-For office use only	Team Control Number	For office use only
T1 ________	**19936**	F1 ________
T2 ________		F2 ________
T3 ________	Problem Chosen	F3 ________
T4 ________	**B**	F4 ________

2013

Mathematical Contest in Modeling (MCM/ICM) Summary Sheet

The arid country of Saudi Arabia is depleting its water resources as agricultural and municipal demands for water overtax the capabilities of the country's primary source of water: its nonrenewable aquifers. Therefore, as the population of Saudi Arabia increases over the next twelve years, a new strategy is needed to govern the principle concerns of a water management plan: acquisition, storage, distribution, efficiency, cost, and sustainability.

We develop a cost-effective strategy designed to manage Saudi Arabia's water resources by the year 2025. Our plan balances both the water consumption needs of the general populace and the necessity of creating a long-term plan that can continue to meet water requirements well into the future. Specifically, our plan encompasses the following aspects of water usage in Saudi Arabia:

- **Fresh water acquisition:** We employ two large desalination plants, one located on the west coast and the other situated on the east coast. These desalination plants provide municipal water for the entire population of Saudi Arabia.
- **Storage capacity**: We utilize Gumbel extreme value theory to determine the frequency of extreme drought events in order to assist in informed decision-making regarding minimum storage levels in reservoirs and other storage mechanisms.
- **Water distribution:** We employ a minimal spanning tree model to connect the cities of Saudi Arabia with a water distribution pipeline network of minimum length. We also consider the location of the desalination plants to minimize the diameters of the pipes.
- **Agricultural efficiency**: We looked at historical price, production, and water requirements for the most produced crops in Saudi Arabia. From this information, we produced a list of the most beneficial crops based on their profit to water use ratio.
- **Cost and sustainability:** We consider the financial costs of each aspect of our plan. We seek to minimize total economic expenses without compromising the project's ability to meet the country's water needs for an extended period of time.

في السَّعودية في المستدامة المياة مورد إدارة بعد وما ٢٠٢٥

SUSTAINABLE WATER RESOURCE MANAGEMENT FOR SAUDI ARABIA IN 2025 AND BEYOND

A NONTECHNICAL WATER PLAN OUTLINE PRESENTED TO THE SAUDI ARABIAN MINISTRY OF AGRICULTURE AND WATER

FEBRUARY 4, 2013

PURPOSE AND OBJECTIVES

Our team was tasked with the development of an effective, feasible, and cost-efficient water plan for Saudi Arabia's projected water needs in 2025. In general, the current water usage situation is characterized by significant depletion of nonrenewable groundwater aquifers to agricultural purposes. Additionally, expensive, modern methods of water harvesting, especially desalination from the Persian Gulf and the Red Sea, are expanding.

We will begin by introducing the magnitude of the current water depletion issue. In 2007, the United Nations classified Saudi Arabia as an area of "absolute scarcity", with annual water supplies below 500 m^3 per person [5]. Under their model, such regions *will not be able to meet their water needs by 2025* by themselves, given current rates of water usage. Due to the extreme scarcity of precipitation in Saudi Arabia, we can consider the majority of its water resources – that is, the groundwater aquifers – as nonrenewable. In our analysis, we applied "peak theory" principles in treating Saudi water supply as nonrenewable and therefore reaching a peak before proceeding into a decline. **We find that we have already reached this peak**, as depicted in **Figure 1**.

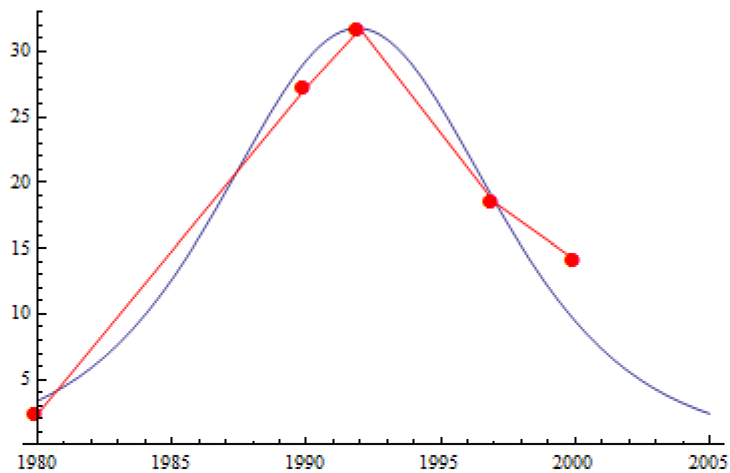

FIGURE 1: WATER SUPPLY CURVE

In accordance with the direness of the water resource situation in Saudi Arabia, we emphasize that **we value water efficiency and conservation significantly above cost**, especially given the nation's relative wealth and longstanding governmental emphasis on water resource management. Thus, our goals are as follows, in order of importance:

1. **Achieve long-term water resource *sustainability* in 2025 and far beyond by limiting non-renewable groundwater aquifer exploitation.**

2. **Develop an *optimal* water pipeline network to *minimize* transport costs for water stores on a city level and for desalination plants on a national level.**

3. **Maximize groundwater welling storage and transport *efficiency* by clearly quantifying and *minimizing* such issues as leakage or contamination in storage systems.**

As will be further discussed, our recommendation is to dedicate water resources generated from precipitation entirely to agricultural purposes, and desalination from seawater entirely to municipal and industrial purposes.

SUSTAINABILITY BY LIMITING AGRICULTURAL OUTPUT

Our first objective revolves around limiting the extent of nonrenewable water usage with long-term interests in mind. In other words, **we seek to decrease the overdrawing rate of non-renewable water resources to zero**, where overdrawing generally refers to the effective annual "water deficit" (with the amount of harnessed precipitation as the input). As seen in **Table 1**, water in Saudi Arabia is dedicated to agriculture over any other purpose by an extremely large margin.

Division	Usage (million m^3 per year)	Percentage of Water Usage
Agriculture	19, 174	89.67%
Industry	308	1.44 %
Domestic	1, 892	8.85 %
Total	**21,374**	**100 %**

TABLE 1: 2004 WATER USAGE IN SAUDI ARABIA [8]

Thus, it is most logical to focus on limiting the massive scale of the agricultural use of water in irrigation, which keeps with the current government strategy of making Saudi Arabia completely import-dependent for wheat by 2016. After imposing the constraint to decrease agricultural water usage to the average amount of precipitation that Saudi Arabia receives in a given year, we analyzed the water requirements and market price of the nine most heavily-produced crops in Saudi Arabia – wheat, barley, sorghum, tomato, watermelon, onion, potato, citrus, and grape – in order to generate a water-cost efficiency ranking defining the ideal crops to grow in the water-scarce environment of Saudi Arabia while still maximizing economic productivity. In order from most economically profitable per water usage: watermelon, grape, tomato, potato, onion, barley, wheat, citrus, and sorghum.

The Saudi Arabian government could encourage the production of crops ranking high on this list – specifically watermelons, grapes, and tomatoes – by extending rich subsidies to farmers growing these crops, much like the policy constructed in the 1990s as the nation was attempting to become completely self-sufficient for wheat.

