Projected Water Needs and Intervention Strategies in India

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Abstract

We formulate an "excess water ratio" (EWR) metric for water scarcity that improves upon currently used metrics such as the Water Stress Index (WSI), by computing the per capita excess water available in a region, thus measuring the impact of water shortage on individuals.

We start with the amount of naturally available water, then subtract personal use, industrial use, and agricultural use. Dividing the result by the total population determines the annual amount of water available but unused per individual, a goal that is unique to our model.

We apply our model to India, which suffers from lack of safe drinking water and a high rate of waterborne diseases. We model growth rates for the environmental and social factors that influence water use so as to determine the growth of water needs. We develop a secondary model that utilizes government predictions of water use and population growth to extrapolate our EWR measure.

Taking these two models together, we conclude that excess water per capita in India will be around half of its current level by 2031.

We explore intervention measures, addressing both supply and demand sides, including watershed development, waste treatment, and broader cultural changes in food production.

We find the cumulative impact of proposed infrastructure improvements to be minimal, delaying the point at which India's EWR diminishes to zero by just one year (from 2083 to 2084).

Changes in agriculture could have more impact. Specifically, switching all rice and wheat production to millet over a 30-year period pushes the year India hits zero EWR back to 2097.

All of this means that large cultural shifts in demand for water will ultimately be necessary for India to achieve long-term water sustainability.

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Introduction

Water has been absolutely critical for all humans, everywhere, since the beginning of time. Every human needs at a bare minimum 20 liters of water to survive [1]. The need for that water is rooted deeply in our biology: at 1% water deficiency humans get thirsty, a 5% shortfall causes fever, at 10% short we are rendered immobile, and death strikes after just a week of 12-15% water loss [2]. Given these biological realities, it is not a surprise that the first and most basic category of water use in human society is personal consumption.

However, it is not enough simply to have sufficient water to drink. In terms of total water consumption, personal use is actually a fairly small—if absolutely essential—piece of the pie, just 5% on average of a given country's consumption [3]. By far, the majority of water that all societies consume, 75% on average, is used not to keep from dying of thirst but rather to keep from dying of hunger; that is, it is used on agriculture. The remaining 20% of water consumption is by industry.

On the face of it, it is hard to imagine why water scarcity could ever be an issue on a planet that is 70% covered with water [4]. The problem arises when we consider the conditions that make water usable: It must be fresh (not too salty), liquid, and physically accessible. The first condition eliminates all but 2.5% of all water from consideration, the second eliminates two-thirds of what remains, and the final condition brings the total of fresh liquid water near or at the surface (i.e., usable water) down to just 0.003% of Earth's fresh water [3].

Due to natural replenishment through the water cycle, even that tiny fraction of available water has managed to sustain all human life that has existed since antiquity. The main reason to expect that condition to be different going forward is the exponential growth of human population growth. It took almost 12,000 years for the human population to go from zero (circa 10,000 BCE) to one billion (circa 1800 CE). It took 125 years to go from one billion to two circa 1930, 30 years to get from two to three billion in 1959, and 15 years or less to acquire each remaining billion, all the way up to today's 7.3 billion people [5], [6]. The UN projects 11 billion people by the year 2100 [7].

This ongoing massive increase drives up water usage in all three categories. More people means more direct individual consumers of their 20 daily liters and more water-intensive industry, but—most importantly—it means that everyone must grow more crops. Industrial and agricultural uses have also contribute to pollution [8].

In short, humanity faces conditions of water scarcity that are unprecedented in human history. Accurately modeling future water needs—plus developing strategies that we are all able and willing to implement to bring necessary water consumption down to (or preferably somewhere far below) the upper limit of physical water availability—will be one of the defining challenges of our time.

Model for Water Needs

Outline of Our Approach

In formulating a quantitative measure of water scarcity, we start with a reflection of the Water Stress Indicator (WSI), created in 2005 by Smakhthin, et al. [9]. This model has credibility due to its use in informing international policy making, since the UN Environmental Programme uses the WSI as its measure of water scarcity on public maps [10]. The WSI is calculated using the following formula:

$$\text{Water Stress Indicator (WSI)} = \frac{\text{Water Withdrawals}}{\text{Mean Annual Runoff (MAR)}}$$

Water withdrawals are thus interpreted as a reflection of water use, and the MAR is interpreted as a reflection of water availability. MAR is the difference between water available from precipitation and water lost due to evaporation [11]. Water withdrawals are taken as a sum of water withdrawals for the primary uses of water within a region: industrial, agricultural, and personal. Beyond its use in the WSI, these concepts have precedents in Vorosmarty's index of local relative water use and reuse (2005) and Shiklomanov and Markova's water resources vulnerability index (1993) [10].

A significant weakness of the WSI is that it does not allow for any conclusions to be drawn about the average impact of water scarcity on an individual level. Two regions with the same levels of water availability and water use will have different strains on the daily living of individuals within the regions depending on their populations. Thus, a more thorough reflection of a region's water scarcity should factor in the population of the region. Our approach is to use data representative of water use and availability and formulate a ratio that determines how much water this leaves *per capita* for recreational, commercial, or hygienic uses.

