are consumed and become increasingly depleted, costs rise and production levels off and ultimately peaks. Finally, increasing scarcity and costs lead to a decline in the rate of production and the growing effort to develop and substitute alternatives. The phrase 'peak oil' refers to the point at which approximately half of the existing stock of petroleum has been depleted and the rate of production peaks. In his classic paper, Hubbert (1956) correctly predicted that oil production in the United States would peak between 1965 and 1970. Indeed, in 1970, oil production in the US reached a maximum and has since declined (Fig. 1).

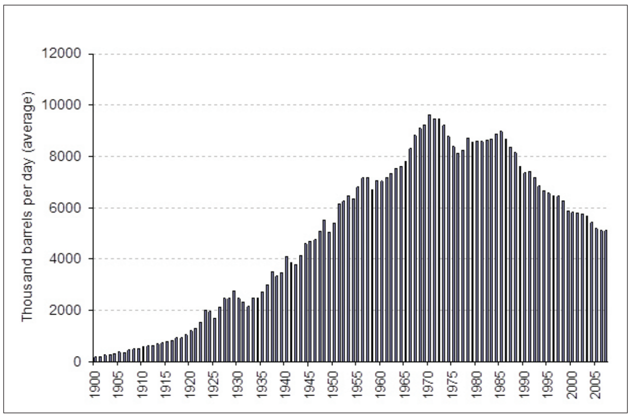

Figure 1. Total annual U.S. production of crude oil, 1900–2007. US production peaked in 1970. Source: USEIA (2008, 2009)

The concept of a roughly bell-shaped oil production curve has been proven for a well, an oil field, a region, and is thought to hold true worldwide, although there is still a significant debate about when the world as a whole will reach the point of peak oil. Forecasts range from the coming decade to substantially after 2025. One of many recent estimates suggests that oil production may peak as early as 2012 at 100 million barrels of oil per day (Gold and Davis, 2007). The actual peak of production will only be identified in hindsight, and its timing depends on the demand and cost of oil, the economics of technologies for extracting oil, the rate of discovery of new reserves compared to the rate of extraction, the cost of alternative energy sources and political factors. But a peak in the production and consumption of non-renewable resources is inevitable.

Analysis: comparison of peak production in oil and water

Does production or use of water follow a similar bell-shaped curve? In the growing concern about global and local water shortages and scarcity, is the concept of 'peak water' valid and useful to hydrologists, water planners, managers and users? In the following sections, we consider the differences and similarities between oil and water. The focus is on the characteristics of renewable and non-renewable resources, consumptive versus non-consumptive uses, transportability and substitutability (Table 2 summarises these characteristics for oil and water), and then we define three forms of 'peak water'.

Key characteristics of renewable and non-renewable resources

There are important differences between renewable and non-renewable resources. As traditionally defined, renewable resources are flow- or rate-limited while non-renewable resources are stock limited (Ehrlich et al., 1977). Stock-limited resources, especially fossil fuels, can be depleted without being replenished on a time-scale of practical interest. Stocks of oil, for example, accumulated over millions of years and are effectively independent of any natural rates of replenishment because such rates are so slow. Conversely, renewable resources, such as solar energy, are virtually inexhaustible over time, because their use does not diminish the production of the next unit. Such resources are instead limited by the flow rate, i.e. the amount available per unit time.

Water demonstrates characteristics of both renewable and non-renewable resources. Renewable water systems experience rapid flows from one stock and form to another, and the human use of water, with a few exceptions, has no effect on natural recharge rates. But there are also stocks of local water resources that are effectively non-renewable cept

Table 1. Major stocks of water on Earth.

	Distribution area (10^3 km^2)	Volume (10^3 km^3)	Total water (per cent)	Fresh water (per cent)
Total water	510,000	1,386,000	100	
Total fresh water	149,000	35,000	2.53	100
World oceans	361,300	1,340,000	96.5	
Saline ground water		13,000	1	
Fresh ground water		10,500	0.76	30
Antarctic glaciers	13,980	21,600	1.56	61.7
Greenland glaciers	1,800	2,340	0.17	6.7
Arctic islands	226	84	0.006	0.24
Mountain glaciers	224	40.6	0.003	0.12
Ground ice/permafrost	21,000	300	0.022	0.86
Saline lakes	822	85.4	0.006	
Fresh water lakes	1,240	91	0.007	0.26
Wetlands	2680	11.5	0.0008	0.03
Rivers (as flows on average)		2.12	0.0002	0.006
In biological matter		1.12	0.0001	0.0003
In the atmosphere (on average)	12.9	0.0001	0.04	

Table 2. Summary comparison of oil and water.