Given the high variation in agricultural import prices, we left an analysis of the economic feasibility of high import dependence for some of the lower ranking crops out of the scope of this project. It is worth noting, however, that the Saudi Arabian government finds it feasible to be completely import dependent for certain crops whose transport resource requirements are relatively small – specifically, wheat.

CONSTRUCTING A PIPELINE NETWORK FOR DESALINATED WATER

We now proceed to the second component of our water plan, involving the transport of desalinated water to the people of Saudi Arabia. One of the biggest issues with the current Saudi Arabia water distribution is that there is no universal water supply network. This leads to intermittent water availability and unpredictable results in the event of a drought or other water shortage. Currently, many coastal cities are desalinating water. There are a total of 21 desalination plants across the country which supplies water to the coastal cities as well as to some inland cities like the capital, Riyadh. These pipelines are in place and work well enough to prevent water shortages anywhere inland, but are not ideal. Riyadh receives piped water once every 2-3 days, and other major cities are still allowed to go 7-9 days without piped water. [16]

Due to the significant cost involved in constructing a comprehensive pipeline network in Saudi Arabia, we wish to minimize the amount of pipelining necessary, by eliminating redundant loops or cycles, such that water is distributed into a city in only one way. This type of network is known as a spanning tree, and an optimal solution for minimzing the number of connection between the cities in this tree is known as Prim's Algorithm. We apply this algorithm to the 117 most populous cities in Saudi Arabia, generating the pipeline network depicted in **Figure 2**.

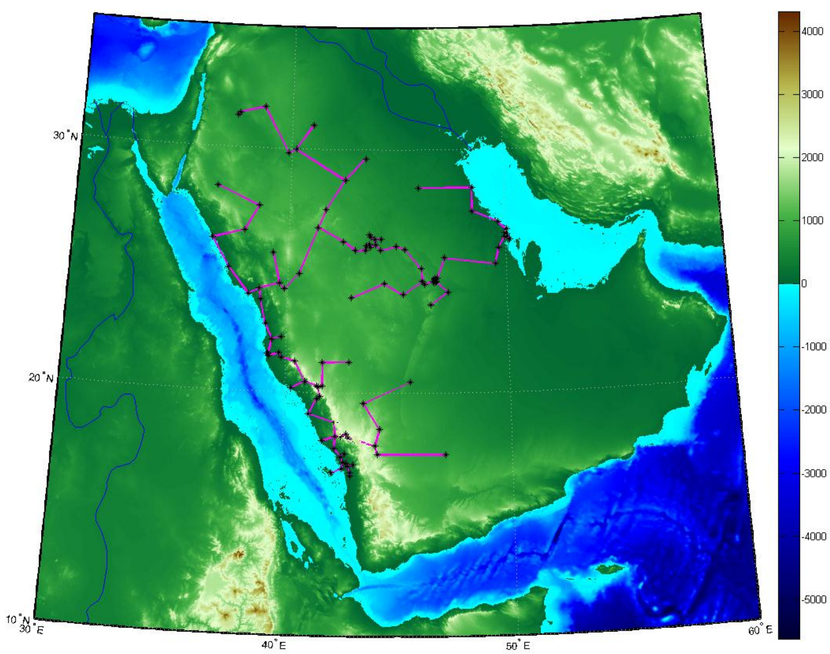

FIGURE 2: CONNECTION PLAN FOR 117 MAJOR CITIES

The total length of this spanning tree is 8,258 kilometers, and has a combined length substantially greater than most pipelines in the world. However, such a pipeline would provide direct water to over 97 percent of the population of Saudi Arabia.

COST

To evaluate the cost of constructing such a pipeline network, we began by following a few principles. First, we note that cost is largely proportional to pipe length, diameter, strength, and peak flow rate through the pipe. Then the amount of water carried by each pipe depends on the population served by that particular pipeline, along with the per capita rate of water consumption in Saudi Arabia. Additionally, a pipe to a given city must transport more than just the water required by that one city; the pipe must also pump water that must pass through that city on the way to other cities farther down the line, so that pipes must be largest near desalination plants, and smallest furthest away from desalination plants.

The most efficient location for a desalination plant must therefore be "populationally concentrated": our analysis indicates that if there is only one desalination plant, it should be located in the city of Rabigh. Rabigh, population 92,072, is located on the west coast of Saudi Arabia by the Red Sea, and it is approximately 140 kilometers north of the major population center of Jeddah. The pipeline network (not counting the desalination plant itself) would cost approximately 18.1 billion dollars.

TWO SOURCES

Merely employing one desalination plant to service the entire population of Saudi Arabia may not be the most advantageous method. For instance, if that one plant were to break down, the entire country would be without water, and there would be no backup plant to provide the people with at least some water (albeit at a reduced rate). Furthermore, pumping water across the entire country is rather inefficient: cities on the east coast would receive desalinated water pumped all the way across the desert from the plant on the west coast. Instead, it might be more cost effective to have two desalination plants, one on the east coast and one on the west coast.

Given our one-source network, we wish to find the "optimal" pipeline to remove from the network in order to split the network into two separate trees. Our analysis suggests that the plants need to be located in Alhart and Alkhirkhir. Alhart is a small suburb located to the larger city of Jeddah on the west coast, placing its desalination plant along the Red Sea. Alkhirkhir, meanwhile, is a suburb of Ad Damman on Saudi Arabia's east coast. Alkhirkhir is situated by the Arabian Gulf, only 50 kilometers from the island nation of Bahrain. **Figure 3** below indicates the locations of Ad Damman and Alkhirkhir within the two-tree pipeline network. The pipe marked in red connects the two networks, and this pipe would only carry water in the event that one desalination plant fails and the other is forced to provide water to the entire country. Note the central location of each city within its own spanning tree.

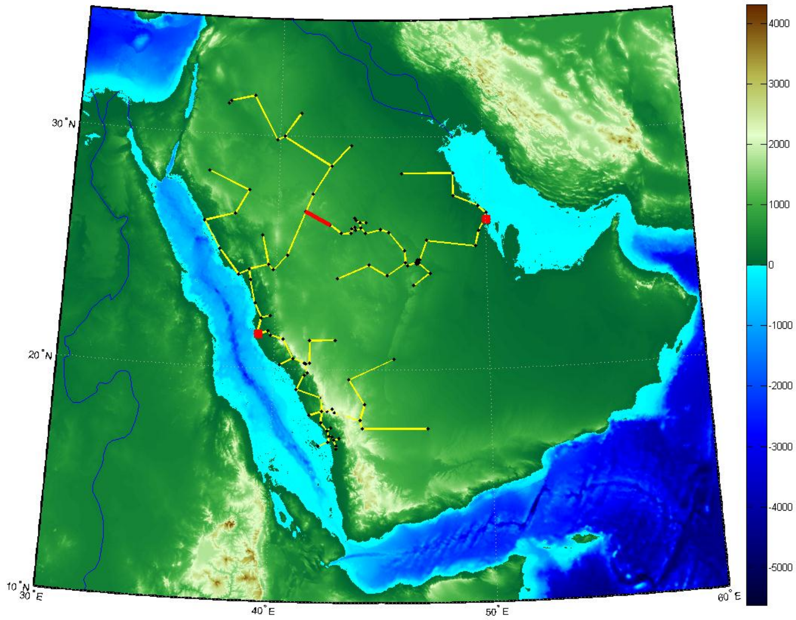

FIGURE 3: TWO SOURCE DESALINATION

The total cost of the pipeline network for two desalination plants is approximately 12.9 billion dollars. This is much lower than the cost of the network for a single desalination plant; however, the second network must also involve the construction of a second desalination plant, which raises the cost considerably. Also, this cost does not include the costs of internal pipelines used to distribute water within cities; however, we assume that most cities already possess adequate pipeline systems.