Assumptions

A myriad of cultural and environmental factors impact the availability of water and how much water is needed to sustain the living standards of a region. Because it is impossible to account for the impact of each of these factors on the overall water demands and availability, we adopt a number of simplifying assumptions for our model:

- The only source of water for a region is its MAR. There is precedent for this assumption in the prevailing models of the Water Stress Indicator

(WSI) and of the U.S. Geological Survey. The assumption is reasonable, because while other technologies exist to acquire water, these are not yet widespread enough to present long-term solutions to water shortages.

- Utility from water use for individuals is a strictly increasing monotonic function. This assumption allows us to conclude that individuals, regardless of current water levels, would enjoy having more water available to them. Therefore, although cultural practices in various regions create a perceived need of different water levels, we assume that an increase in water availability would be appreciated by any individual.
- The current aggregate level of water use is in a temporary equilibrium, as the region seeks to efficiently use all water available based on existing demands and technologies. This assumption is reasonable, because to assume the opposite would imply that the region is currently using more water than is physically present.
- Government policy and individuals are informed about the safety of the water available to them and accordingly use the available water for appropriate purposes. Historically, this assumption has not always held because unclean water has led to diseases. A more complex model would take into account the ubiquity of this knowledge throughout the population.
- Geographic distribution of water sources and consumption is not a factor in a country's water scarcity. In reality, available water in one region does not necessarily provide adequate water to another region, due to the economic and logistical challenges of transporting large quantities of water. However, because people commonly settle and farm in land with abundant water, we do not consider the effects of transportation of water.

An Approach to Projecting Water Availability

We formulate an Excess Water Ratio (EWR), which represents the amount of unused water in a region that is available per person. A higher ratio implies that more water is available per person, and thus a higher EWR for a region suggests that water scarcity is less of a concern for the region:

$$\begin{aligned}\text{Water Use} = \text{Water Use from Industry} &+ \text{Water Use for Agriculture}\\ &+ \text{Water Use for Personal Use}\end{aligned}$$

$$\text{Water Availability} = \text{Mean Annual Runoff}$$

$$\text{EWR} = \frac{\text{Water Availability} - \text{Water Use}}{\text{Population}} = \frac{\text{MAR} - \text{WU}_i - \text{WU}_a - \text{WU}_p}{\text{Population}}$$

For the model to be used for projections into how water scarcity of a region will change in the future, it is important to break down the variables of the EWR into components that factor into the long-term growth rate. By understanding the trends of these components and the relationship between the components and the long-term growth rate of water use, rates for future water needs can be extrapolated.

Water use in agriculture has several factors that are similar to the factors of water use in industry, such as the level of agricultural production and the water-intensity of agricultural products. For instance, in low-income countries, irrigation can make up to 90% of water withdrawals. The most water-intensive crops include rice and cotton, which require up to 29,000 and 5,000 liters of water per kilogram of crop respectively [12]. Other factors important to take into consideration are the availability of irrigation technology and the increase in needed water due to climate change. In particular, climate change increases the amount of water needed for agriculture, through rising temperatures, and requires modifications in agricultural practices due to shifts in global climate systems [13].

Water use in industry is primarily influenced by the level of production in a country and the water efficiency of the production [14]. The most water-intensive industries include paper, chemicals, and coal products [15]. The water-intensity of the industry is typically measured by its "water footprint," the amount of water needed throughout production. We assume that water use in industry in a country is proportional to the product of the amount of the economy based in industry and the average water footprint of industry in that country. This would be scaled differently depending on the total economic output of a country.

Water use in personal use is directly related to the population of the region; and we assume that in a region, an individual's water use remains constant over time. We acknowledge that there may be variations in water use depending on the economic development of a region, but because significant changes in economic development are difficult to predict and often occur sporadically, economic development should only be taken into consideration when there is a large potential for a region to experience significant growth.

Finally, mean annual runoff is most directly related to the climate of the region and the amount of precipitation that it receives [16]. When extrapolating the potential mean annual runoff for a region in the future, the historic MAR of the region should be plotted against factors such as precipitation and average temperature.

Evaluation of the Model

Correlation with Water Stress Indicator (WSI)

The scatterplot of **Figure 1** compares the WSI (on the horizontal axis) and the EWR (on the vertical axis); we observe a strong relationship. One significant strength of our model is that the differences between the EWR in water-scarce and water-abundant countries is more extreme than the WSI, thus allowing for a more precise measure of water scarcity.

Additionally, the impact of water scarcity on individual citizens is made clearer by factoring in population. For instance, China and the United States have a very similar WSI (0.48 and 0.50); but the difference in populations means that this water shortage has a larger impact on a citizen of China than on a citizen of United States, so China's EWR is one-third as great (**Table 1** and **Figure 1**).

Table 1.

WSI and EWR for several countries.

	WSI (dimensionless)	EWR ($times10^3$ gal / person / year)
Saudi Arabia	0.995	1
India	0.967	5
South Africa	0.687	273
USA	0.499	393
China	0.478	116
Spain	0.181	837
Russia	0.111	956
Argentina	0.352	422
Sweden	0.040	1675
Colombia	0.037	1673

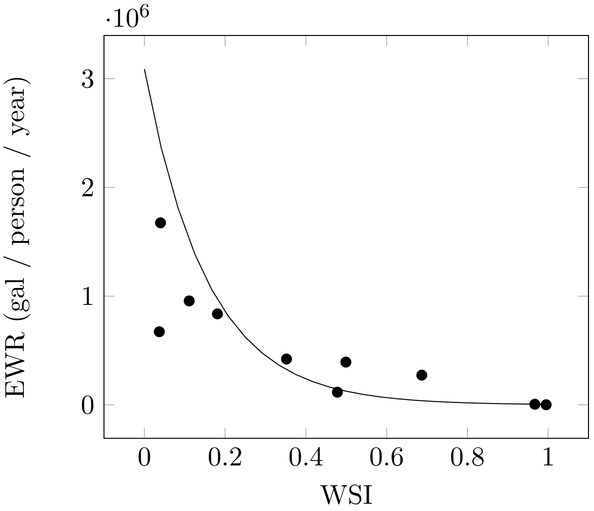

Figure 1. EWR vs. WSI.