Characteristic	Oil	Water
Quantity of resource	Finite	Literally finite, but practically unlimited at a cost
Renewable or non-renewable	Non-renewable resource	Renewable overall, but with locally non-renewable stocks
Flow	Only as withdrawals from fixed stocks	Water cycle renews natural flows
Transportability	Long-distance transport is economically viable	Long-distance transport is not economically viable
Consumptive versus non-consumptive use	Almost all use of petroleum is consumptive, converting high-quality fuel into lower quality heat	Some uses of water are consumptive, but many are not. Overall, water is not 'consumed' from the hydrologic cycle
Substitutability	The energy provided by the combustion of oil can be provided by a wide range of alternatives	Water has no substitute for a wide range of functions and purposes
Future prospects source	Limited availability; substitution inevitable by a backstop renewable source	Locally limited, but globally unlimited after backstop (e.g. desalination of oceans) is economically and environmentally developed

ble because they are consumed at rates far faster than natural rates of renewal. Most non-renewable resources are ground water aquifers – sometimes called 'fossil' aquifers because of their slow recharge rates. Tiwari et al. (2009) recently calculated that a substantial fraction of water used in India comes from non-renewable ground water withdrawals and leads to ground water depletion. Syed et al. (2009) found similar transfers of non-renewable ground water for a wide variety of ground water basins using new data from the GRACE satellite. Some surface water systems in the form of lakes or glaciers can also be used in a non-renewable way where consumption rates exceed natural renewal, a problem that may be worsened by climate change, as noted below.

Consumptive vs. non-consumptive uses

Another key factor in evaluating the utility of the concept of a resource peak is whether the resource use is 'consumptive' or 'non-consumptive.' Practically every use of petroleum is consumptive; once the energy is extracted and used it is degraded in quality. According to the law of the conservation of energy, energy is never literally 'consumed' – simply converted to another form. But the use of oil converts concentrated, high-quality energy into low-quality, unusable waste heat. Almost every year, the amount of oil consumed closely matches the amount of oil produced. Thus a production curve for oil depends on pumping rates from fixed stocks.

Not all uses of water are consumptive and even water that has been 'consumed' is not lost to the hydrologic cycle or to future use – it is recycled by natural systems. Consumptive use of water typically refers to uses that make water unavailable for immediate or short-term reuse within the same watershed. Consumptive uses include water that is evaporated, transpired, incorporated into products or crops, heavily contaminated or consumed by humans or animals. There are also many non-consumptive uses of water, including water used for cooling in industrial and energy production and water used for washing, flushing or other residential uses if that water can be collected, treated and reused. This water recycles into the overall hydrological cycle and has no effect on subsequent water availability in a region.

Substitutability

The concept of peak resource use also depends on the availability and form of 'substitute' resources. The purpose of using oil is not to 'use' oil, but to provide social or economic benefits, such as transportation, heating, cooling, industrial production and more. With very few exceptions, there are other means or resources (e.g. solar, natural gas and alternative liquid fuels) that can produce these same benefits. As oil production declines and prices increase, substitutes for oil become increasingly attractive. In this sense, any resource that can be depleted, such as fossil fuels, serves only as a transition to long-term renewable options. Like energy, water is used for a wide variety of purposes and, like energy, the efficiency of water use can be greatly improved by changes in technologies and processes. Unlike oil, however, fresh water is the only substance capable of meeting certain needs and has no substitutes for most uses.

As a result, when peak water limits are reached, there are only a few possible options for satisfying new needs; (1) reducing demand, (2) substituting one use of water for another that has higher economic or social value, (3) physically moving the demand for water to a region where additional water is available, or (4) investing in a higher priced source of supply, including bulk imports or transfers of water. For water, the cost of a new supply, including the cost of transporting water, is often a key limiting factor.

