Preventing the Hydrocalypse: A Model for Predicting and Managing Worldwide Water Resources

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Summary

We examine and model trends in water withdrawal throughout the world and develop plans to prevent using water beyond its renewable capacity.

We look at the three major components of water consumption: agricultural, industrial, and municipal uses. We formulate a differential model to account for the rates of change of these uses, and how this change would affect the overall consumption of water within the studied region. We also incorporate feedback based on economic and political stimuli that force a decrease in water usage as it approaches dangerous consumption levels.

Using historical data from the United States, we determine initial conditions for our model and project U.S. water usage to the year 2025. The model simulates how a country could react to water scarcity without drawing from nonrenewable water sources.

In addition to the model, we also discuss policies for effective water management by reducing freshwater usage and preventing tapping into nonrenewable resources. By being able to predict problem areas and suggesting methods of improving water usage in those areas, we can hope to prevent the "hydrocalypse."

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Introduction

Two-thirds of the Earth is covered in water, but only 2.5% of it is freshwater. Fortunately, each year some seawater is naturally desalinated by evaporating from the ocean and precipitating on continents and islands. Globally, this supply of freshwater from rain is plentiful—humanity does not use it all, and most of it simply washes back into the oceans—but locally, water can be very scarce. Some regions use vastly more water than is naturally supplied to them each year. To make up for this deficit, fossil water sources are tapped and exploited. Many communities are walking a dangerous road, as they may exhaust their fossil water sources within the next 20 to 50 years.

The Basic Model

We model past data for water use with linear and with logistic functions. The two models correspond to continuing withdrawal vs. eventual plateauing, due to factors such as availability, population growth, and arable land. A more complex model follows that considers these factors, as well as possible political and economic influences.

For simplicity, we model net water withdrawal in the United States.

Table 1 shows data for net water withdrawal of the United States from 1950–2000 [Shiklomanov 1999].

Table 1.

U.S. water withdrawal 1950–2000.

Year (after 1900)	Water withdrawal (km^3/yr)
50	247
60	347
70	470
80	538
90	492
95	503
100	512

The models show trends but have two major limitations.

- Most importantly, they fail to incorporate any external factors, such as population and technological growth, as well as economic and political influences. The models are likely to fail if a country's water withdrawal rates approach the amount of renewable water available, as increased prices and political regulation drive down the amount of additional water consumed.

- The models assume that the area modeled has a stable enough past for the trend to predict the future accurately. Even for the U.S., there is enough variability in the data that we cannot convincingly extrapolate.

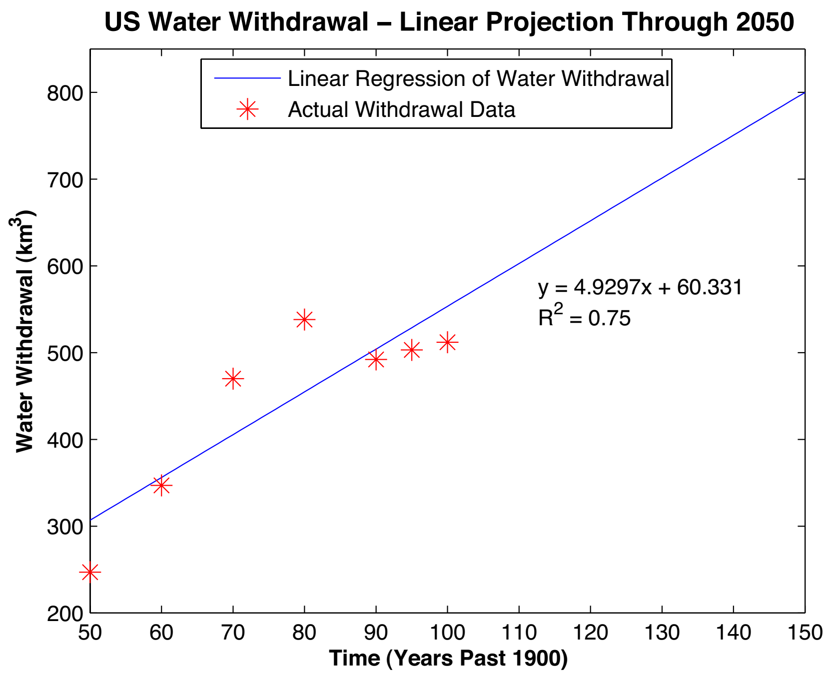

Figure 1. Linear regression of U.S. water withdrawal 1950–2000, extrapolated to 2050.