Strengths

- **Impact of population.** The most pertinent statistic in water scarcity is how much spare water there is per person, which is taken into account by our model. This accurately reflects that countries with large populations face more significant challenges in harnessing their water supply.
- **Lack of an upper limit on available water.** Other measures, such as the WSI, include a lower limit of 0 on water stress, which makes it difficult to determine the extent to which countries have a surplus of water. Because our equation goes in the opposite direction, such that a high value correlates to little water scarcity, regions can potentially continue to increase their EWR.
- **Predictive power.** By breaking the data into the components that impact their long-term trajectories, our model has more predictive power than pre-existing models. It accounts for the underlying causes of changes in water usage and can take the growth rates of those factors into consideration when predicting the growth rate of water usage.

Weaknesses

- **Availability of data.** Ideally, the model should be applied to a region of any size to determine the overall water scarcity in the area. However, typically information is available only on a national level, which makes it particularly hard to determine levels of water scarcity in small regions within countries.
- **Broadness of categories.** Our model treats agriculture, industry, and personal use as monolithic categories, when in reality each of these factors has various components that can move independently. However, other models such as the WSI have this same drawback, so our model is no weaker than established models in that regard.

A More Complex Model for Water Availability

More recent formulations of the Water Stress Indicator (WSI) acknowledge the importance of environmental needs in calculations of a region's water use [9]. Such calculations are an improvement because they recognize that the maintenance of the environment of a region requires a constant flow of water for the well-being of nearby plants and animals (WU_e). While this water previously was included in the water available to humans for industrial, personal, and agricultural use, the previous model ignores the fact that dipping into the supply of water required for the environment harms the overall ecosystem.

Additionally, a more complex model recognizes that while a region used to get all of its water primarily from its surroundings, technology now enables regions to import water from areas that naturally have more abundant water sources. For instance, Singapore recently has been importing water from the Johore River catchment in Malaysia to make up for its large water needs, and India has established water treaties with Pakistan and China [16].

A more complex model for water is therefore reflected below:

$$\text{EWR} = \frac{\text{MAR} + \text{Import} - \text{WU}_i - \text{WU}_a - \text{WU}_p - \text{WU}_e}{\text{Population}}$$

Case Study: India

Rationale

We have select India for our case study, with its 1.3 billion people [17], just over 18% of the total population of Earth.

Simply put, this massive country is in a major water crisis. The following excerpt from a paper published by the National Bureau for Asian Research sets the scene:

> The World Health Organization estimates that 97 million Indians lack access to safe water today, second only to China. As a result, the World Bank estimates that 21% of communicable diseases in India are related to unsafe water. Without change, the problem may get worse as India is projected to grow significantly in the coming decades." [18]

Main Drivers of Water Scarcity

One important cause of the water scarcity in India is "large spatial and temporal variability in the rainfall" [19]. This means that water is distributed unevenly throughout the country in terms of both geography and of time. Each of these conditions produces water scarcity in specific contexts: the former in relatively dry regions during otherwise wet months, and the latter during relatively dry months in regions both wet and dry.

Another factor exacerbating water stress is poor irrigation systems [19]. This unfortunately is a self-perpetuating problem, because the rates charged for users of the system are very low. The low rates mean that insufficient revenue is generated to support the operation and maintenance of high-quality infrastructure. This results in low-quality infrastructure, which renders stakeholders reticent to pay more for it, which means the quality won't get better, etc.

Some farmers have responded to the previous two challenges by drawing water directly from the ground to irrigate their crops. This has led over the years to widespread overuse of the groundwater, far past the point of environmental sustainability. The resulting depletion of naturally occurring groundwater for agricultural / irrigation purposes has become a driver of water scarcity in its own right [20].

All three leading causes of water stress pointed out above are for agriculture. This is because agriculture is responsible for a staggering 92% of water usage in India. However, in the relatively short-term future, the population is expected to grow rapidly and industrialize. Both of these trends will require more water, both in absolute terms, and as a percentage of water used. What this means is that over the long term, the country will be required to "produce more [food, to support the expanded population and industrialization] with less water" [19]. Or else India will face massive food shortages and / or be unable to develop industrial resources.

Finally, one additional challenge related to rapid population growth that is very much in evidence in India is contamination. "More than 100 million people in India are living in places where water is severely polluted. Out of the 632 districts examined to determine the quality of groundwater, only 59 districts had water safe enough to drink" [21]. Even assuming that the same amount of water is being collected—which may or not be a valid assumption— keeping all of it clean enough to use will be imperative as the country grows.