A relevant concept to both peak water and peak oil, therefore, is the introduction of a 'backstop' technology when the price of the resource rises. This was described early by Nordhaus (1973) who defined a backstop to be an alternative capable of meeting the demand with a virtually infinite (or renewable) resource base. According to classical economics, as oil production peaks and then declines, the price of oil will rise until the point when a substitute, or backstop, for oil becomes economically competitive. At this point prices stabilise at the new backstop price.

Similarly, for water, as cheaper sources of water are depleted or allocated, more expensive sources must be tapped, either from new supplies or the reallocation of water among existing users. Ultimately, the 'backstop' price for water will also be reached. Unlike oil, however, which must be backstopped by a different, renewable energy source, the ultimate non-renewable water backstop is to identify and tap a renewable source, such as desalination of ocean water. The amount of water in the oceans that humans can use is limited only by how much we are willing to pay to remove salts and transport it to the point of use, and by the environmental constraints of using it. The growing use of costly desalination in regions where water is scarce is a clear example of peak water limits falling back on an expensive renewable alternative (NRC, 2008; Cooley et al., 2006).

Transportability

Because the Earth will never 'run out' of fresh water, concerns about water scarcity result from the tremendously uneven geographic distribution of water (due to both natural and human factors), the economic and physical constraints on tapping some of the largest volumes of fresh water (such as deep ground water or ice in high-latitude environments), human contamination of some readily available stocks and the high costs of moving water from one place to another.

This last point – the 'transportability' of water – is particularly relevant to the concept of peak water. Oil is transported around the world because it has a high economic value compared to the cost of transportation. For example, one of today's supertankers carries as much as 3.6 million barrels of oil. At prices approaching $100 per barrel in 2011, that oil would be worth $360 million dollars and the cost of transportation is minor. As a result, regional limits on oil availability can be overcome by moving oil from any point of production to any point of use and there is a large international trade in oil. In contrast, that same supertanker filled with fresh water would have an economic value of only around $500,000 assuming a price equivalent to what industry and urban users might pay for high-quality reliable municipal supplies. This is far too little to support the high costs of long-distance shipping. As a result, we see almost zero international trade in water, with the exception of very short term and short distance emergency transfers such as those associated with the recent Japanese earthquake, tsunami and nuclear disaster where emergency water was brought in by tanker.

As a result, the concept of 'peak water' is primarily a local issue. Where water is scarce, water constraints and the real implications of a 'peak' in availability are already apparent. Because the costs of transporting bulk water from one place to another are so high, once a region's water use exceeds its renewable supply, it will begin tapping into non-renewable resources, such as slow-recharge aquifers. As noted above, once extraction of water exceeds natural rates of replenishment, the only long-term options are to reduce demand to sustainable levels, move the demand to an area where water is available, or to shift to increasingly expensive sources, such as desalination or imports of goods produced in regions with adequate water supplies, the transfer of so-called 'virtual water' (Allan, 1999).

Science and policy relevance: three peak water concepts

Given the physical and economic characteristics of resources presented above, how relevant or useful is the concept of a peak in the production of water? Gleick and Palaniappan (2010) present three definitions of 'peak water' in the context of water resources management – 'peak renewable', 'peak non-renewable' and 'peak ecological' water. These peak water concepts should help drive important paradigm shifts in how water is used and managed.

Peak renewable water

A significant fraction of the total human use of water comes from renewable water resources taken from rainfall, rivers, streams and ground water basins. Such systems experience stochastic and variable hydrology, but the use of the water does not affect the ultimate renewability of the resource, much like solar energy use. Because a particular water source may be renewable, however, does not mean that it is unlimited. Indeed, the first 'peak' water constraint is the limit on total renewable flows of water that can be withdrawn from a system.