PROPOSED DESIGN COSTS

To constrain our pricing analysis, we examined case of two large and separate desalination plants. This process could easily be extended to a design that includes 5, 50, or any other number of desalination plants. The results of our analysis are summarized in **Table 2**.

Plant Locations	Alhart
	Alkhirkhir
Price of Desalination Plants	$ 4.56 Billion
Kilometers of Pipe Used	8,258 km
Price of Pipe Used	$ 12.9 Billion
Total Price	$ 17.46 Billion

TABLE 2: OPTIMUM PLANT AND PIPE NETWORK SUMMARY [19]

The cost of the desalination plants depended less on the number of plants that need to be constructed and more on the total amount of water that the plants must process daily. Since cost is a function of the total amount of water that must be desalinated, the final price of the desalination plants is concerned more with a unit cost of dollars per cubic meter of water desalinated per day, as opposed to the number of plants produced.

The unit cost for a large-scale desalination plant—such as those that need to be built to supply all the cities of Saudi Arabia with municipal water—is at most three dollars per gallon per day, which becomes 792.52 dollars per cubic meter of water per day in metric [19]. Considering that the rate of municipal water consumption in Saudi Arabia is 2.1 cubic kilometers per year [18], then the total cost of the desalination plants becomes $US 4.56 billion.

This is a final cost. It includes the price of labor for a desalination plant, but does not include the price of labor for the pipeline construction. It also does not include any maintenance costs. Assuming a linear distribution of costs from start to finish, then the price would be US$ 1.45 Billion per year to complete this project by 2025.

STRENGTHS AND WEAKNESSES

As with any model, assumptions are made, imperfections exist, and deviations from reality will occur. Here, we attempt to examine where the strengths as well as potential shortcomings of the model exist.

MUNICIPIAL WATER

The plan for our design of a municipal water system is very effective. The design of the spanning tree itself is a guaranteed minimum distance, and it provides connection redundancy in the case that one of the desalination plants fails. We designed our system by first looking at distances between cities, then looking at the diameter of pipe needed. We made the assumption that length of pipe dictates cost much more than the diameter of pipe needed. This is usually a fair assumption to make based off of data that we have seen, however it could in some cases (especially with extremely large pipes) become inaccurate. Finally, the pipe diameter calculations were based off of current population information. However, the population of Saudi Arabia is increasing [9] and could eventually outstrip this design.

AGRICULTURAL WATER

The agricultural water recommendations were not based off of many assumptions. The recommendations were entirely based off of historical production and economic data. Assuming that the data is accurate and stays consistent over the next few decades, the crop recommendations should be valid. Where the model falls apart is when economic theory comes into play. By only growing the foods that are listed at the top of this list, the supply of these foods will outstrip the demand, profits will be reduced, and effort will be wasted. So, the most effective way to use this information is to use these crops as guidelines, nothing more, for crop growth.

COST ANALYSIS

Where most of our potential errors exist is in the cost predictions for this distribution system. We used historical data [19] to predict the cost of the desalination plots, but the plants that we are planning to build (at least in our two source design) are much larger than any other desalination plant built. We also neglect labor costs in the construction of any pipelines, which could be considerable, especially when considered over a 12 year time frame. There are many other costs which were also not considered such as the cost of pumping stations, any possible maintenance costs, efficiency costs, etc.

*Please note that references cited in this non-technical position paper presented to government officials are placed with the references for the technical paper.

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إدارة مورد المياة المستدامة في السَّعودية في ٢٠٢٥ وما بعد

SUSTAINABLE WATER MANAGEMENT FOR SAUDI ARABIA IN 2025 AND BEYOND

A TECHNICAL REPORT ON THE DESIGN OF A WATER PLAN FOR SAUDI ARABIA

THE IMPORTANCE OF WATER MANAGEMENT IN SAUDI ARABIA

The extreme aridity of the Saudi Arabian climate presents a significant challenge to the development of an effective and cost-efficient water policy, as the lack of precipitation (approximately 60 mm per year [1]) contributes to an overall inadequacy and unreliability of renewable surface water resources within the country. As a result, Saudi water supply policy is currently characterized by major investment in seawater desalination and distribution from the Persian Gulf and the Red Sea as well as extraction of non-renewable groundwaters from deep fossil aquifers.

The discovery of these significant groundwater sources in the 1960s spurred efforts to create an extensive irrigation network in the hopes that the country could become agriculturally self-sufficient for wheat, one of the country's most important agricultural products by usage. While this goal was actually attained in the early 1990s, the project was abandoned by the early 2000s due to the alarmingly rapid decay in aquifer resources. Al-Ibrahim foresaw this problem in 1991, noting that given the depletion rate in the 1980s, the limited aquifer network would be depleted by the 2060s [2]. In fact, the quick loss of groundwater resources to agriculture (accounting for around 85% of total water usage [2])has prompted the Saudi government to institute a plan to make the nation 100% import-dependent for wheat by 2016 [3].

The other primary water-harnessing strategy, desalination and subsequent transport, is also problematic due to the high costs involved. For instance, the construction of the Shoaiba power and desalination plant was commissioned to serve the Jeddah-Mecca metropolitan area at a cost of US$ 2.8 billion [4].

The goal then is to create a water plan for Saudi Arabia. This plan must be sustainable, cost effective, and efficient in order to be considered. This plan can be determined by investigating the best way to retrieve water, distribute water, and manage these water resources over long periods of time.

MAJOR ASSUMPTIONS

1. Saudi Arabia does not have an existing water resource infrastructure in place.

For example, instead of recommending extensions to the current desalination and water pipeline network, we propose such a network "from scratch". This is necessitated for our purposes by the almost complete lack of specific, publicly-available hydrological infrastructure spatial data available for Saudi Arabia. Still, we recognize that Saudi Arabia is one of the most extensive practitioners of desalination and aquifer harvesting in the world, so we will generalize the principles in our recommendations so that they can be easily extended from an existing system.

2. The water available for use in Saudi Arabia originate from one of three sources and are harvested in certain ways:

- Renewable surface water, stored and harvested using dams,
- Nonrenewable groundwater, harvested by welling from aquifers, and
- Seawater, harvested through desalination.

This description of the fundamental human interaction with the hydrocosm is actually quite common in water resource management analysis [5].