Prediction of Water in India in 15 Years

Determining the Current State of Water Scarcity

Applying our model for water needs to India means calculating an EWR for India. A variable in our model that is not readily available for the country as a whole is the MAR, which varies significantly throughout the country. For example, in 1997 the MAR of the Ganges River at Farakka was approximately 415×10^9 m^3, while the MAR of the Brahmaputra at Pandu was approximately 511×10^9 m^3 [22]. However, the published WSI statistic requires an estimate of a total MAR for the country, so we can manipulate the formula for WSI to write the EWR in terms of WSI rather than MAR:

$$\text{WSI} = \frac{\text{withdrawals}}{\text{MAR}}$$

$$\text{EWR} = \frac{\text{MAR} - \text{withdrawals}}{\text{population}} = \left(\frac{1}{\text{WSI}} - 1\right)\frac{\text{withdrawals}}{\text{population}}$$

As of 2009, India had a WSI of 0.967, total water withdrawals of 761×10^9 m^3, and a population of 1.25×10^9 [14], [23]. This gives an EWR of $20.75m^3 \approx 5482$ gallons / person / year. This means that the average individual in India has 15 gallons per day of extra water that could theoretically be used, a number extremely low relative to the amount of water currently being used. Moreover, a lack of technology in much of rural India prevents this water from being used. Thus, there is a large strain on India's water, especially when compared to the EWR of other countries. For example, China, with a much lower WSI of 0.478, has an EWR of $374m^3$, which puts it in a much better position.

Preliminary Estimation of Growth Rates of Water Use

We assume that in the relatively short span of 15 years, the MAR for India will remain constant. This assumption is not fully accurate, since climate change will likely alter India's climate in a way that decreases water availability. However, the proposed model will still be helpful because it places a lower bound on the state of India's water scarcity, such that water shortages in the next 15 years will be at least as bad as proposed by the model.

We start by formalizing our assumptions about the factors that impact the water use from industry, agriculture, and personal. Water use from industry and agriculture are each assumed to be a product of their respective production levels and water footprints. We also assume that there are two distinct population groups, urban and rural, with differing personal water use (assumed constant for each group). These equations are formalized below:

$$\begin{aligned}&\text{Industrial Water Use}(I)\\&\qquad= \text{Industrial Output}(O_i) \times \text{Industrial Water Footprint}(F_i)\end{aligned}$$

$$\begin{aligned}&\text{Agricultural Water Use}(A)\\&\qquad= \text{Agricultural Output}(O_a) \times \text{Agricultural Water Footprint}(F_a)\end{aligned}$$

$$\begin{aligned}\text{Domestic Water Use}(I) &= \text{Urban Pop.}(U) \times \text{Avg. Urban Water Use}(W_u)\\&\quad+ \text{Rural Pop.}(R) \times \text{Avg. Rural Water Use}(W_r)\end{aligned}$$

$$\text{Total Water Use}(W) = I + A + D$$

$$\text{Growth Rate of Water Use from } I(g(I)) = g(O_i) + g(F_i)$$

$$g(A) = g(O_a) + g(F_a)$$

$$g(D) = \frac{U \times W_u}{D} g(U) + \frac{R \times W_r}{D} g(R)$$

$$\begin{aligned}\text{Water Use(target year)} &= I\big(1 + g(I)\big)^{\text{target}-\text{current}}\\&\quad+ A\big(1 + g(A)\big)^{\text{target}-\text{current}}\\&\qquad\qquad+ P\big(1 + g(D)\big)^{\text{target}-\text{current}}\end{aligned}$$

In the equations, we use the common approximation that the growth rate of a product is approximately equal to the sum of the growth rates of each factor. According to the World Bank, India's urban population growth is 2.38% and rural population growth is 0.68%, with a total population growth of 1.2% [24]. Additionally, the average urban citizen of India uses 126 liters of water per day for personal use [25]. Factoring in information on India's population, total personal water use in India, and the current percentage of the population that is urban, we calculate the growth rate of water for personal use:

$$g(D) = (0.319)(0.0238) + (0.681)(0.0068) = 0.0122 \approx 1.22\%/\text{yr}$$

Because of the large variations in water footprints for different industries and crops in India, we assume that $g(F_a) = g(F_i) = 0$ within the 15 years of our projections. However, we ultimately conclude that this assumption is reasonable, since India's government has been slow to adopt policies that promote drastic economic change. [26] Therefore, within the relatively short timespan of 15 years it is unlikely that the economy will change in a way that drastically alters the average water footprint of industries. The growth rate of India's agriculture sector varies significantly each year but has centered around 3.8% between 2006 and 2014 [27]. Additionally, the growth rate of India's industrial sector has been about 5.0% during the same timespan [28]. We therefore estimate that water use in 2031 will be given by:

$$\begin{aligned}\text{Water Use}(2031) = (688 \times 10^9\text{m}^3)(1.038)^{15} + (56 \times 10^9\text{m}^3)(1.0122)^{15}\\ + (17 \times 10^9\text{m}^3)(1.050)^{15} = 1306 \times 10^9\text{m}^3\end{aligned}$$

This means that unless water use decreases or water availability increases beyond this projection over the next 15 years, the EWR will become negative, since water use will surpass availability. Effectively, this simplistic first model shows that with no change in current behavior India will be out of water before 2031.

Our model presents a more extreme outcome than other models, such as those of the Indian government [29]. One factor that accounts for this is that we assume that each realm of water use is growing exponentially, which represents a worst-case scenario. Additionally, we assume that average water footprints remain constant, while it is entirely possible that the average water footprint decreases with the scale of industry.