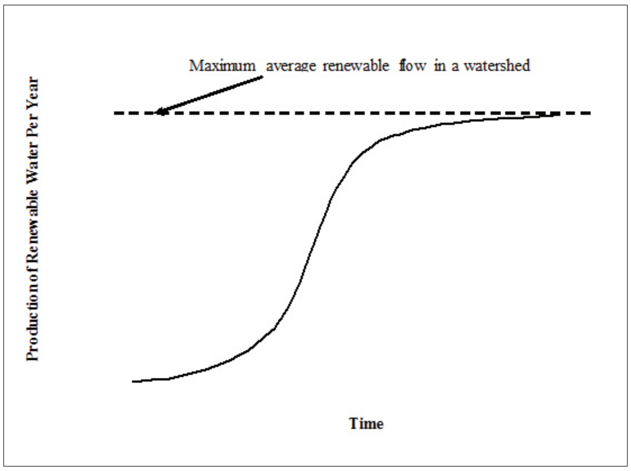

Figure 2. The theoretical logistics curve shows increasing annual production of renewable water from a watershed. Annual renewable water production increases exponentially, and then levels off as it reaches the total annual renewable water supply in the watershed.

When the production of renewable water from a watershed reaches 100 per cent of renewable supply, it forms a classic logistics curve (Fig. 2). Each watershed only has a certain amount of renewable water supply that is replenished every year. If the annual production of renewable water from a watershed increases exponentially, it eventually approaches the natural limits of the total annual renewable supply of water (shown as a dashed line). This limit may go up or down with natural hydrologic variability, but it is an ultimate limit in terms of appropriation of a renewable water supply. The appropriate practical limit may be substantially less than this, as discussed below under peak 'ecological' water. Increasing annual renewable water use to the theoretical renewable limit has been shown to result in ecological, environmental and human damage.

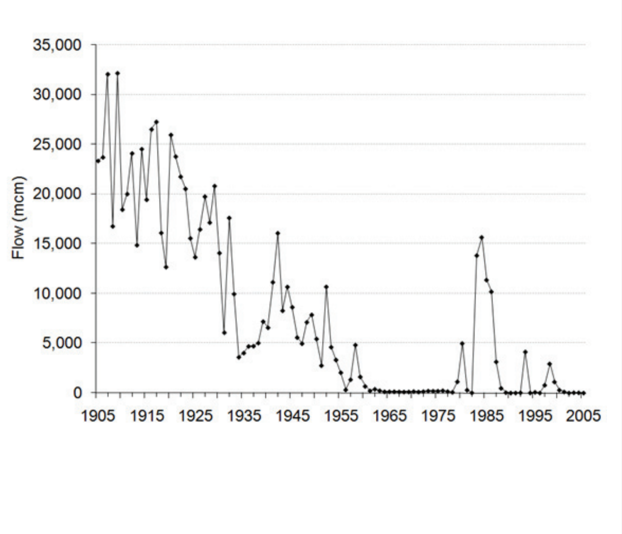

Figure 3. Annual flows (in million m3) of the Colorado River into the delta from 1905 to 2005 at the Southern International Border station. Note that in most years after 1960, flows to the delta fell to zero as total withdrawals equalled total (or peak) renewable supply. The exceptions are extremely high-flow years when runoff exceeded demands and the ability to store additional water (IBWC, 2010).

For a number of major river basins, peak renewable water limits have already been reached as human demand consumes close to the entire annual supply. The Colorado River in the US, for example, is shared by seven U.S. states and Mexico, and in an average year no water reaches the delta (Fig. 3). For this watershed, the limit of peak renewable water is an average of around 18 billion m3 annually – the total average annual flow. Other rivers are increasingly reaching their peak renewable limits as well, including the Huang He (Yellow River) in China, the Nile in northern Africa and the Jordan in the Middle East, where formerly perennial river flows now often fall to zero.

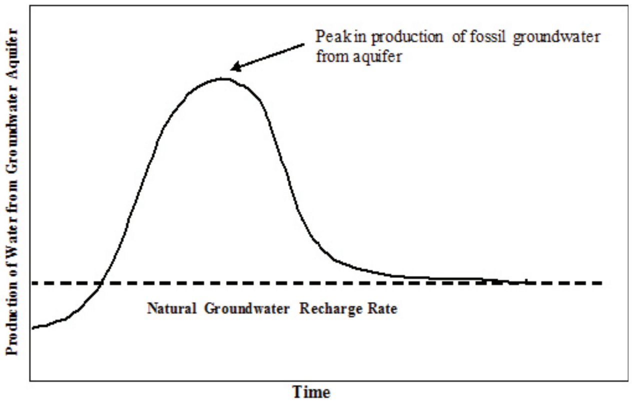

Figure 4. This theoretical curve shows the progression of unsustainable water extraction from a ground water aquifer, hypothesizing a peak-type production curve for water after the production rates surpass the natural ground water recharge rate and production costs rise. Long-term sustainable withdrawals cannot exceed natural recharge rates.