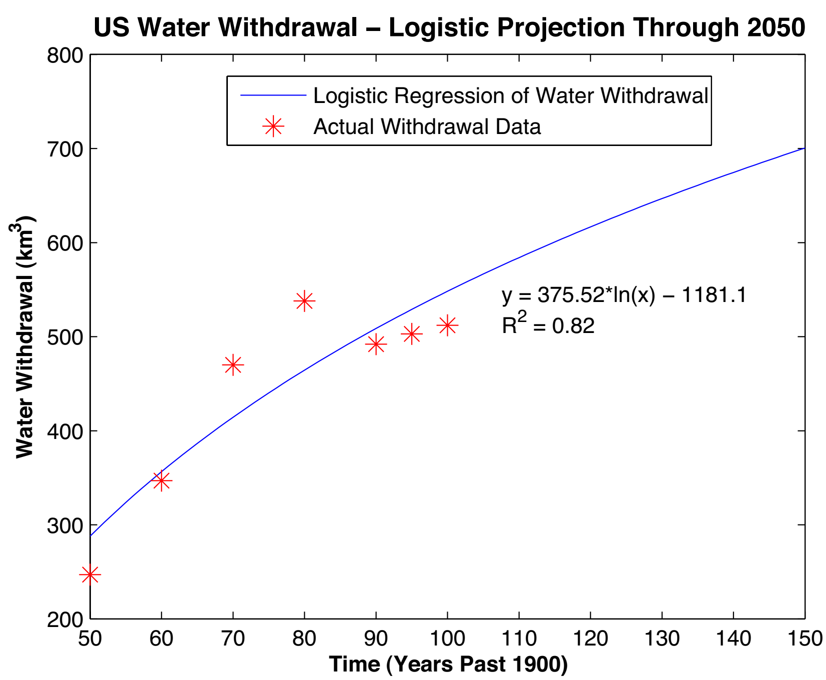

Figure 2. Logistic fit of U.S. water withdrawal 1950–2000, extrapolated to 2050.

A Better Model

While a simple data fit may indicate trends, a better model should take into account how the water is used, how the use of water is changing over time, and what other influences affect the use of water. The three major categories of human water use are agricultural, industrial and municipal. Each has its own trends in growth and water use and can be affected differently by the economy or by political influences. Thus, it is important to consider them separately.

Table 2 shows the variables that we use, their definitions, and measurement units.

Table 2.
Variables used in the model.

Symbol	Definition	Unit
R	Renewable water	km^3/yr
C	Water withdrawn	km^3/yr
A	Size of agriculture	10^3 Ha
I	Size of Industry (GDP in 1990)	$US/person
M	Size of the municipality	10^3 people
C_A	Water withdrawn by agriculture	km^3/yr
C_I	Water withdrawn by industry	km^3/yr
C_M	Water withdrawn by the municipality	km^3/yr
t	Time	yr

Agriculture

We discuss the influence on agriculture and extrapolate our conclusions to industry and municipality. As with the simple model, we use the U.S. as an example.

First, we consider the rate at which agriculture changes. We quantify agriculture as the net irrigation area within the region. We employ a logistic model, since there is a fixed amount of arable land available, and as land use approaches that, the net increase in agriculture will tend towards zero. We arrive at the logistic model by linear regression of change in irrigation area on time. Using data for the U.S. 1970–1995 [Shiklomanov 1999], we find

$$\frac{dA}{dt} = 15326 \ln t - 49039 \qquad (R^2 = .889).$$

To calculate the additional demands for water that increased agriculture will place on the U.S. We multiply current water consumption due to agriculture, C_A, by the rate of change of agriculture, and normalize by dividing by the current amount of agriculture:

$$\frac{dC_A}{dt} = \frac{dA}{dt}\frac{C_A}{A}. \tag{1}$$

Finally, we must adjust this for political and economic factors.

- Consider the case when net consumption of water (from all three categories) does not approach the amount of renewable resource. There should be little, if any, political or economic inhibition of water use.
- Now consider the case when water use approaches available resources. In this scenario, the price of water will increase, and the government will likely place restrictions on each of the three sectors to help keep water consumption within limits of the resource.
- Finally, consider the scenario when consumption exceeds resource. Ideally, in this scenario, political and economic factors will actively drive the use of water down over time, decreasing net use, and returning the region to a stable state.

This set of circumstances can be modeled by factoring the following coefficient into **(1)**:

$$\text{Political influence} = \left(1 - \frac{C}{R}\right)^{P_A},$$

where R is the amount of renewable water, C is the amount of water withdrawn, we define the parameter P_A to be the economic and political influence on the agricultural sector of the region. This parameter can be easily scaled to simulate the economy and government's response to changes in environmental factors, such as a drought. When $C > R$, the influence on water usage is negative (the government inhibits further water usage), and when $C < R$, it is positive (the government encourages further water usage).