A More Robust Computer Model

Because the Indian government predicts the amount of water available and water used in different sectors of the economy [29], we can estimate the excess water ratio in a given year by matching the amount of water in each category to a polynomial function using Matlab's `polyfit` function. We use the Indian government's predictions rather than data from past years. We reason that interpolation of the EWR for a year between the years predicted by the government will be more accurate than an estimation extrapolated from data from many years before. To find the EWR, we compute the excess water ratio with each component's value corresponding to its output of the polynomial function for that year:

$$\begin{aligned}&\text{Excess Water Ratio}\\&\quad=\frac{\mathrm{WU}_a+\mathrm{WU}_d+\mathrm{WU}_i+\mathrm{WU}_p+\mathrm{WU}_{in}+\mathrm{WU}_{ec}+WU_{ev}}{\text{Population}}-\text{WAPC},\end{aligned}$$

where WU_a represents water use for agriculture and irrigation, WU_d represents domestic water use, WU_i represents industrial water use, WU_p represents water use for power, WU_{in} represents water use for inland navigation, WU_{ec} represents water use for ecology, and WU_{ev} represents water lost to evaporation. These are the categories detailed in [29] as significant Indian water uses. WAPC is water available per capita.

Furthermore, we can use the model to assess the effects of intervention policies. We graph India's EWR from 2000 to 2050, rooted in the Indian government's predictions of water availability and usages in 1997, 2010, 2025, and 2050. For the purpose of demonstrating the model, we assume that intervention projects will increase the amount of water by 30 billion m^3 in 2020 and 50 billion m^3 in 2030. **Figure 2** shows the EWR without interventions, and **Figure 3**) the estimated results with interventions. In each graph, the lower curve is a high projection for increases of water usage while the upper curve above gives a low projection. Because the government predictions assume the development of the nation as a whole, the added components for intervention policies are for policies not already envisioned and accounted for by the government.

Assumptions for the Computer Model

- Changes to population and amounts of water available/used are predictable. A variety of political, economic, and social factors influence how much water India consumes and has available, some of which are not quantifiable. To avoid arbitrarily quantifying possible events, our model assumes that the Indian government's predictions in [29] will be accurate.
- Changes to quantities over the time interval can be interpolated accurately with polynomials.

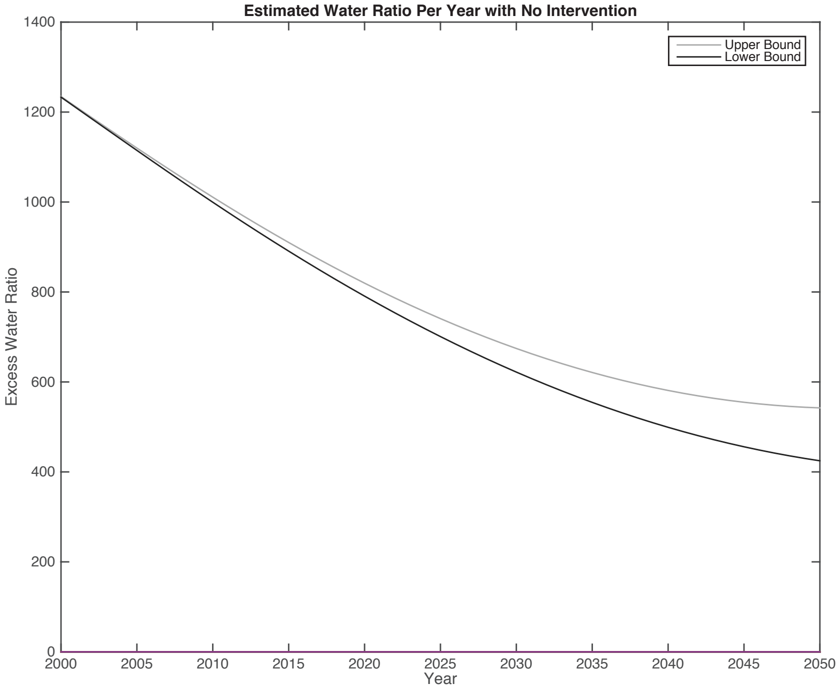

Figure 2. India's projected excess water ratio (EWR) without interventions, 2000 to 2050.