Peak non-renewable water

In some watersheds, a substantial amount of the current water use is satisfied by non-renewable sources, such as ground water aquifers with very slow recharge rates or over-pumped ground water systems that lose their ability to be recharged due to compaction or other physical changes in the basin. When the use of water from a ground water aquifer far exceeds the natural recharge rate, this stock of ground water will be quickly depleted; or when ground water aquifers become contaminated with pollutants that make the water unusable, a renewable aquifer can become non-renewable.

Peak non-renewable water is most analogous to the concept of peak oil. Continued production of water above natural recharge rates will become increasingly difficult and expensive as ground water levels drop, leading to a peak of production, followed by diminishing withdrawals and use. This kind of unsustainable ground water use can be seen in the Ogallala Aquifer in the Great Plains of the U.S., the North China Plains, around Bangkok, Thailand, in parts of California's Central Valley and numerous basins in India (Chatterjee and Purohit, 2009). Tiwari et al. (2009) estimate that the non-renewable use of water in India averaged 54 ± 9 km3 per year between 2002 and 2008 or around 8 per cent of India's total water withdrawals. Overdraft of ground water from California's Central Valley has been estimated at between 1.2 and 2.5 km^3 per year (CDWR, 2003).

Even when the rate of withdrawal from a ground water aquifer passes the natural recharge rate for the aquifer (shown as a dashed line, Fig. 4), the production of water from the aquifer can continue to increase until a significant portion of the ground water has been removed. After this point, deeper boreholes and increased pumping will be required to obtain additional water, potentially reducing the rate of production of water and substantially increasing the cost. When production of water from the aquifer becomes too expensive, the production of water drops quickly to the renewable recharge rate where economically and physically sustainable pumping is possible.

Peak ecological water

For many watersheds, a more immediate and serious concern than 'running out' of water is exceeding a point of use that causes serious or irreversible ecological damage. Water provides many services; it sustains human life and commercial and industrial activity, but it is also fundamental for the sustenance for animals, plants, habitats and environmentally dependent livelihoods (Daily et al., 1997, 2000; Gleick, 1998).

Each new water project that takes water for human use and consumption decreases the availability of that same resource to support ecosystems. The water taken by humans was once sustaining habitats and terrestrial, avian and aquatic plants and animals.

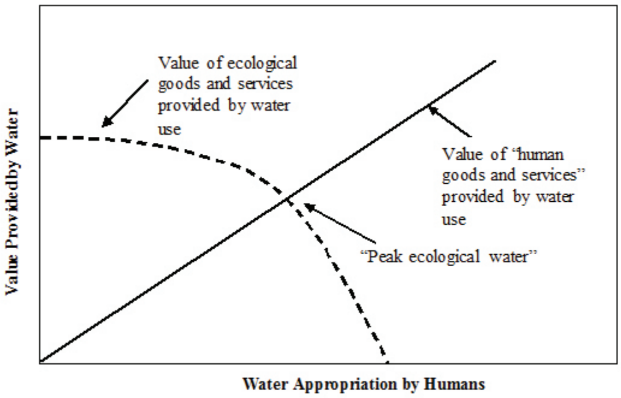

Figure 5. This graph charts the value of water provided by increasing supply from various sources in a watershed against the loss in value of ecological services provided by that water. As water withdrawals for human needs increase (solid line), the ecological services provided by same water are in decline (dashed line). At a certain point, the value of water provided through new supply projects is equal to the value of the ecological services. Beyond this point ecological disruptions exceed the benefits of increased water extraction. We call this point 'peak ecological water'

