Introduction and Problem Statement

Sustainable United States fresh water supplies have generally stagnated relative to the burgeoning demand from residential, industrial, agricultural, and commercial sources. As the presence of fresh water is necessary for most human development, whether for drinking water, irrigation or industrial usage, it is imperative that the United States develop a plan to meet this challenge in order to ensure its continued capacity to develop as a nation. We seek to develop a comprehensive policy plan to present to the United States Congress to manage the growth of water supply and demand over the period until 2025 according to four significant criteria. First, this plan must supply all projected water needs in every area and allow for variations in water supply. Second, it must not assume the existence of technology that is materially superior to present-day technology, either in function or in cost-efficiency. Third, the plan must not require decreases in water demand due to conservation which cannot be explicitly actualized through empirical statistics and robust public policy. Fourth, it must not result in inflation-adjusted per capita water supply costs of more than twice present values. Fifth, it must not result in cumulative inflation-adjusted capital investment of upwards of $2 trillion (feasibility). To quantify the effects of our plan, we seek to design a computerized model which would represent the cost of transporting fresh water from significant sources of fresh water within a given region to regional processing centers and the cost of transporting this processed fresh water from the processing center to agricultural, industrial, and residential water usage areas within the region. Further, we sought to model the effect of inter-regional water transport and storage procedures, in addition to the fixed costs associated with the maintenance of water transportation methods, e.g. pipelines. Finally, we sought to model the effect of concerted conservation initiatives, balancing this against feasibility concerns and the desalination that it offsets.

Necessary Assumptions for the Model

As the abstract problem presented would provide excessive difficulties for modeling effectively and efficiently, we found the need to make several assumptions. To begin with, it was assumed that the cost of desalinating conventional seawater is a constant $3.79 per 1000 gallons of fresh water produced. According to Yuhas and Daniels (2006), the approximate cost of producing 1 m^3 of water through desalination generally tends to range between $0.70 and $1.40 per m^3, depending on the factory at hand (Yuhas and Daniels, 2006, p. 577). Given this, an average cost of $1.00 per m^3 represents a reasonable approximation of the data points given. This is equivalent to $3.79 per 1000 gallons. In addition, it was assumed that the cost of processing groundwater derived from aquifers was approximately $0.55 per 1000 gallons. Based on data given in Yuhas and Daniels (2006), this seemed to best fit the range of production costs presented for ground water processing, after conversion to Imperial units. Further, the cost of processing surface water was assumed to be $1.10 per 1000 gallons. Similarly, this seemed to best fit the range of production values demonstrated (Yuhas and Daniels, 2006, p.577). Finally, it was assumed that other non-negligible sources of fresh water could not be relied upon. This is justified by the fact that, at present, the US water supply is almost entirely derived from the combination of these three, and that no viable sources have been readily identified for providing cost-effective fresh water.

A number of assumptions were also made about the hydraulics of the pipeline system and the economics of transportation. To begin with, it was assumed that the cost of transporting a given quantity of water over a given distance through pipelines was a constant \$0.00344 per 1000 gallons per mile. The implicit assumption that the cost of transporting water a given quantity of water over a given distance is constant is justified through the Hazen-Williams Equation (Lansey, p. 1), which states that the head loss h_l inherent in the movement of a given quantity of water satisfies $h_l = 4.73LQ^{4.73}/(C^{1.852}D^{4.87})$, where L represents the length of the . If we idealize flow rate, friction, and diameter as constant, then we observe that the energy of transporting a given quantity of water horizontally is directly proportional to the length. Further, as the tendency toward a difference in height above sea level between two points is related to their distance, the assumption that general marginal transportation cost is constant can be justified and the difference will not be excessive. We obtain the specific value from a study conducted in Kally, 1993, which found a cost of \$0.214 per m^3 for freshwater transportation from the Nile River to Gaza over a pipeline of 200 km, of which 0.04 was the cost of the water itself and 0.061 was associated with other expenses not directly related to the water transported. Hence, the remainder, \$0.113 per m^3, is the marginal cost associated with the transportation of water over the pipeline. Approximately half of this is associated with a height differential of 200 m between starting and ending point, and the other half is associated with the horizontal distance. Taking the height difference as typical, we obtain \$0.000565 per m^3 per km as the general cost of water transportation. This is equivalent to \$0.00344 per 1000 gallons per mile. In addition, we assumed that all water is transported by pipeline, which is justified by the fact that nearly the entire United States has access to running water and uses it overwhelmingly over other less efficient forms of water transportation.