Combining these two equations, the change in water consumption over time due to agriculture is

$$\frac{dC_A}{dt} = \left(1 - \frac{C}{R}\right)^{P_A} \frac{dA}{dt}\frac{C_A}{A}. \qquad \textbf{(2)}$$

Industry

The reasoning for the industrial use of water falls along similar lines as agriculture. We quantify industry as the region's Gross Domestic Product (GDP) per person. Working from GDP data from the Groningen Growth & Development Centre [2005] and population data from UNESCO [Shiklomanov 1999] for 1970–1995, we fit a linear regression of GDP/person for the U.S. to time, since industry tends to grow at a steady rate, despite the nonlinear dynamics of economy and population. We find

$$\frac{dI}{dt} = 392.99t - 12929 \qquad (R^2 = .998).$$

Since the rate of change of water consumption by industry is likely to follow the same trends as agriculture, just with a different power of the political and economic scaling factor, we use the same differential equation, replacing P_A with P_I. Thus:

$$\frac{dC_I}{dt} = \left(1 - \frac{C}{R}\right)^{P_I} \frac{dI}{dt}\frac{C_I}{I}. \tag{3}$$

Municipality

Water consumption of the municipality is probably the easiest of the three models; population is the best indicator of the size of a municipality. Further, population growth tends to be logistic—it will plateau at a certain level. Fitting a logistic model to U.S. population 1970–1995 gives

$$\frac{dM}{dt} = 194163 \ln t - 616608 \qquad (R^2 = .991).$$

Similarly, only the power of the political and economic scaling factor will differentiate consumption of the municipality from that of the other two sectors, so

$$\frac{dC_M}{dt} = \left(1 - \frac{C}{R}\right)^{P_M} \frac{dM}{dt}\frac{C_M}{I}. \tag{4}$$

Bringing it Together

We combine the rates of change of water consumption for each of the three sectors into one governing equation. Since total consumption is the sum of the consumption of these sectors, the rate of change of the total consumption is also simply a sum of the rates of change of the three sectors, or the equations **(2, 3, 4)**. Therefore, our final governing equation is:

$$\frac{dC}{dt} = \left(\frac{dC_A}{dt} + \frac{dC_I}{dt} + \frac{dC_M}{dt}\right). \tag{5}$$

Derivation of the Values of the Parameters P

We use initial conditions to identify the values of the parameters P (powers of the political influence). We rearrange **(2)** to get:

$$P_A = \frac{\ln\left(\dfrac{\frac{dC_A}{dt}}{\frac{dA}{dt}\frac{C_A}{A}}\right)}{\ln\left(1 - \dfrac{C}{R}\right)}.$$

Using data for the U.S. 1990–1995 [Shiklomanov 1999], we solve for the country's three political and economic constants. We find dC_A/dt by calculating the change in water consumption due to agriculture over the five years; C and R are also known for the U.S. in 1990 ($C = 492\text{ km}^3$, $R = 2930\text{ km}^3$) and dA/dT can be found from the logistic fit for agriculture; and C_A and A are both known for 1990 [Shiklomanov 1999]. Plugging these values (and their counterparts for industry and municipality), we find:

$$P_A = 1.052, \qquad P_I = 7.36, \qquad P_M = 3.45.$$

Running the Model

To solve the differential equations in our model, we use the ODE45 numerical integrator in MATLAB on **(5)** to find the results in **Figure 3**. Agricultural, industrial, and municipal withdrawal rates each increase steadily, as does the total withdrawal rate. The economic and political scaling factor makes virtually no attempt to curb the increasing water usage, since the U.S. has a significant surplus of renewable water sources.