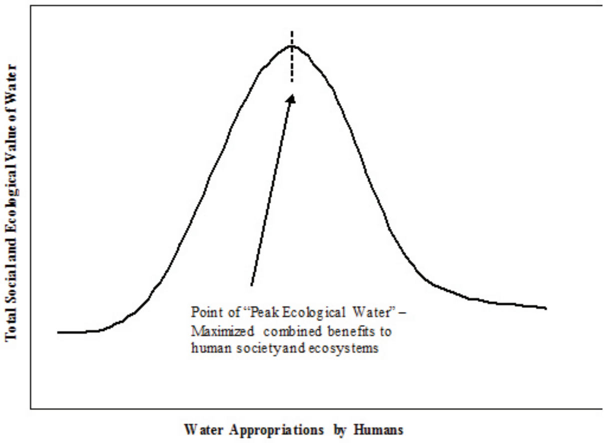

Figure 6. This graph charts the overall value of water – a combination of social, economic and ecological values – as water appropriation by humans increases. The value increases to a peak, where benefits to society and ecosystems is maximised, but then declines as increased appropriations lead to excessive ecosystem and social costs. Non-monetary costs and benefits are hard to quantify, but must be included to avoid exceeding the point of 'peak ecological water.'

Since 1900, half of the world's wetlands have disappeared (Katz, 2006). The number of fresh water species has decreased by 50 per cent since 1970, faster than the decline of species on land or in the sea. River deltas are increasingly deprived of flows due to upstream diversions, or receive water heavily contaminated with human and industrial wastes.

Figure 5 is a simplified graph of the value that humans obtain from water plotted against the declining value of the ecological services that were being satisfied with this same water. The graph assumes that ecological services decrease as water is appropriated from watersheds (though in nature such declines may be non-linear).

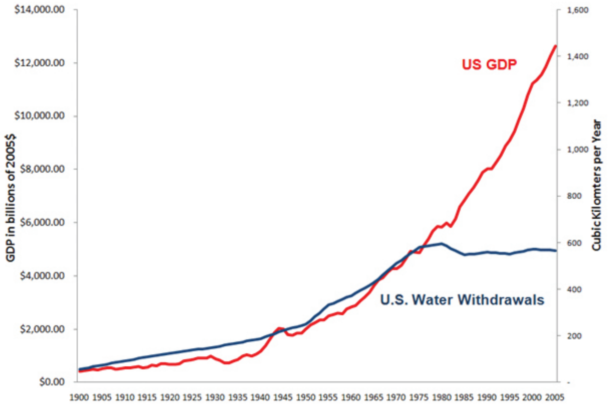

Figure 7. U.S. gross domestic product in 2005 dollars from 1900 to 2005 (left axis) plotted with total water withdrawals for all purposes in km3 per year (right axis). Source: Gross domestic product data, U.S. Department of Commerce (2011). U.S. Bureau of Economic Analysis , http://www.bea.gov/national/index.htm#gdp; water use data, Kenny et al. (2009).

The pace or severity of ecological disruptions increases as increasing amounts of water are appropriated. Because ecological services are not easily valued in financial terms, the y-axis should be considered the overall (economic and non-economic) 'value provided by water'.

At some point, the loss of ecological services provided by water is equivalent to the increased value of human services satisfied by using that same unit of water. After this point, increasing human use of water causes ecological disruptions greater than the value that this increased water provides to humans. Gleick and Palaniappan (2010) define this as the point of 'peak ecological water' – where society will maximise the total ecological and human benefits provided by water. The total value of water then declines as human appropriation increases (Fig. 6). While it is difficult to quantify this point because of problems in assigning appropriate valuations to each unit of water or each unit of ecosystem benefit in any watershed (Daily et al., 2000), the incorrect assumption that such values are zero has led to them being highly discounted, underappreciated, or ignored in 20th century water policy decisions.