3. Water in Saudi Arabia is used for one of two purposes: agricultural and municipal.

We exclude industrial water considerations due to time considerations: it seems that resolving agricultural and municipal water management matters is more pressing. Again, water investment in agriculture is largely the cause of the current water deficit, while water investment for municipal uses must always be of primary consideration for its necessity to human life and welfare. It is also worth noting that agricultural and municipal water uses comprises over 98% over the total water usage in Saudi Arabia [6].

4. Saudi Arabian demand for certain fundamentally water-intensive crops can be completely met by importation.

While we are not actually making such a drastic suggestion, our assumption is that supplies from other countries will be able to handle a large increase in demand for certain crops imports from the Saudis. While this is an important consideration in reality, it is difficult to predict the future availability and cost of these imports on a large scale, especially given the currently tenuous political situation for many countries in the Middle East region, and thus we will exclude it from the scope of our model.

WATER PLAN OBJECTIVES

In 2007, the United Nations classified Saudi Arabia as an area of "absolute scarcity", with annual water supplies below 500 m^3 per person [7]. Under their model, such regions *will not be able to meet their water needs by 2025*, given current rates of water usage. Thus, we seek to develop a water resources plan with the following objectives optimized in our model, in order:

1. **Achieve long-term water resource *sustainability* in 2025 and far beyond by limiting non-renewable groundwater aquifer exploitation.**

   We assume complete agricultural "outsourcing" of wheat by 2016 as planned by the Saudi government, which should assist in the achievement of this goal. However, we must account for increasing water demand given Saudi Arabia's rapidly-growing population (currently 2.3% annual increase [8]) and economy (currently 6% GDP real growth rate [9]). Implicit in this goal is the quantification of the necessary expenditure on supplementary water harvesting methods that are more costly, especially desalination from the Persian Gulf and the Red Sea. Also, we must consider natural and artificial means of enhancing and recharging groundwater supply capacity.

2. **Develop an *optimal* water pipeline network to *minimize* transport costs for water stores on a city level and for desalination plants on a national level.**

   The water pipeline network needs to span all of the cities of Saudi Arabia so as to provide water for the entire population of the country. However, the cost of such a pipeline network depends on both the length and the size of the pipes used. Specifically, the cost of a pipe is approximately 1.98 million dollars per kilometer of length per meter of width [10]. Therefore, the pipeline network should not only connect the cities of Saudi Arabia with as short of pipelines as possible, but should also place the desalination plants in central locations so each individual pipe does not need to carry as much water, reducing the size of each pipe.

3. **Maximize groundwater welling storage and transport *efficiency* by clearly quantifying and *minimizing* such issues as leakage or contamination in storage systems.**

   A better information infrastructure must be developed in order to properly address potential problems -- the amount of basic information on metrics such as leakage rates and metering performance is frankly inadequate. Specifically, unaccounted-for water, or produced water that is "lost" before it reaches the consumer, ranges between 30% and 55%, and leakage rates between 30% and 50% [6].

   We emphasize that we value water efficiency and conservation significantly above cost, given the direness of the water situation combined with the nation's relative wealth, given its oil resources. This is consistent with the Saudi government's history as one of the greatest investors in water resource management as a percentage of total budget, with more than US$100 billion invested between 1975 to 2000, or approximately 1.5% of GDP [5].

JUSTIFICATION OF A NEW WATER PLAN

As previously mentioned, the scarcity and unreliability of surface freshwater in Saudi Arabia forces the harnessing of groundwater through nonrenewable aquifers as the country's primary water source. In fact, Saudi Arabia ranks first in the world in the overdrawing of natural freshwater resources [11]. As of 2005, Saudi Arabia 2,400 x 10^6 cubic meters of renewable freshwater per year, but is using a total of 21,374 x 10^6 cubic meters per year, with 17,321 x 10^6 cubic meters of water are being drawn from fossil aquifers yearly, for an approximate overdrawing rate of 890%. To enumerate the magnitude of the conservation problem in coming years, Table 0.5 and Table 0.6 provide the publicly-available data on groundwater usage and groundwater supply in Saudi Arabia over the past thirty years.

Water Source	1990 (10^6 m^3)	1992 (10^6 m^3)	1997 (10^6 m^3)
Treated Wastewater	110	185	185
Desalination	540	795	795
Surface Water and Shallow Aquifers	2100	2140	2140
Groundwater	24, 489	28, 576	15, 376
Total	**27, 239**	**31,696**	**18, 496**

TABLE 1:WATER SOURCES SUPPLY [12]

Year	Domestic and Industrial (10^6 m^3)	Agricultural (10^6 m^3)	Total (10^6 m^3)
1980	502	1850	2352
1990	1650	25589	27239
1992	1870	29826	31696
1997	2063	16406	18469
2000	2900	11200	14100

TABLE 2: WATER SOURCE USAGE [12]

One would expect that with these aquifers, the yearly supply would start out small, quickly increase until a maximum yearly supply is reached, then slowly decrease until the supply is fully depleted.

This kind of behavior has been studied before with the theory of "Peak Oil." The drilling of many oil wells often follows this same kind behavior of exponential growth, followed by leveling followed by exponential decay. This kind of curve has been called a Hubbert Curve. While usually associated with oil drilling, it can be extended to the usage of any kind of finite resource usage. This has led to it being applied to coal ("Peak coal"), uranium ("Peak uranium"), copper ("Peak copper"), and water("Peak water") among others.

While water itself is a renewable resource, water drawn from fossil aquifers ("Fossil water") is most certainly finite, and thus supply can usually be modeled by this kind of curve. There is a significant lack of data on the water supply in Saudi Arabia but some information exists. Table 1 and Table 2 showed the state of the groundwater supply. Below are plots of the data in Table 1 and Table 2 with a superimposed Hubbert Curve.