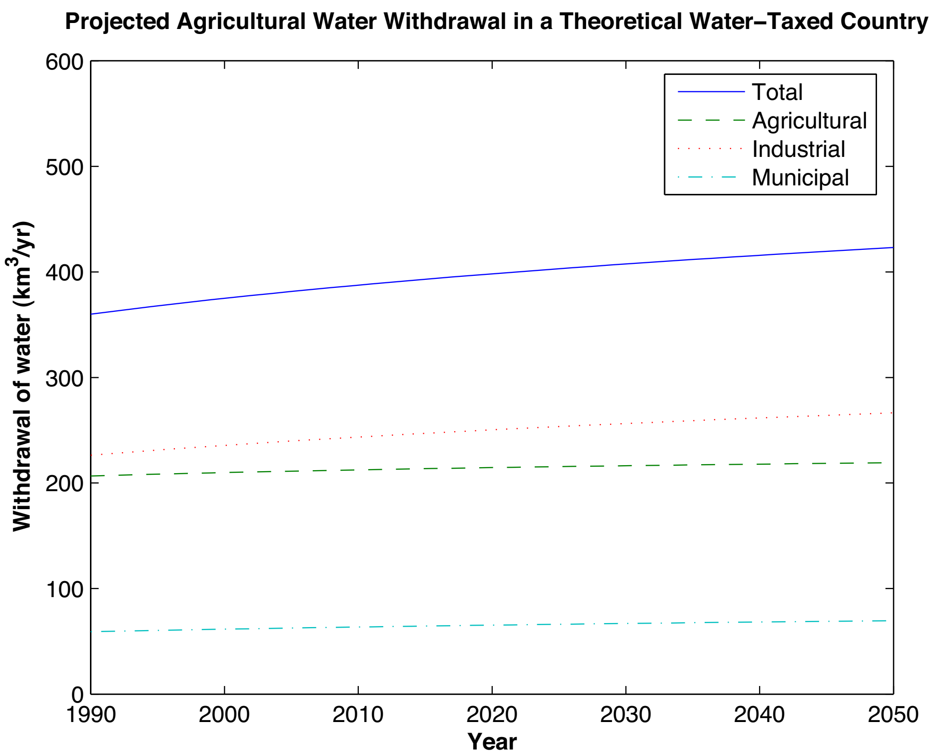

Figure 3. Projected water usage in the U.S. 1990–2050.

The second example, seen in **Figure 4**, is a simulation of a water-taxed country that is currently OK but approaching dangerously low levels of renewable water resources. As total withdrawal approaches total available, the economic and political scaling factor becomes negative and forces reduction of water use, even though the population is still increasing. This fictional country is similar in agricultural, industrial, and municipal trends to the U.S.; but because it has greatly decreased water renewability, the outlook is particularly bleak.

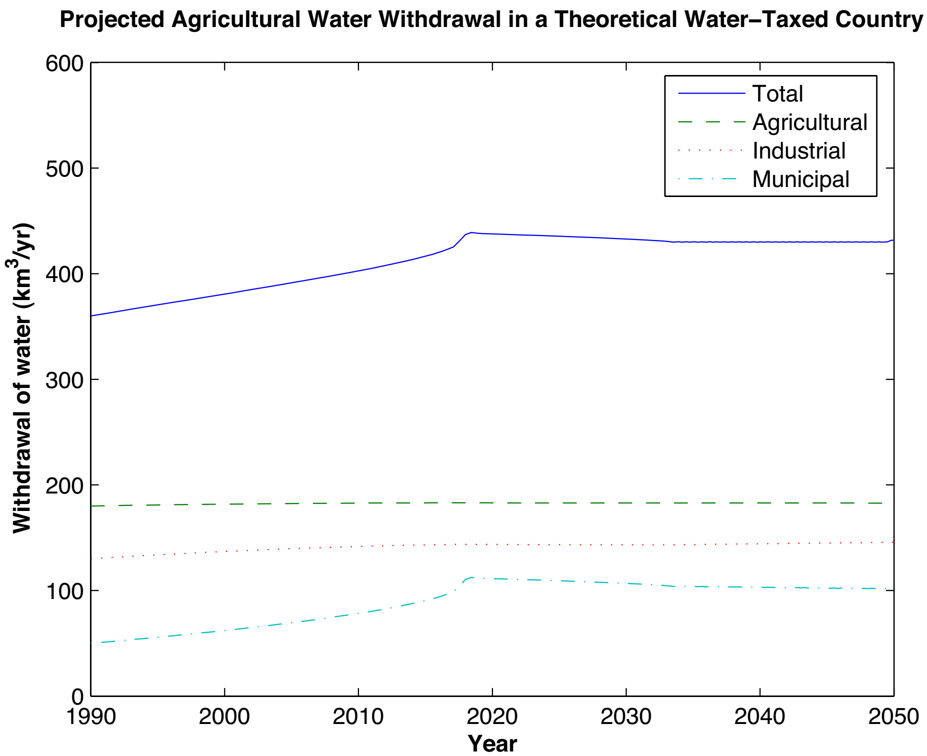

Figure 4. A theoretical country on track for water problems. Initial withdrawal is 360 km^3/yr with total renewable resources 430 km^3/yr.