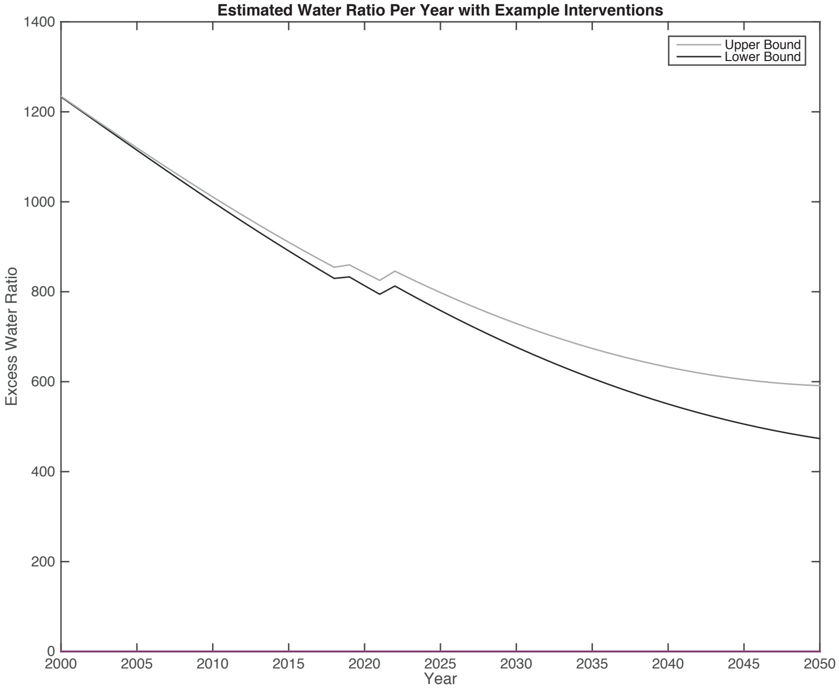

Figure 3. India's projected excess water ratio (EWR) with interventions, 2000 to 2050.

Conclusions for Impacts on Citizens

From the first model, we note that a demographic shift impacting water scarcity in India is the increasing proportion of the population living in urban areas. Because urban populations typically use more water than rural populations, this puts a larger strain on India's water supply and is one of the largest sources of predicted water increases in the next 15 years. Therefore, an impact of water scarcity will be a decrease in standard of living for cities, as resources strain.

The first model also assumes that water use will increase along with the current growth rates of industry and agriculture. However, one of our assumptions is that society cannot use water beyond the water physically available. Thus, the prediction of water use from the first model should be interpreted as the ideal amount of water availability given current growth rates. Realistically, a water shortage will limit India's economic growth potential, as agriculture and industry will have to slow down their current rate of expansion with water as a limiting resource. However, the most powerful impacts are the impacts of water shortages on the lives of ordinary citizens in India. With its current water shortages, over 21% of India's diseases are water-related and only 33% of the country has access to traditional sanitation [31]. Unless the pace of technology improvement is somehow able to keep up with the pace of water needs, these issues will only worsen.

Intervention Plans for India

Intervention Plans for India's Water Scarcity

In [32], the UN Food and Agricultural Organization (FAO) notes that the most comprehensive water scarcity interventions address both the demand and supply sides of water scarcity to help align the goals of parties on each side. This report in fact deals with interventions for agricultural water use in India, which is particularly relevant since this category makes up the largest share of India's water use. We discuss two intervention strategies that for increasing supply: watershed development and water recycling from waste. We also discuss intervention strategies that focus on decreasing demand, such as societal changes in food consumption and changes in agricultural production. Some additional projects may be helpful but are limited. For instance, many scientists believe that dams would help to improve India's water supply; but dams also have many adverse side effects, as illustrated by the Narmada Dam project in India, which displaced 200,000 people and had disastrous environmental consequences such as the flooding and salination of land near the dam that ruined crops [30].

Watershed Development

Water supply can first be improved by constructing watersheds throughout India. A 2005 study performed a meta-analysis of 311 watershed development case studies and determined that the construction of watersheds increases water storage capacity, increases cropping intensity, reduces water lost to runoff, and reduces soil loss [33]. The same report concludes that approximately 380 watershed projects have been constructed in India, allowing for an increase of 260,000 hectares of agricultural production. On average, then, each project has provided irrigation needed for 684 hectares. Different crops require different amounts of water, so the water requirement is not uniform for each hectare of land. However, due to the absence of more specific data, we make the simplifying assumption that water consumption per hectare is constant throughout India's farmland. India cultivates 170×10^6 hectares and uses 688×10^9 m^3 of water for irrigation [19], which averages out to 405 m^3 per hectare. We conclude that each completed watershed allows for an increase of $276,800$ m^3 of water for agriculture.

Of course, watersheds cannot be constructed infinitely, because there is a limit on how much water can be recovered; but so far, no limiting capacity of watershed development has been seen in India. We therefore recommend that the Indian government selects 50 areas that could potentially benefit from a watershed and begin construction immediately, which would give a yearly increase of 1.38×10^7 m^3 of water. Studies suggest that the areas that would benefit most are semi-arid regions with erratic monsoons that prevent water from quickly recharging [34]. We assume in our model that these watersheds will begin construction in the next year, and will follow the timeline of the Neeranchal National Watershed, which was built over six years. The changes will then go into effect in 2022 [35].

Water Recycling and Waste Treatment

India's population produces a large amount of waste that can be treated to be used for agricultural purposes. There is precedent for treating waste that can be expanded over the next several years to provide a consistent source of water. Water from waste can only be used in agricultural purposes, because it does not meet the quality standards for personal or industrial use [30]. Currently, this water is being used to irrigate trees in public parks in Hyderabad, to cultivate wheat paddies over 2100 hectares along the Musi River, and to support fisheries in East Calcutta. As of 2011, India had 270 municipal wastewater treatment facilities, which have the total capacity of treating 4.573×10^9 m^3 per year [19]. They treat 4.416×10^9 m^3 per year, but 11.03×10^9 m^3 per year is left untreated.

Based on the current capacity of the treatment facilities, each facility can treat 1.69×10^7m^3 per year, so constructing new facilities for the treatment of wastewater would require the construction of 651 new treatment plants. While pricing information for waste treatment plants is not readily available, the construction would be very expensive. However, we believe that the plants would be worth the cost in the long run because they would provide a future sustainable source of water for agriculture.