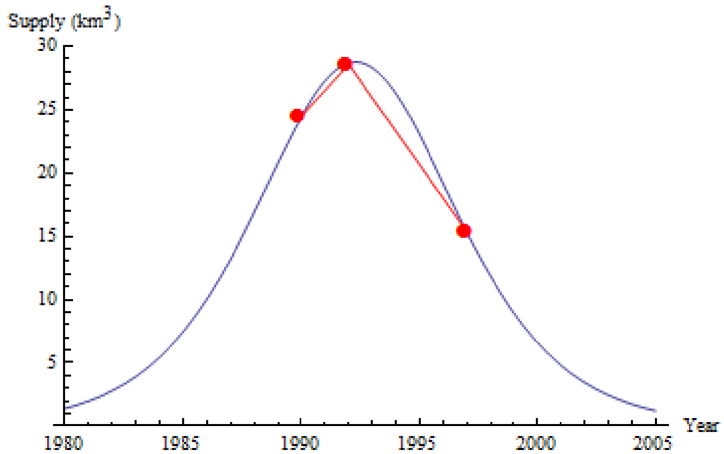

FIGURE 2: FOSSIL AQUIFER SUPPLY VS YEAR

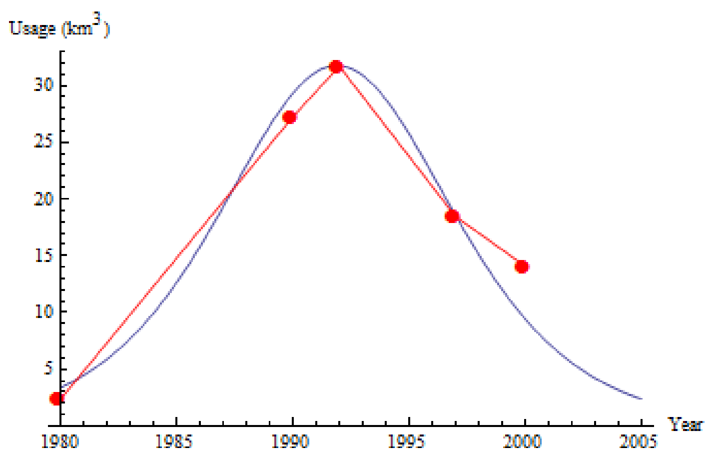

FIGURE 3: FOSSIL AQUIFER USAGE VS YEAR

Again, it is important to see that there are a very small number of data points available. It is impossible to make any kind of mathematical argument that the data will follow this trend, but historical data of other limited resource mines has suggested that this will be the case.

Now, making the assumption that the fossil aquifers will follow a Hubbert Curve, it is easy to see that the fossil aquifers will soon be running out of water to supply to the country. This is what motivates the strong recommendation to move to desalination for as much of Saudi Arabia's water sources as possible.

We are planning to isolate Saudi Arabia from these nonrenewable aquifers. Removing the aquifers, we divide up the available water resources to different divisions of the population.

Division	Source
Municipial Water	Desalination
Industrial Water	Desalination
Agricultural Water	Surface water

TABLE 3: WATER SOURCE DISTRIBUTIONS

DESIGN OF A NEW WATER PLAN

The scarcity of water in Saudi Arabia has led to unreliable means of distribution and supply. Currently, water usage in Saudi Arabia follows the following distribution (as of 2004):

Division	Million cubic meters per year	Percentage of Water Usage
Agriculture	19, 174	89.67%
Industry	308	1.44 %
Domestic	1, 892	8.85 %
Total	**21,374**	**100 %**

TABLE 4: 2004 WATER USAGE IN SAUDI ARABIA [6]

However, it is important to note that projected usage will change by the year 2025, when this plan has been fully implemented. In the year 2020, domestic water has been projected to reach 6,450 million gallons per year [10]. However, the Saudi government has also put plans into action that by the year 2016, 100% of food will be imported, essentially negating the need for an agricultural water supply.

It is also important to note that the water in Saudi Arabia comes chiefly from three distinct sources. Information was found on 2008 water usage, which may be inconsistent with 2004 usage above, however it still gives a clear picture of the state of water system.

Source	Million cubic meters per year	Percentage of Water Usage
Desalination	1, 653	7.73 %
Renewable ground water and surface water	2, 400	11.23 %
Fossil aquifers	17, 321	81.04 %
Total	**21, 374**	**100 %**

TABLE 5: 2008 WATER USAGE IN SAUDI ARABIA [11] [13] [14] [15]

*There is little data on fossil aquifer usage, so that amount of water is estimated based off of historical water usage data

Mining fossil aquifers for water has been a practice for many years in Saudi Arabia. However, these sources provide interesting challenges for water management. These fossil aquifers are not renewable. While it is certainly feasible to continue using them until they are depleted, it is virtually impossible to know when that would happen, which could lead to a water crisis. Ultimately, the goal would be to no longer use fossil aquifers and switch entirely to renewable water resources such as desalination plants, surface water, and replenishable shallow aquifers.

The problem then becomes the distribution of the water. The technology is already in place to desalinate water or to pipe fresh surface water long distances. The only limiting factor is cost, time, and effectiveness of the solution.

MUINICIPAL AND INDUSTRIAL WATER

Municipal and industrial water use is essentially all of the water use that is not agricultural. Any drinking water, residential water, or water used for manufacturing falls into this category. It is also characterized by having higher water quality and safety standards than water that is used for agriculture. In many cases, untreated water can be used without ill effect to water crops, while the same water could cause serious health problems and sickness if it was distributed as drinking water. Thus, the distribution of municipal and agricultural water can be seen as two separate problems because of the different standards to which the water must be treated.

CURRENT DISTRIBUTION INCONSISTENCIES

One of the biggest issues with the current Saudi Arabia water distribution is that there is no universal water supply network. This leads to intermittent water availability and unpredictable results in the event of a drought or other water shortage. 97% of the urban population has access to clean water, but only 63% of the rural population has that privilege. A universally connected pipe system would greatly reduce any issues that would occur during an event like this. [12]

Currently, many coastal cities are desalinating water. There are a total of 21 desalination plants across the country which supplies water to the coastal cities as well as to some inland cities like the capital, Riyadh. These pipelines are in place and work well enough to prevent water shortages anywhere inland, but are not ideal. Riyadh receives piped water once every 2-3 days, and other major cities are still allowed to go 7-9 days without piped water. [16]

The pipelines already in place succeed only occasionally in maintaining water to their destinations. Many smaller towns do not have piped water supplies, and get their water delivered by truck. This has low upfront costs, but extremely high maintenance costs. An interconnected, country-wide, pipeline system is clearly the best option to consistently and permanently deliver water to all of the residents of the country.

DISTRIBUTION SOLUTION

The pipelines already in place succeed only occasionally in maintaining water to their destinations. Many smaller towns do not have piped water supplies, and get their water delivered by truck. This has cheap up-front costs, but extremely high maintenance costs. An interconnected, country-wide, pipeline system is clearly the best option to consistently and permanently deliver water to all of the residents of the country.

The biggest issue that comes into play is the way to connect all of the major cities with the least amount of pipelining necessary. First of all, a minimum amount of pipeline necessitates that there are no redundant loops or cycles in the pipeline system, such that water could be sent to the same city via two different pipelines that travel different paths. Rather, there must only be one possible pipeline that connects a given city to the source of the water, the desalination plant. In this way, the pipe network constitutes a *spanning tree* for the set of all cities that are to be connected by pipeline: the set of cities is completely connected by the pipelines, there are no cycles (closed loops of pipeline) in the network, and consequently the number of pipelines connecting *n* cities is *n-1*. [17]

PIPELINE MAP

The issue then becomes how to best connect all of the cities of Saudi Arabia with the least amount of pipes in order to minimize economic cost. In a mathematical context, this is called a *Minimum Spanning Tree*. A minimal spanning tree, by definition, has a shorter length than any other spanning tree that connects all of the points in the set; in this case, the minimal spanning tree uses less pipeline than any other network that connects all of the cities in Saudi Arabia. For a tree to be a minimal spanning tree, each possible (but unused) connection between cities must be longer than each network pipeline that would be placed in a closed cycle by the addition of the unused connection [17].Otherwise, if a possible connection were shorter than one pipeline currently employed in the minimal spanning tree, the length of the pipeline used to connect the cities in the cycle could be decreased by using the new, shorter connection rather than the longer one currently in use. In other words, the minimal spanning tree removes the longest connection in any cycle to leave an acyclical path of minimum length.