In our model, we treat each of the values of the parameters P as a regional constant derived from past data. However, it is much more likely that each value changes dynamically. The assumption of constant P prevents our model from adapting to radically changing times.

Figure 5 shows how changing P_A has drastic effects on how water scarcity is affected by political and economic factors. For our fictional country, P_A is 1.05, based on our initial values. Different values do very little to stymie agricultural withdrawal until it is essentially too late. The larger values exhibit a very large dampening effect, keeping agricultural withdrawal low. P_I and P_M affect industrial withdrawal and municipal withdrawal in similar ways.

Limitations of the Model

- The model will have difficulty adjusting to a drastic change in one of the three sectors that instantaneously throws the region from stable to unstable. This is because we chose our political and economic factors to be a constant property of the region. If these values were adjustable, the model would likely be able to adjust for a catastrophe.

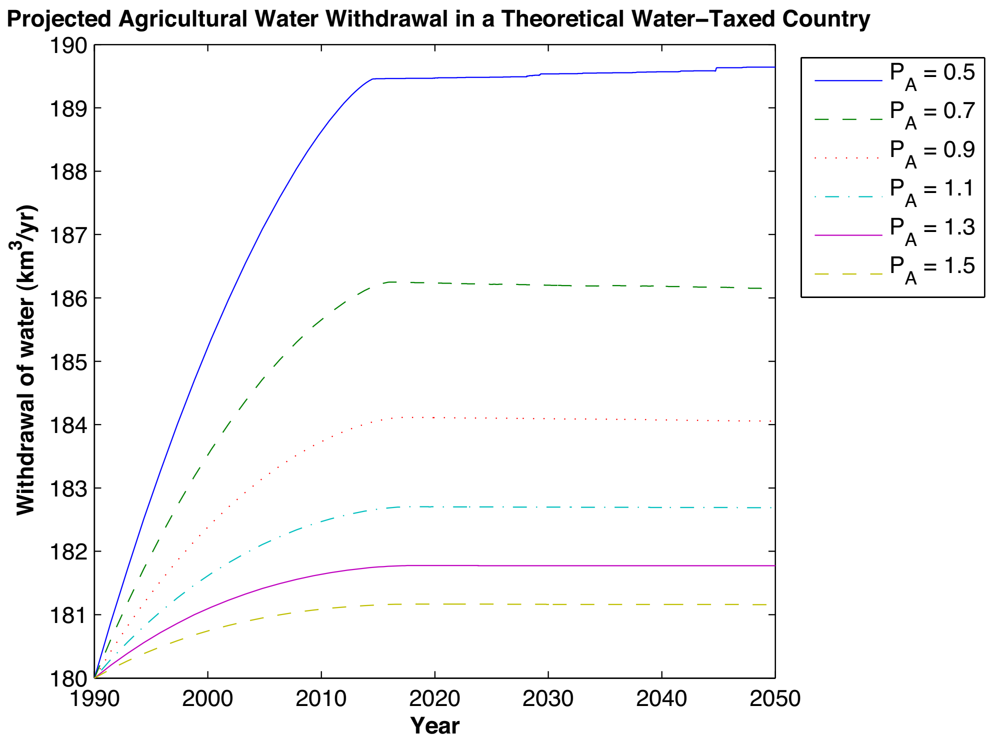

Figure 5. Graph illustrating the damping effects of deliberate variation of the P_A constant

- Since the model relies on trends in population, GDP, and agricultural data, a country with an unstable past might not be able to extrapolate domestic trends accurately enough for the model to be useful.

- We must consider the scope of the region being modeled. More often than not, applying aggregated data for a country to all regions in the country will result in inaccurate assumptions about those regions. For example, even though the U.S. as a whole, has an overabundance of water, the Southwest uses more water than is naturally renewed. A smaller region can apply its own historical data to this model to attain a more accurate representation of its current and projected water situation.

New Approaches to Water Harvesting

Only 2.5% of the Earth's water is freshwater and less than 1% of that amount is renewed each year by natural means [Sayegh 2004]. Growing communities, when faced with the need for freshwater, rely more and more heavily upon fossil water sources, aquifers, and wells to remedy their water deficits. While these sources can naturally refill over long periods of time, people are drawing from them at a rate that is far too fast for the sources to regenerate.

Localities must change how they conceptualize water acquisition. In the status quo, too much emphasis is placed on finding the cheapest water source to fuel economic growth. Instead, communities should focus on strategies to use naturally renewable water sources efficiently and prefer those over nonrenewable sources.