The next major assumption that we made was that each metropolitan area and its surrounding region could be modeled without excessive inaccuracy as concentric circles with equivalent areas to the city and the region, respectively for the purposes of modeling transport expenses. Although this does not fit the shape of the state, it can be verified that the sum of all water consumption values weighted by distance in the state is approximately equivalent to the sum of idealized evenly distributed water consumption over all points on the circle.

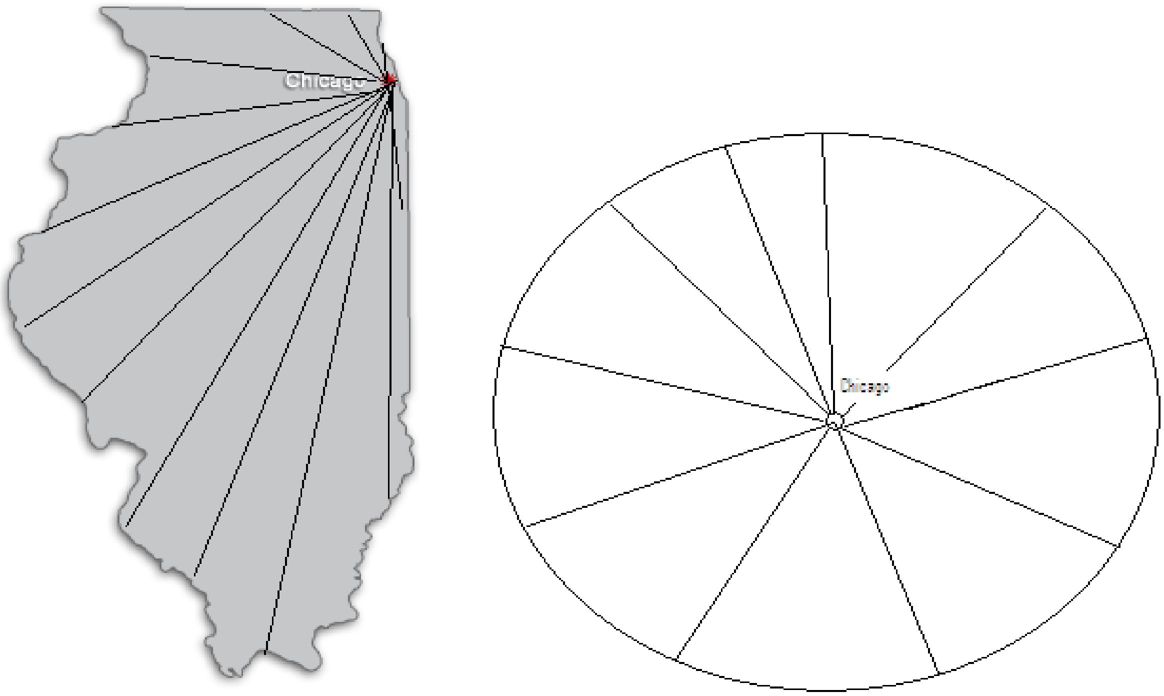

Figure 1. An application of the idealization procedure to modeling Illinois's water transportation costs.