This property of the minimal spanning tree, that every pipeline not in the network must be longer than the network pipelines which would be put in a cycle by its addition, can be employed in an algorithm to compute the minimal spanning tree for a given set of cities in Saudi Arabia. We do this using *Prim's Algorithm.* Prim's algorithm is a way to determine the minimum spanning tree from a set of points. Roughly, it follows this form:

1. Create a set of all points which need to be connected
2. Create a set of all possible connections that could connect these points
3. Add a connection of the lowest distance that connects a point in the tree to a point not in the tree
4. Repeat 3 until all points are contained in the tree

We begin by using Prim's algorithm and MATLAB to find the minimal spanning tree that connects the 20 largest cities in Saudi Arabia. These 20 cities contain approximately 72 percent of the total population of Saudi Arabia. The resulting pipeline network has a total length of 3,603 kilometers and is shown below.

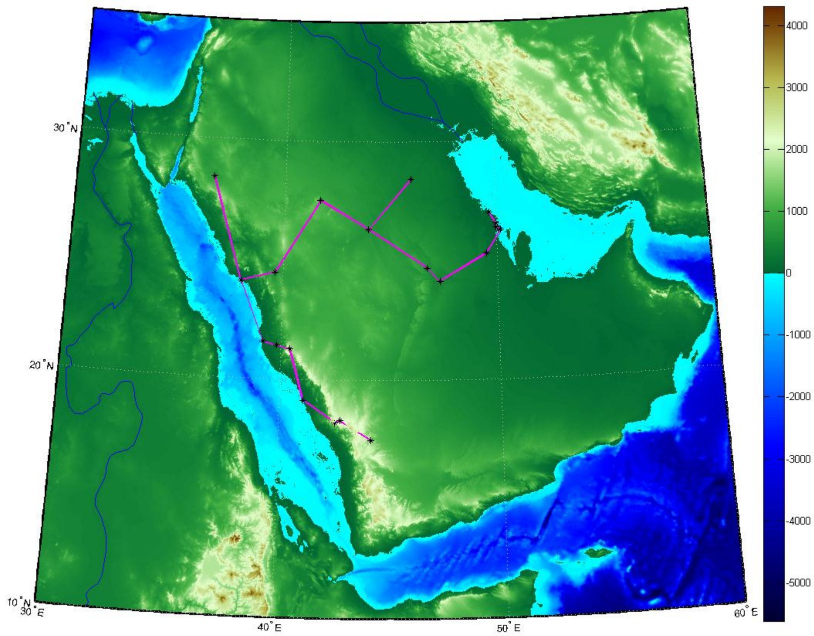

FIGURE 4: CONNECTION PLAN FOR 20 MAJOR CITIES

Next, we analyze a network containing the 117 most populous cities of Saudi Arabia. can be considered. That gives a pipeline network that looks like the following:

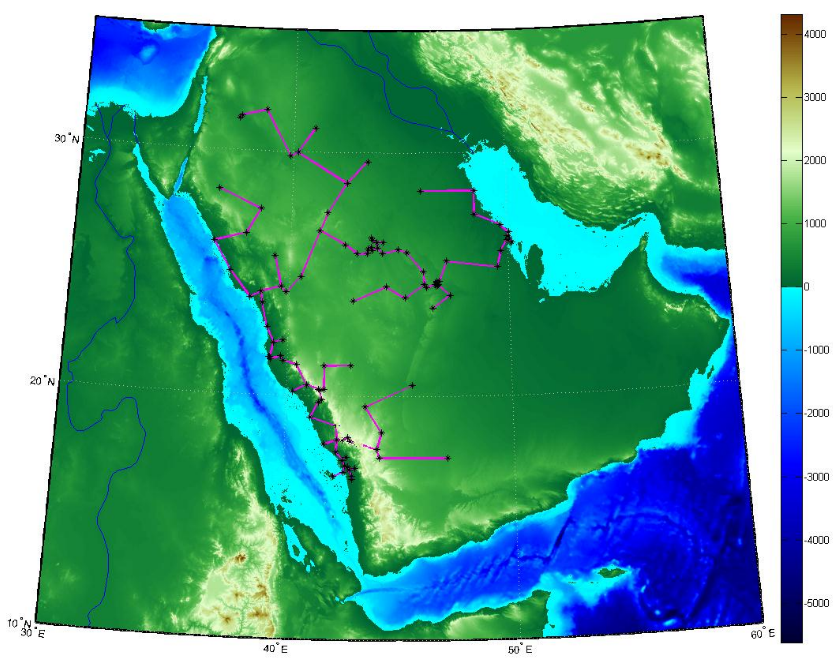

FIGURE 5: CONNECTION PLAN FOR 117 MAJOR CITIES

The total length of this spanning tree is 8,258 kilometers. Note that this network has a combined length substantially greater than most pipelines in the world. However, such a pipeline would provide water to over 97 percent of the population of Saudi Arabia, making the pipeline well worth the cost.

COST OF THE PROPOSED DESIGN

Before the cost of the pipeline can be computed, the diameter of each individual pipe must be found. The cost of a pipeline is proportional to the following parameters:

- Length of the pipe
- Diameter of the pipe
- Strength of the pipe and peak flow rates

We neglect the strength of the pipe for simplicity's sake and due to the fact that we have no plan to strain the pipes above the recommend operating conditions. The cost of pipelines is approximately 1.98 million dollars per kilometer of length per meter of width [10].The length of each pipeline has already been calculated using the spanning tree model. However, the size of each pipe depends on the rate at which the pipe must transfer water. In turn, the amount of water carried by each pipe depends on the population served by that particular pipeline. For instance, a pipe supplying water to the capital city of Riyadh must serve a very large population, so the pipeline must be quite large.

The relative size of each pipeline is determined based off of data for a pipeline that is currently being built to transport water into Riyadh. The specifications of that pipeline are outlined in the table below:

Diameter	1.83 Meters
Flow Rate	990,000 m^3/day

TABLE 6: RIYADH PIPELINE SPECIFICATIONS [13]

By assuming that volumetric flow rate is proportional to the cross sectional area of a circular pipe, we can determine the diameter needed to obtain a given flow rate.

The amount of water that needs to be transported to each city depends on that city's population and the per capita rate of water consumption in Saudi Arabia. The total municipal rate of water use is approximately 2.1 cubic kilometers per year [18].This translates into 5.75 million cubic meters of water per day, or a per capita value of 0.205 cubic meters per person per day. The total daily water needs of a city can be found by multiplying this per capita value by the total population of that city.

However, for a spanning tree network, a pipe to a given city must transport more than just the water required by that one city; the pipe must also pump water that must pass through that city on the way to other cities farther down the line. For instance, if City A is at the end of a branch in the spanning tree such that City A is only connected to City B, then the pipe flowing into City B must be large enough to transport enough water for both City A and City B. Of course, the pipeline to City A only needs to be big enough to carry water for City A, since the city is at the end of the line.