Individual Responsibility

To reduce the strain on centralized water acquisition and distribution systems, the responsibility for water harvesting must first be shifted from the community to the individual. Domestic rainwater harvesting systems would provide a feasible alternative to the inefficiencies of centralized water systems or well-drilling, by allowing individual households to supply a substantial fraction of their water needs. Furthermore, implementing such rain-harvesting technologies is not as far fetched as one might think. Modern rainwater-harvesting systems range in complexity from inexpensive rain barrels to contractor-designed and -installed systems costing thousands of dollars. By using locally harvested water, individuals can mitigate water's growing environmental and economic costs and avoid health concerns regarding its source and treatment [Texas Water Development Board 1997]. In addition, by collecting their own water, citizens can further appreciate the efforts that are necessary to harvest water, and hopefully be more willing to embrace the concept of water conservation. Already, island states such as Hawaii and entire continents such as Australia promote rainwater harvesting as the principal means of supplying household water. Throughout the Caribbean, public buildings, private houses, and resorts collect and store rainwater. Rainwater harvesting can even be used in urban areas with high population densities. In Hong Kong, skyscrapers collect and store rainwater to help supply the buildings' water requirements [Jiwarajka 2002]. Municipalities should require the installation of rainwater harvesting devices in all new construction and encourage the retrofitting of older properties through subsidies or tax incentives.

Municipal Strategies

While residential and commercially-based rain harvesting systems will take significant pressure off of municipal water grids, it is likely that there will not be a sufficient or reliable source of water year round. Municipalities should begin positioning their current water supplies as the "fallback" for when individual water harvesting is not sufficient, and as a result charge more for municipal water. Prices should be intentionally set at a premium over the cost of harvesting the water, to encourage people to conserve and to promote improvements in water use efficiency by returning the excess capital to the community in the form of grants.

Similarly, municipalities must also work to improve the efficiency of their water use. The City of New York has a long tradition of investing in the protection and improvement of much of the watershed from which it receives the 1.3 billion gallons of water it needs every day. As result of this careful planning, the city uses no fossil water, relying solely on its network of 19 reservoirs in a 1,969 square-mile watershed that extends 125 miles north and west of New York City [City of New York . . . 2002].

Some cities, however, may not have an abundant supply of renewable water. When naturally renewable water sources seem to be exhausted, municipalities should prioritize investing in additional technology to account for their shortfall of water, instead of turning to fossil-water pumping. This may be more expensive in the short term; but investing in efficiency programs, improving water purification and desalination techniques, or buying and rerouting water from other regions with abundant natural sources will save in the long run, by lowering dependence on fossil water and preventing exhaustion of nonrenewable water sources.

Agricultural Rain Harvesting

In agriculture, rainfall can be captured, diverted, and stored for plant use. If fields are plowed so that the plowing contours wrap around the terrain rather than run down inclines, a higher fraction of the water can infiltrate into the ground. This method also reduces water pollution by preventing soil erosion, preventing contamination of usable water downstream. Similar effects can be achieved by deploying precision leveling of fields, eliminating inclines and thus the means for wasteful runoff. Both of these techniques do not require sophisticated machinery but instead simply modify current practices. Improving agriculture water efficiency in the United States alone would save over half a cubic kilometer of water per year, enough to satisfy the needs of 3.6 million people [Pacific Institute 2002].

Last Resort: Fossil Water

Communities and individuals should turn to fossil water as a last resort and should take steps to protect and maintain the aquifers or wells they harvest from. In addition, drawing from these wells should come at an added premium, to further discourage use. Fortunately, many regions with seasonal water scarcities also have a "rainy season." By installing new methods of groundwater management such as artificial recharge or injection of surface waters during seasonal wet periods, it is possible to extend the life of many freshwater aquifers. Such practices have already been successful in the U.S. [Slattery 2004].

For illustration of the ideal progression of water use, see **Figure 6**.

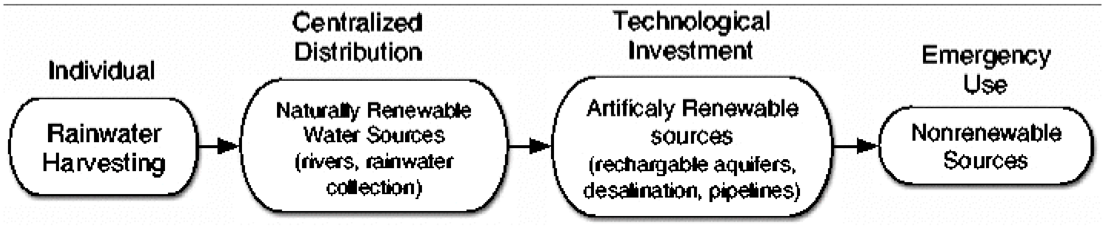

Figure 6. Ideal progression of water usage.