It was also assumed that regionally, there exists an approximately direct connection between any given point on the map with water consumption and the water distribution center. Although water must first travel through mains and often must move along grid-based distribution, we judged that the difference would generally be negligible because over large scales, paths between points on the water distribution grid should approach the idealized distance. To model the distribution of industrial (miscellaneous industrial, mining, and thermoelectric), agricultural (irrigation, livestock, and aquaculture), and residential (public supply and domestic) water consumption, we assumed that industrial water consumption was evenly distributed over the municipal area and that agricultural water consumption was evenly distributed over the area outside of the central municipal area of a region. Further, it was assumed that residential water consumption was proportional to population, and that the population of the central municipal area was evenly distributed over the municipal area and that the population outside of the municipal area was evenly distributed outside of the municipal area. The industrial assumption is justified by the general observation that most significant industrial activity occurs in major urban centers, and the assumption about agricultural usage is justified by the fact that agriculture almost always occurs in the rural areas. Since the overestimates caused by excessively close placement of agriculture relative to the model and the underestimates caused by excessively far placement of agriculture relative to the model, the Law of Large Numbers dictates that the overall consumption figure will be approximately the same. In addition, it was assumed that the water processing and distribution centers for a given region both lie within the largest city in the region. Although this is a considerable idealization, it is generally true that large cities have their own water works (allowing the municipal cost data to be approximately equivalent), and this should not appreciably affect the cost data for extra-urban areas due to the inconclusive nature of the expected difference. It was assumed that the percentage growth in industrial and residential water consumption in a given region in 2025 relative to 2000 would be equivalent to the percentage growth of the population of the region relative to 2000. Although this does not take into account shifting industrial bases in regions which could lead to appreciable effects for water consumption, the industrial base is generally approximately proportional to the population which it anchors and therefore the growth in population should correspond to growth in industry and hence (as the expected effect of shifting industrial bases is inconclusive), the growth in industrial water consumption. The assumption that residential water consumption follows this proportion is more straightforward, as it simply reduces to the assumption that per capita water consumption will remain roughly constant, which is a plausible assumption over such a short period as 15 years. Finally, we assumed that agricultural consumption over that time period would remain constant, as there are no definitive trends toward either increased acreage or decreased acreage, and there are no indications about changes in efficiency of irrigation.

Further, it was assumed that groundwater and surface water gathering is evenly distributed throughout the entire region, for all regions. This is justified by the fact that most regions have little climatic variation within themselves, so groundwater will be close to evenly distributed (the effect of differences in geology throughout should not have a bias in its effect). However, the assumption for surface water is considerably more of an idealization, as rivers and lakes may have some relationship with the position of the largest city in the region. In general one would expect a negligible effect for deviations in surface water relative to the city, so this does not represent an unreasonable assumption. We also assumed that desalination is only available to regions containing segments of coast, and that the cost of transportation is the distance from the nearest point on the coast to the largest city in the region. This is a reasonable assumption because non-coastal regions would not generally have significant access to saltwater, and the distance between the nearest point on the coast to the processing plant would be approximately equivalent to the expected distance between the saltwater collection site and the desalination treatment plant. Furthermore, it was assumed that groundwater and surface water production have already attained their maximum sustainable production values. This is a basic premise of the problem that we are currently studying, and although new sources of fresh water may arise, these will generally be negligible and possibly offset by negative effects of present consumption.

In addition to this, we assumed that any region which has a shortage of water (more consumption than native production) will draw water from the nearest region which has a surplus of water (more native production than total consumption, including transfer to other regions), and that inter-regional water pipelines pass between the distributional centers of these regions. This is justified because, historically, regions with insufficient water to support their base, such as Southern California, on several occasions have drawn from the water supplies of other regions, such as the Colorado River basin (Zetland, 2009). Furthermore, given the other assumptions that we have made, it is reasonable to expect that the inter-regional water pipelines will pass between the distributional centers, as distribution centers serve by definition as the general collection point form which water is sent to sources throughout the area.

We also assume that storage costs vary directly with demand. Furthermore, we assume that pipeline maintenance (miscellaneous non-routine operating expenses) are generally constant (adjusted for inflation). According to data derived from EPA statistics (EPA, 2000), this represents approximately $167.8 billion dollars. This is justified because maintenance is generally proportional more to the length of the pipeline than to the amount of usage necessarily, and other non-operating expenses (such as fixed employee costs, interest, and amortization), will not vary directly with growth in the amount of water transported. Finally, we assume that successful conservation efforts uniformly decrease demand in the relevant area by an identical percentage over all regions. Although conservation efforts may have different actual effects in different areas, the difference between uniform decrease and variable decrease should be negligible as the minor variations in distance should not be extremely significant to the cost data obtained.