When we account for this intervention policy in our model, we assume that all untreated wastewater will eventually be treated and used for agriculture, adding 11.03×10^9 m^3 per year. Based on building times for large-scale waste treatment facilities in the United States, we estimate that these could be built in three years and begin working by 2019.

Societal Changes in Food Consumption

One of the largest impacts on demand for water is currently due to food consumption, as "90% of personal water footprints are devoted to food in the form of crop and animal production" [36]. To predict future water availability, we do not assume that this change will be enacted or successful. However, to approach the supply and demand sides of the water consumption issue, governments will soon need to address the unsustainable eating habits of populations. Meat and dairy products are much more water intensive than crops, and the consumption of these foods increases as populations move to urban areas. A cultural shift in eating habits, while requiring a change in attitudes toward foods that would take several years, may eventually become necessary as lower water levels decrease the potential for water-intensive farming.

Changes in Food Production

One of the most significant intervention techniques that India can undertake is to decrease the demand for water from agriculture by subsidizing the production of more water-efficient crops. For example, millet is a much more water-efficient crop than rice or wheat, which currently make up the largest shares of India's agriculture [19]. Specifically, the growth of rice requires 1250 mm on average of rain or irrigated water, wheat requires 550 mm, and millet requires just 350 mm [40], [41]. Millet can also be grown in soil that is far poorer quality than traditional crops. Critically, millet is nutritionally equivalent to rice or wheat, containing comparable levels of protein, fiber, minerals, iron, and calcium.

In our model, we have considered the water impact of switching all of India's wheat and rice production to millet over the course of 30 years. For each land unit of water converted from rice to millet we save 900 mm of water annually, with 200 mm more in savings added for each land unit converted from wheat to millet. Over the timespan modeled, we expect this intervention to produce considerable water savings.

Impact of Water Available of Surrounding Area

One of the most significant strengths of watershed development is that there is no evidence of negative impacts on the surrounding areas. Typically, watershed development serves the purpose of making degraded lands suitable for agriculture, which is independent of the agricultural output of surrounding regions. While the treatment of wastewater has the potential to provide large amounts of additional water for agriculture, studies suggest that the use of treated water may alter soil quality over time [30]. According to the International Water Management Institute, "Ample evidences are available which show that the groundwater in all wastewater irrigated areas has high salt levels and is unfit for drinking. Further, high groundwater tables and water-logging are also common features of these areas" [30]. This poses a health risk to communities that are located downstream of the area, since it may be difficult to separate this agricultural water from personal use in communities that do not have the technology for advanced water purification.

Evaluation of Strengths and Weaknesses

A World Resource Institute report identifies many social and economic benefits of watershed development and concludes that there is a net present value between $5.08 million and $7.43 million. It also points out other benefits that could not be included in the cost-benefit analysis, such as "improvements in nutrition, dietary diversity, and human health" as well as "improved resilience to drought and temperature fluctuations" [30]. A weakness of this proposal is that the development of watersheds can be expensive, and modifications of the natural environment can have unpredictable consequences on the ecosystems. Additionally, a social problem brought up by watershed construction is that historically the construction of watersheds has negatively impacted women in India [37]. The development of watersheds required the closing of common areas where poorer women grazed goats, which deprived them of a large source of income. However, in carrying out future projects,"Some of the negative effects on women could be overcome if a great effort was made to include them in decision making" [37]. Finally, watersheds require a significant upkeep cost, and historically a lack of attention to constructed watersheds has caused them to be leaky or damaged [38].

One strength of waste treatment is that it creates a reliable source of water supply for agriculture, removing much of the uncertainty that characterizes water scarcity in developing countries. The Weighted Anomaly Standardized Precipitation (WASP) index computes deviations in monthly precipitation, and shows that parts of Central India frequently are drier than their average precipitation, making it difficult to group crops given uncertain weather conditions [39]. By diverting treated wastewater to these areas, water can be more efficiently used. Additionally, the treatment of wastewater has a positive externality of long term economic growth for workers in the region. The construction of the facilities requires the hiring of several construction workers, and the constant treatment of waste requires a large permanent staff. As noted above, however, wastewater has the potential to make water less usable downstream, and the construction of the facilities will require a large initial cost from the government. Thus, it is unlikely that the government would be able to fund the construction of all of the plants at one time.

The main benefit of shifting crop production away from rice / wheat and towards millet (and more generally towards more water-efficient varieties) is water savings. Other strengths of this approach include consumers taking advantage of the enhanced nutritional value of millets vs. wheat and rice, and the existence in the status quo of prototype models of effective programs that already provide “training via internet and mobile phone, adapted to smallholder farmers and practitioners, on the best farming practices for drought and heat tolerant crops such as millet and sorghum” [42]. There are at least two key challenges standing in the way of adopting this approach:

- Local tastes have to be taken into account. If no one wants to eat millet, and thus there was no demand for it, no sensible farmer would grow it. Accordingly, gathering and heeding input from the local population of both farmers and consumers to create demand for millet as a food crop would be critical to the success of this intervention.
- Even assuming that it possible to convince everyone to love millet overnight, far more investment would be needed to ensure that sufficient training in proper millet growing techniques, and financial support to purchase millet seed was available to every small farmer that could and would use it to convert their wheat or rice farm into a millet farm [42].