Developing Alternatives to Water

Salt Water

Though salt water has limited applications in agriculture and industry, due to the corrosive nature of salt, China already uses some salt water to conserve freshwater. A major domestic use of water is flushing toilets (30–35% of domestic water). However, there is little reason that toilets must contain freshwater. Instead, some Asian cities have begun experimenting with parallelizing the plumbing in houses in an attempt to replace the freshwater in toilets with seawater. Using seawater in this way not only allows freshwater supplies to be stretched over a longer period of time, it is also more cost-effective. In China, residents pay for processed seawater only 0.5 yuan ($U.S. 0.06) per ton, about one-eighth the price of fresh tap water [A liter here . . . 2004].

Greywater

Greywater—wastewater except toilet wastes and food wastes from garbage grinders—can serve as a substitute in some applications; 30–50% of all water used domestically is greywater, most of which can be easily reused in a variety of applications. Industrially, greywater can be used for air conditioning, cooling, general washdown, and street cleaning. Fire protection is another potential use, as are construction activities such as making cement [Emmerson 1998]. Strategies to reuse greywater do not have to change radically how people interact with water. For example, washing industrial parts can be done in stages starting with greywater and using progressively cleaner water [Accepta 2005]. Greywater, after filtering, can also be used for landscaping or agriculture irrigation. Though it may require more upfront infrastructure to use, greywater reuse can ultimately save municipalities money by reducing sewage flows and reducing the demand on potable water supplies [Martin 1997].

Desalination of Salt Water

Regrettably, desalination of seawater is not the answer to the world's freshwater needs, because it is highly energy-intensive. Since most of the world's energy is generated by fossil fuels, intensive desalination would simply replace one nonrenewable resource (water) with another (coal, oil, gas). However, desalination is still an option for locations that desperately need additional water.

Regulation of Harvesting

Almost every body of water in the world has been negatively impacted by human water harvesting, whether from over-harvesting, nutrient enrichment, agricultural runoff, or toxic pollution. Mexico's Lake Chalapa, the country's largest body of freshwater, lost 75% of its original volume as a result of over-harvesting water from its tributaries, for irrigation purposes and for the water supply of Guadalajara. [Living Lakes 2003] In Central Asia, the freshwater Aral Sea, which lies astride Kazakhstan and Uzbekistan, was once the fourth largest lake in the world. Today, the lake is only 20% of its original volume as result of Soviet diversion for agriculture of water from its tributaries. In Africa, Lake Chad, which spanned 25,000 km^2 of surface area in 1963, has shrunk to 1,350 km^2 today as a result of aggressive expansion of irrigated agricultural projects [Coe 1998]. In each case, local wildlife paid the price of the water diversions as the salinity of the lakes increased and available habitats were destroyed.

Large lakes are natural gauges of water use: Use a lot of water, and they go down; use too much water, and they die. In Los Angeles, simple water reduction and reclamation measures were implemented to compensate for the water that would have been used from Mono Lake, saving it from annihilation.

Water storage is an important issue in many regions throughout the world. During dry seasons, such localities often experience water shortages, while during the rainy season, usable water is lost to flooding. Aquifer recharging provides a simple and effective way to store water during the plentiful rainy season. Excess rain water is channeled into recharge basins where it naturally filters through hundreds of feet of earth before entering the groundwater aquifer. In this way, groundwater supplies can be naturally recharged and available for future use during the dry season [City of Peoria ... 2003]. Actively maintaining these natural freshwater storage regions is essential to securing freshwater for much of the world. Underground aquifers store 97% of the world's unfrozen freshwater, and they provide drinking water to almost one-third of the world's people. In Asia alone, more than a billion people rely on groundwater for drinking, and in Europe it is estimated that 65% of public water supplies come from groundwater sources [Ramsar Convention ... 1995].

Another danger of excessive water harvesting is greater susceptibility to droughts. As communities harvest more water from renewable sources, their members grow accustomed to elevated levels of water availability. However, during a drought, the amount of naturally renewable water is much less than typical. If the drought drops renewable water levels below the threshold of water needed by the community or nation, a water crisis may result [Dykstra 1999]. Minimizing water needs (and water-harvesting) through conservation or efficiency improvements can insulate communities from droughts, since communities will not have grown accustomed or dependent on unnecessarily generous water use policies. Beyond basic water dependency, excessive water-harvesting also increases vulnerability to droughts by altering the water table and distribution of water.