In addition, we assume that the capital costs associated with the development of desalination are approximately $6.50 per gallon per day. We derive this from the cost data associated with the Tampa Bay Water project, $158 million dollars for a capacity of 25 million gallons per Diem (Pittman, 2009). Finally, we assume that the capital cost of installing a new efficient irrigation system per 160 acres of irrigable farmland is $700, that the average annual maintenance cost is 4% of the irrigation system's cost, and that installing these new irrigation systems increases efficiency from 75% to 90%, and that the cost of less efficient irrigation systems is $500. We derive the data for cost from statistics given by the Agriculture Department of the North Dakota State University (Scherer, 2005), taking the value of the advanced systems to the nearest $100. We get the efficiency data from a conservative underestimate (to allow for parts of the system already operating at this degree of efficiency).

Finally, it was assumed that the total amount of irrigable farmland in the United States was 60 million acres

Variables

In accordance with the assumptions made, the constant parameters are:

S = , the cost of desalination per 1000 gallons of processed water produced
G, the cost of processing and purification of ground water per 1000 gallons of processed water produced.
U, the cost of processing and purifying surface water per 1000 gallons of processed water produced.
K, the cost of transporting water over a distance, per 1000 gallons per mile
D_{ij} the distance between the centers of regions i and j, for all regions.

The independent variables of the model are:
A_k, the industrial water consumption of region k.
B_k , the urban population of a region k.
D_k , the total population of a region k.
E_k , the agricultural water consumption of a region k.
F_k , the residential water consumption of a region k.

C_k, the radius of the idealized circular city at the center of the region.
R_k, the radius of the idealized circular region k.
J, the coefficient of water conservation
L_k, the total groundwater and surface water production of the region

The integrated variable is
r the distance of an arbitrary point on a radius of a circle.

The dependent variable is

C_k, the cost of water supply to a given region

The Model

Our model broke up the measurement of the cost of water provision into three variable parts and one constant part. First, we developed a list of 84 cities which was obtained by combining the 62 largest cities in the United States with the largest city in each given state. If a state only had one city in this list, then it was regarded as its own region and all of the assumptions about regional population applied above apply to the statistics of the state. However, if a state had multiple cities, the state was divided up into multiple regions, each encompassing one such city. As an idealization, Statistics obtained from the USGS Circular 1268 (Hutson et al., 2000), which enumerates the production and consumption of water by source in the year 2000, were used as the data sources for the fresh water consumption by type for each state and the amount of ground water and surface water for each state.
To analyze the cost of transporting water from a production and distribution center (city), we simply regarded the area of the city limits as a circle with equivalent area, and the region as a concentric circle with area equivalent to that of the region itself. Now we considered the cost breakdown separately for urban industrial and residential, and non-urban residential and agricultural. We considered the urban industrial and urban residential water consumption cost according to our assumption by taking the integral over all points in the region, weighted for distance from the center. This is equivalent to the integral of the weighted circumferences of the circles with the same center and radius n from n = 0 to c, where c represents the radius of the idealized city. This is

$$\int_0^c 2\pi r^2 \, dr = 2\pi c^3/3$$

As we are assuming that industrial and urban residential water consumption is evenly distributed over the inner circle, we observe that the water consumption is proportional to the area
so we can simply multiply by the ratio of water consumption to the area, getting

$$\frac{0.00344 * 2\left(\frac{B_k * F_k}{D_k} + A_k\right)}{3}$$

, where a is the water consumption in the inner circle (the metropolitan area), as the total cost of transportation of industrial water. We find that this also takes care of the urban residential water expenses (as they are also evenly distributed over the region). Finally, we can apply a similar procedure to the distances from c to R, where R is the radius of the idealized region in general. Taking

$$\int_{c}^{R} 2\pi r^2 \, dr = \frac{2\pi(R^3 - c^3)}{3}$$

As, once again, agricultural and rural residential regions are assumed to be evenly distributed over this, it yields a cost of:

$$\frac{0.00344 * \left(e_k + \frac{F_k(\mathrm{S}_k - B_k)}{D_k}\right)(2R^3 - 2c^3)}{3R^2 - 3c^2}$$

Therefore, the total cost will be the sum of the costs over these two areas.