Consequently, pipes must be largest near the desalination plants, and then pipe sizes can decrease farther away from the plants where there are fewer cities down the line that still need water. This means that the location of the desalination plant or plants must be chosen carefully to minimize the total cost of the pipeline network by ensuring that as many pipes as possible can be made as small as possible.

ONE SOURCE SOLUTION

We initially consider the case where there is only one desalination plant supplying the entire country. While this may not be the most effective way of providing for the entire nation, it does provide a starting point for analysis and a baseline of total costs. MATLAB analysis indicates that if there is only one desalination plant, it should be located in the city of Rabigh. Rabigh, population 92,072, is located on the west coast of Saudi Arabia by the Red Sea, and it is approximately 140 kilometers north of the major population center of Jeddah. The pipeline network (not counting the desalination plant itself) would cost approximately 18.1 billion dollars.

However, merely employing one desalination plant to service the entire population of Saudi Arabia may not be the most advantageous method. For instance, if that one plant were to break down, the entire country would be without water, and there would be no backup plant to provide the people with at least some water (albeit at a reduced rate). Furthermore, pumping water across the entire country is rather inefficient: cities on the east coast would receive desalinated water pumped all the way across the desert from the plant on the west coast.

TWO SOURCE SOLUTION

Instead, it might be more cost effective to have two desalination plants, one on the east coast and one on the west coast. Therefore, we next consider the possibility of two desalination plants. In this case, the pipe network is split into two separate spanning trees, each network containing one desalination plant. To determine the locations of the desalination plants to obtain minimum cost, each combination of coastal cities is examined, along with each possible pipeline to remove from the overall spanning tree in order to split it into two separate trees. We again use MATLAB to analyze all of these options, while ensuring that the two cities containing desalination plants are in separate trees, on opposite sides of the pipe that is removed from the original, single network.

Running the simulation indicates that the pipe network indeed costs less when two desalination plants are employed. This result is to be expected, since each desalination plant serves a smaller network than before, so it does not need to desalinate and distribute as much water as when there is only one plant. As a result, the pipes nearest to the desalination plants can be much smaller than they were previously, since they do not need to distribute nearly as much water.

To minimize the total cost of the pipeline network for two desalination plants, the plants need to be located in Alhart and Alkhirkhir. Alhart is a small suburb located to the larger city of Jeddah on the west coast, placing its desalination plant along the Red Sea. Alkhirkhir, meanwhile, is a suburb of Ad Damman on Saudi Arabia's east coast. Alkhirkhir is situated by the Arabian Gulf, only 50 kilometers from the island nation of Bahrain. The map below indicates the locations of Ad Damman and Alkhirkhir within the two-tree pipeline network. The pipe marked in red connects the two networks, and this pipe would only carry water in the event that one desalination plant fails and the other is forced to provide water to the entire country. Note the central location of each city within its own spanning tree.

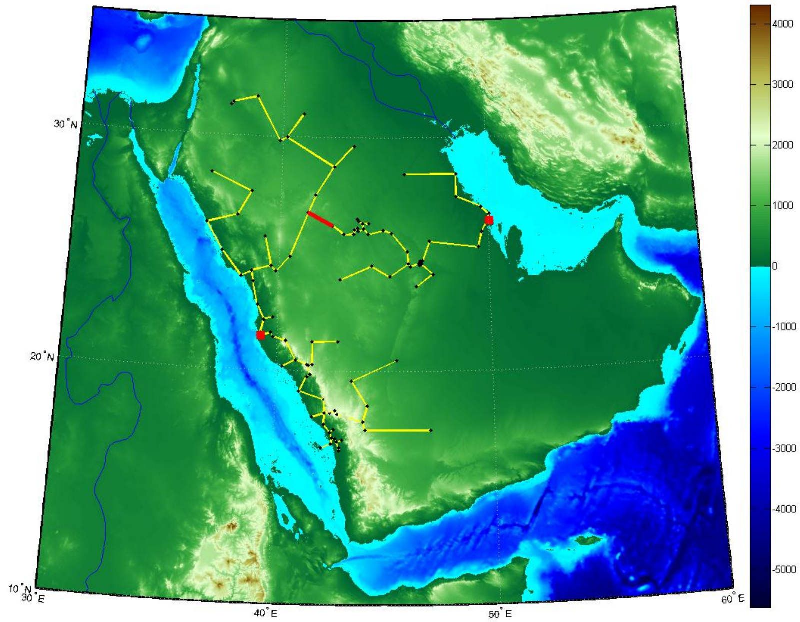

FIGURE 6: TWO SOURCE DESALINATION

The total cost of the pipeline network for two desalination plants is approximately 12.9 billion dollars. This is much lower than the cost of the network for a single desalination plant; however, the second network must also involve the construction of a second desalination plant, which raises the cost considerably. Also, this cost does not include the costs of internal pipelines used to distribute water within cities; however, we assume that most cities already possess adequate pipeline systems.

N SOURCE SOLUTION

This kind of approach could then be applied to further optimize the costs. Simply running the simulation again with different numbers of starting cities would further optimize the design. Currently, the solution is being found by a method of exhaustion, where the minimum cost is calculated for each pair of coastal cities shown. However, this could be improved by examining other parameters to determine optimal cities such as:

- Population densities
- Geographic locations and distances
- Desalination plant site (ease of construction, etc)

Once a short list of “optimal” sites for desalination plants are chosen, the amount of brute force calculations could be greatly reduced.

AGRICULTURAL WATER

Recall that the first objective thus revolves around limiting the extent of nonrenewable water usage with long-term interests in mind; **we seek to decrease the overdrawing rate of non-renewable water resources to zero.** Agricultural water makes up the majority of the water that is used in Saudi Arabia. The main source of this water is the fossil aquifers found deep beneath the ground. However, in the southwestern part of the country, there are seasonal rivers, cultivated land, and limited surface water. This makes it the best location for growing in the whole country.

PROPOSED SOLUTION

It is difficult to entirely reduce the amount of water that is spent on agriculture. Farming is simply one of the most water intensive activities that can be done. It may be impossible to completely eliminate fossil aquifer usage without an even bigger overhaul of the country's water system. However, we have investigated how results could be achieved with smaller changes in farming practices. This was done using a simple optimization model.

We began by creating an equation for profit:

$$P(x) = \sum_{j=1}^{n} \left(\frac{revenue}{hectare}\right)_j x_j$$

In this case, the revenue per hectare is specific to the crop being grown, x_j is the number of hectares of each crop being grown, and n is the number of different crops. We then created an equation for water use:

$$W(x) = \sum_{j=1}^{n} \left(\frac{water}{hectare}\right)_j x_j$$

Finally, we created an equation for the amount of land being used.

$$L(x) = \sum_{j=1}^{n} x_j$$

We then began our optimization. We optimized for the maximum profit as well as the minimum water use. This, as expected, gave the result to grow the most profitable food and the most water efficient food respectively. This is not economically efficient, for the supply of each of the crops would exceed the demand, and essentially be wasting effort and reducing profit. Bringing in economic concepts of demand and necessity of different foods would improve these recommendations and make them more realistic.