Protecting the World's Water

Unfortunately, water is not as abundant as it may seem—by 2025, the United Nations projects that 1 in 3 people in the World will not have adequate freshwater for life [CNN.com 2000]. Thus, it is imperative that the governments of the world take steps to help prevent degradation of the world's freshwater supply. Such measures can be taken by focusing efforts in three different areas:

- effective international allocation of water,
- building consciousness among those who may not be aware of the need to preserve water, and
- prevention of lost water due to pollution.

International Allocation

Probably the area of most contention, and the one that requires the most governmental regulation, is allocation of international waters. Over the past 50 years, there have been are 1,800 international incidents concerning the use of international freshwaterways. More than 500 were conflicts, and 21 resulted in military action [Cosgrove 2003, 68–70]. Generally, what causes these disputes is one country monopolizing a waterway, preventing the flow of some water to neighboring countries. Thus, it is crucial that the international community help countries work together to solve disputes over water.

Another way to solve international water allocation disputes is purification technology. One example of technology resolving a conflict is Israel's use of desalination. Of the freshwater for the West Bank of the Palestinian Territory, 80% is owned by Israel. To preempt conflict, Israel (with U.S. help) will construct a large desalination plant to purify water from the Mediterranean Sea and pump it to regions in the West Bank [Pearce 2004].

Other water purification technologies can drastically help prevent degradation of the world's freshwater supply. Currently, many countries discharge waste directly into freshwater sources. While this is the easiest and least expensive solution to wastewater disposal, every cubic meter of waste discharged in this way pollutes about 8–10 cubic meters of consumable freshwater [Rosegrant et al. 1995, 255]. This unnecessary pollution could be prevented by building basic sewage treatment systems, perhaps with international help.

Building Consciousness

Governments can provide some answers to water conservation, but it is also important for individual citizens to be educated about the world's water problems. Generally, when people feel as though a resource is abundant enough to last forever, they use it with reckless abandon. However, if people were to realize that water is a resource to be conserved, drastic improvements in the amount of wasted consumable water can be seen. In the U.S. despite a growing population, per capita use of water has decreased steadily since 1995; and net water use in many countries, including highly populated ones such as China, is beginning to plateau [Gleick 2000, 290–293]. These changes come from domestic and economic reforms of the countries' governments but also from increased societal awareness about water conservation. From domestic improvements such as low-flush toilets to improved agricultural water-saving techniques, countries are beginning to conserve water in daily life.

Avoiding Water Pollution

Governmental regulations have helped control negative side-effects of industrial water use. For more drastic reductions, new regulations or social initiatives need to "shift the corporation's thinking from [pollution] compliance to pollution prevention" [Greer et al. 1999]. The company itself can save substantially with reduced resource consumption and waste [Greer et al. 1999]. An initiative to support such organizations, and universalize their scientific waste-reduction procedures, would serve as yet another mechanism to decrease the continuing abuse of the world's freshwater supplies.

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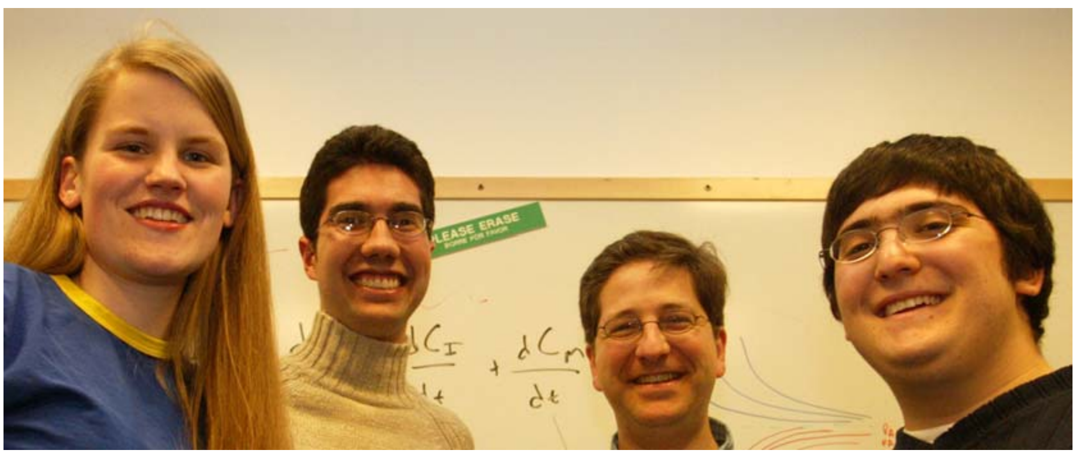

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