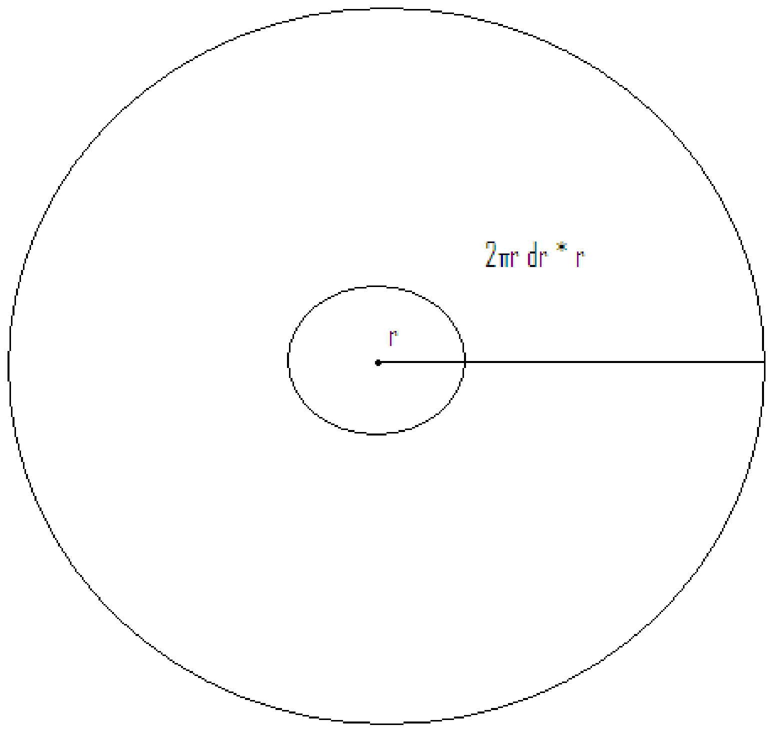

Figure 2

The integrand was derived by integrating their circumferences over the radii of the concentric circles, weighting the circumferences according to distance from the center (r).

We can apply the same procedure to finding the cost of transporting raw groundwater, surface water, and desalinated water, as we applied the same assumptions about uniform distribution (however, as there is no distinction between urban and non-urban areas, we can take the value derived for the inner urban region and substitute R for c. Hence, by summing these three together according to our assumptions, we get the total cost of transporting raw water for processing. We get the cost of processing by simply multiplying out the quantities produced by the values consumed. This yields:

Finally, we simply transferred all excessive water demand to specific hubs of desalination production, accounting for increased expense.

The program itself used custom-made object-oriented file manipulation routines to actualize the mathematical model of the water system. Enclosed is the source code for the first model, which computes the yearly cost of water for the United States in 2000.

Proposed Solutions

Based on the above information about the precarious state of the ground and surface water sources, it would violate our goal of a sustainable environmental effect to further draw upon these resources. Therefore, the only sources of new water that would be potentially feasible and generalizable would be water derived from desalination of sea water. Furthermore, after investigation of potential sources of cost-effective conservation, we observe that a significant source of highly cost effective conservation is replacing highly inefficient flood irrigation systems with efficient drip irrigation or spray irrigation systems. Therefore, it was proposed to consider the cases of day-to-day and fixed expenses associated with goals of 0%, 5%, and 10% water conservation, to be derived from improvement in the efficiency of irrigation systems. The remainder of increase in demand would be taken up by increased investment in efficiently-chosen desalination facilities which would serve as hubs from which desalinated water would emanate out according to distance from the hubs. The cities of Boston, MA, Virginia Beach, VA, Columbia, SC, New Orleans, LA, Portland, OR, and Los Angeles, CA, were chosen to serve as these hubs in order to be both dispersed throughout the country's coastline (to allow for efficient transportation) and due to their prime waterfront locations.