Projection of Future Water Availability

Interventions in infrastructure (**Figure 4**) are insignificant: India would run out of water between 2084 and 2094, rather than between 2083 and 2093 without improvements.

By replacing wheat and rice crops with millet (**Figure 5**), water use significantly decreases, leading to a much higher EWR. Instead, India will run out of water between 2097 and 2107.

Conclusion

We created the new metric of “excess water ratio” (EWR) that improves upon current measures by illustrating the extent to which water shortages

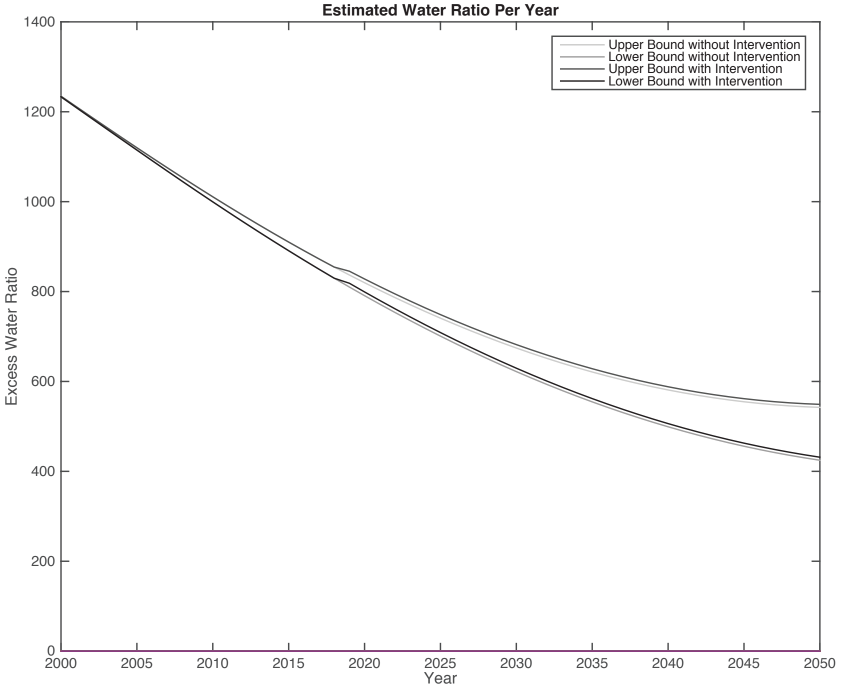

Figure 4. India's projected excess water ratio with and without infrastructure interventions, 2000 to 2050.

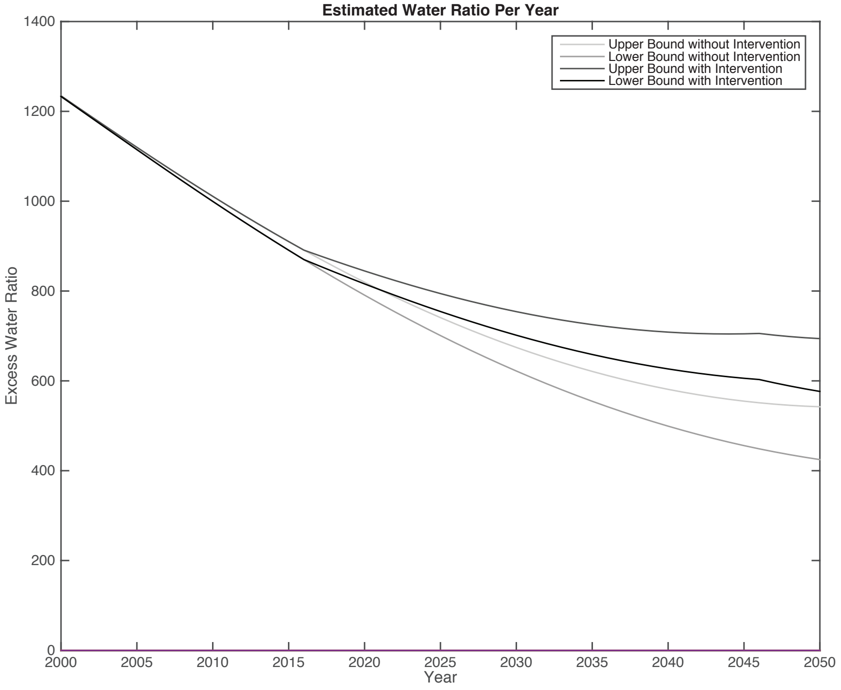

Figure 5. India's projected excess water ratio with and without millet interventions, 2000 to 2050.

impact an average individual. Taking India as a case study, we identified the components that contribute to the EWR and predicted their growth rates so as to extrapolate the growth rate of water needs in India over the next 15 years. Our results illustrate that at current growth rates, the average excess water per capita will be half of the current value by 2031.

We concluded by exploring intervention possibilities to develop long-term solutions for India's water issues. We first looked at strategies that increase the supply of water, but found that these techniques were expensive and did very little to offset the rapidly increasing water demands. When we turned to attempts to decrease the demand for water, such as switching some crop production to the water-efficient grain millet, we found that these could be much more effective in the long term, assuming that they are properly implemented by the government.

Fundamentally though, we conclude that more drastic societal changes will need to be adopted to decrease India's water demand enough to matter.

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