Evidence for peak water in the US

Few countries or regions collect or release comprehensive data on human uses of water. Nevertheless, there is some strong evidence that some major regions of the world have already passed the point of 'peak water,' including all three of the concepts described above. Here we offer some examples from the US Figure 7 shows US gross domestic product (in 2005 dollars) plotted with total water withdrawals in the US, for all purposes, from 1900 to 2005, based on data from state and federal water agencies, compiled largely by the US Geological Survey's water use assessments (Kenny et al., 2009). These two curves grew exponentially, and in lockstep, through the first three-quarters of the 20th century. After the late 1970s, however, the two curves split apart, and total water withdrawals in the US are now well below their peak level. Per-capita water withdrawals have fallen even more, as the population has continued to grow. Some of the reasons for this dramatic change include improving the efficiency of water use, changes in the structure of the US economy, the implementation of the national Clean Water Act, which led to reductions in industrial water use and discharges, and physical, economic and environmental constraints on access to new supplies (Gleick, 2003).

Whether the US has truly reached a peak in water use is unknown. In theory, total water withdrawals could resume their rise again, but many factors suggest this is unlikely in the long run. Significant expansion of irrigated agriculture, which dominates US water use, seems improbable, especially in the western US where new land and water resources are simply unavailable to any significant degree or at an acceptable ecological and economic price. Almost all major rivers and aquifers are at the limits of their renewable and non-renewable supplies. Significant expansion of cooling water demand also seems unlikely because of physical constraints on water withdrawals (even in relatively well-watered regions), environmental restrictions on in-stream temperatures and flows, and because efforts to move from central water-intensive thermal plants to less water-intensive renewable systems are expanding.

Conclusions and recommendations

This paper presents three separate definitions of peak water – renewable, non-renewable and 'ecological' water – together with evidence that many regions of the world, including major portions of the US, have already passed the point of peak water. Peak water limits are far more worrisome than are constraints on petroleum, which has many substitutes. Water is fundamental for ecosystem health and for economic productivity, and for many uses it has no substitutes.

The concept of peak water does not mean we will 'run out' of water. Water is a renewable resource and is not consumed in the global sense; hence water uses within renewable peak limits can continue indefinitely. But not all water use is renewable; indeed some water uses are non-renewable and ecologically unsustainable. Ground water use beyond normal recharge rates follows a peak-oil type curve with a peak and then decline in water production. Such peak non-renewable water problems are increasingly evident in major ground water basins with critical levels of overdraft, such as the Ogallala and California's Central Valley in the US, the North China Plains, and in numerous states in India, such as Andhra Pradesh, Rajasthan and Tamil Nadu. 'Peak ecological water' limits are being reached where the cost of disruptions that occur in the ecological services that water provides exceeds the value ad provided by additional increments of water use by humans for economic purposes. Defined this way, many regions of the world have already surpassed 'peak ecological water' – humans use more water than the ecosystem can sustain without significant deterioration and degradation.

The concepts around peak water also lead to some important recommendations that result from new paradigm shifts in the use and management of water – what we call the "soft path for water." In regions approaching peak renewable and non-renewable limits, new efforts to rethink the concept of both water 'supply' and 'demand' are already underway in order to move back down the peak water curves to more sustainable levels. New 'supply' concepts, focused on expanding renewable limits, include recycling of water, tapping into salt water stocks through desalination, rainwater harvesting and new treatment techniques to permit new forms of reuse. Equally important are efforts at improving water use efficiency as a way to continue to meet current demands for food, industrial and commercial goods and services, and basic human needs with less water. These efficiency improvements permit withdrawals of renewable and non-renewable water to decrease, and in regions approaching peak constraints, such efficiency improvements are proving to be among the easiest, fastest and cheapest alternatives available (Gleick, 2002). Finally, in regions suffering from 'peak ecological water' limits, new efforts are underway to restore water for natural ecosystems – effectively moving back down the curve to the left in Fig. 6. Sometimes this takes the form of reducing human use of water or guaranteeing minimum ecosystem flows. These kinds of policies can be effective if we are willing to both identify peak limits and act to overcome them.

In conclusion, there are growing efforts to quantify peak ecological limits and to develop policies to restore water for ecosystem services in basins experiencing serious ecological disruptions. Regions that rely on ground water basins suffering from non-renewable withdrawals are under pressure to reduce withdrawals to more sustainable levels, or to better integrate surface and ground water management. The bad news is that we are increasingly reaching peak water limits. The good news is that recognizing and understanding these limits can lead to innovations and changes in behaviours that reduce water use and increase the productivity of water in a more sustainable way.

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