Model Testing

An integral part of verifying the utility of a model is not only ensuring that it intuitively covers the scope of the phenomenon to be modeled but also to check its performance against actual data. To verify the usefulness of the data, it was decided to check it based on 2000 levels of population and water consumption, to verify that it approximately matched (to within an accuracy of approximately 20-30%) the data given by the EPA for the total expenses of US water production (from the perspective of supply-side expenses). The EPA (2000) gives the average cost of producing and delivering water as $3.17/1000 gallons. In 2000, the US total freshwater consumption is 345,453,000,000 gallons per day (Hutson et.al., 2000). Therefore, the total annual freshwater consumption of the US was approximately 1.2605×10^{14} gallons per annum. Assuming that the cost data given by the EPA represents the entire cost of production (including maintenance and operation), the total cost of water of the US was approximately $399,581,432,250. After entering the population data and relevant consumption data for the United States in the year 2000 into the program that was developed, an overall cost of $343,000,000,000 was identified for the supply of freshwater to the United States. As this is only off by 14.47%, for a model that attempts to synthetically model a highly complex phenomenon, it seems that this model is generally well-suited to projections about future events, as with those which we are attempting to evaluate.

Conclusion

In conclusion, the strategy that was developed to meet the projected water demand of the United States in a cost-effective and sustainable manner over the past 50 years was to offset declines through a strategy combining construction of desalination plants in strategic coastal locations and emphasis on subsidies on efficient irrigation techniques, perhaps one of the most cost-effective means of water conservation. Three possible cases were inputted into the model, one of which allowed for 0% water conservation, one of which allowed for 5% water conservation, and the other of which allowed for 10% water conservation. Inputting 0% water conservation caused water provision expenses to climb significantly due to the expensive nature of water desalination programs, and the ultimate value of the water expenses exceeded $427 billion. Furthermore, inputting 5% water conservation caused water provision expenses to climb to a somewhat lesser value of $380 billion. Furthermore, the fixed expenditure at this point were of the order of $89 billion, according to our assumptions. Finally, 10% conservation was rejected upon examination, as under our assumptions that irrigation reform would result in increased efficiency of approximately 20%, even if all irrigated farmland were converted on this basis, it would lead to a maximum efficiency gain of approximately 8% of water usage. Therefore, it does not match the feasibility criterion required by the problem.

In addition to the obvious quantitative advantages of 5% conservation, there are also significant environmental advantages to such a policy. The reverse osmosis process of desalination consumes more than 10 times more energy (Yuhas & Daniels, 2006) than comparable processes for other forms of water, implying a significant potential effect for energy efficiency of excessive use of reverse osmosis desalination. Therefore, the policy of striving toward 5% energy efficiency under the 5% solution outlined above (construction of desalination plants able to produce approximately 11.3 billion gallons per day of water), while subsidizing the conversion of approximately 60% of US irrigable acreage to efficient irrigation processes would produce an optimal combination of economic viability, feasibility, and water provision while minimizing negative environmental and economic impacts of the plan.

Strengths and Weaknesses of the Model

As a measure of the total cost of production and distribution of freshwater, the model exhibits a number of strengths in accurately conceptually modeling the cost dynamics of water transportation and of various water resource development options. Furthermore, it has a number of strengths in its respect for the nature of the national geography. However, it could be improved through less use of extreme idealizations such as the circular nature of every distribution region. In conclusion, this, while a strong model, could certainly be improved upon given time and computational resources.

Position Paper to Congress

The problem of supplying the increasing population of the United States with sufficient fresh water to fill all of its needs is certainly a significant problem. It certainly must be considered with a great deal of gravity through all of its effects, economic, environmental, and even cultural. After careful modeling and data collection, we believe that we have developed a policy that would help the United States to face these difficulties cost-effectively, with minimal difficulty on the part of the populace, and with minimal environmental degradation. We would advocate the immediate investment of approximately $90 billion into the development of desalination plants along the Atlantic and Pacific coastline in such a manner that all regions can have relatively ready access to the products of these desalination plants (to within 1000 miles). Furthermore, we would advocate the placement of approximately a $300 subsidy on the purchase of standard drip irrigation and spray irrigation systems to allow for a massive increase in the efficiency (up to 20%) of irrigation of farmland, which could save as much as 8% of the United States' annual consumption of water. If this policy is adopted, according to our policy, it will mitigate the potential costs of the water shortage while helping to prevent environmental degradation. It will cause the annual cost of the water systems, adjusted for inflation to present values, to change to approximately $380 billion dollars. We hope that you find our plan to be as effective as possible.

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