However, we eventually decided to settle by determining the best crops to grow by their profit to water use ratio. After applying this model to the major exports of Saudi Arabia, we have come up with an ordered list of the best crop choices, sorted by their revenue per unit of water usage.

1. Watermelon
2. Grapes

3. Tomato
4. Potato
5. Onion
6. Barley
7. Wheat
8. Citrus
9. Sorghum

These crops are profitable but still minimize water usage. By instituting government programs that encourage growing crops that are near the top of this list, then perhaps water usage can be even further minimized. The Saudi government has already taken some steps in this direction and has made a decision to import all wheat by the year 2016. Clearly, wheat is low on the list of effective crops, and thus should be replaced something better.

Government subsidies or recommendations are one step in the right direction, but a more sustainable water usage plan could be attained by further increasing water supply. Similar to the municipal water distribution plan above, by piping desalinated water to farmlands, the issue of water restrictions could be reduced even more. Realistically, many farmers will continue to use fossil aquifers for water, but seeing as the water supply is on a downward trend, any steps in the right direction will be beneficial and prolong the water supply in Saudi Arabia.

STORAGE CONSIDERATIONS

Fundamentally, our purpose in considering storage questions is to ensure that the water supply for agricultural or municipal purposes is never completely depleted. Specifically, we are interested in maintaining water resources in such storage mechanisms as reservoirs and water tanks from dropping below a certain "days of supply" level, even in the case of "extreme" events like drought [1]. This type of behavior is readily modeled by the Gumbel extreme value distribution, whose cumulative distribution function is given by

$$F(x;\alpha,\beta) = e^{-e^{-\frac{x-\alpha}{\beta}}}.$$

As seen in [2], this distribution function can be manipulated in order to generate the minimum weather event as a function of time period length; that is:

$$x_T = \frac{1}{\alpha}\ln\left(-ln\left(1-\left(\frac{1}{T}\right)\right)\right) + \beta,$$

where T represents the time scale considered, and x_T the minimum 24-hour rainfall event during that time period considered. Using the method of moments estimation, it can be derived that:

$$\alpha = \frac{1.282}{\sigma}, \beta = 12\left(\mu - \frac{0.5772}{\alpha}\right).$$

where T is taken in time scale units of months, σ represents the standard deviation of rainfall on a monthly basis, and μ represents the mean of monthly rainfall. **Error! Reference source not found.** depicts the decreasing amount of rain as the time scale considered increases, and thus provides information regarding probabilistically-based frequency of extreme drought events, allowing for informed decisions to be made regarding storage capacity.

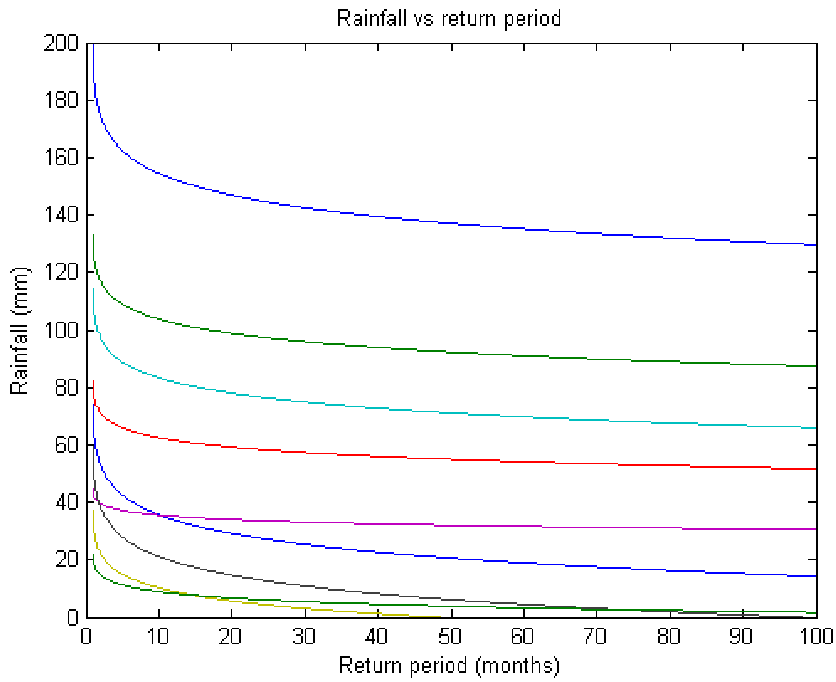

FIGURE 7: RAINFALL VS RETURN PERIOD

The rainfall data (represented by the different colors) is derived from nine different rain-gauge stations throughout Saudi Arabia, which experience different amounts of rainfall. Storage policy clearly must be determined for each city independently, such that given a certain number of expected extreme consecutive drought days, water availability for municipal uses is reduced.

COSTS OF THE PROPOSED DESIGN

The proposed design, while certainly effective, does not take into account the price of the piping. The cost of the pipeline is determined by four factors

- Size of the supplying desalination plant
- Length of pipe used
- Diameter of pipe used
- Number of desalination plants

In the pipeline design above, the length of the pipe has already been determined. By choosing the number of desalination plants, the respective sizes of the desalination plants can be determined.

IDEAL DESIGN COST

To constrain our pricing analysis, we examined case of two large and separate desalination plants. This process could easily be extended to a design that includes 5, 50, or any other number of desalination plants. The results of our analysis are summarized below.

Plant Locations	Alhart
	Alkhirkhir
Price of Desalination Plants	$ 4.56 Billion
Kilometers of Pipe Used	8,258 km
Price of Pipe Used	$ 12.9 Billion
Total Price	$ 17.46 Billion

TABLE 7: OPTIMUM PLANT AND PIPE NETWORK SUMMARY [19]

The cost of the desalination plants depended less on the number of plants that need to be constructed and more on the total amount of water that the plants must process daily. Since cost is a function of the total amount of water that must be desalinated, the final price of the desalination plants is concerned more with a unit cost of dollars per cubic meter of water desalinated per day, as opposed to the number of plants produced.

The unit cost for a large-scale desalination plant—such as those that need to be built to supply all the cities of Saudi Arabia with municipal water—is at most three dollars per gallon per day, which becomes 792.52 dollars per cubic meter of water per day in metric [19]. Considering that the rate of municipal water consumption in Saudi Arabia is 2.1 cubic kilometers per year [18], then the total cost of the desalination plants becomes 4.56 billion dollars.

This is a final cost. It includes the price of labor for a desalination plant, but does not include the price of labor for the pipeline construction. It also does not include any maintenance costs. Assuming a linear distribution of costs from start to finish, then the price would be$ 1.45 Billion per year to complete this project by 2025.

EFFECTS OF REDUCTION

We also examined the effects of reduction of this system on the population of Saudi Arabia. By decreasing the amount of piping used and money invested, different results can be achieved. For example, supplying water to only the 20 most populous cities uses roughly half of the pipe required for the 117 most populous and still provides water to 72% of the population. Below are graphs that show how some of these parameters affect service to the citizens of Saudi Arabia.

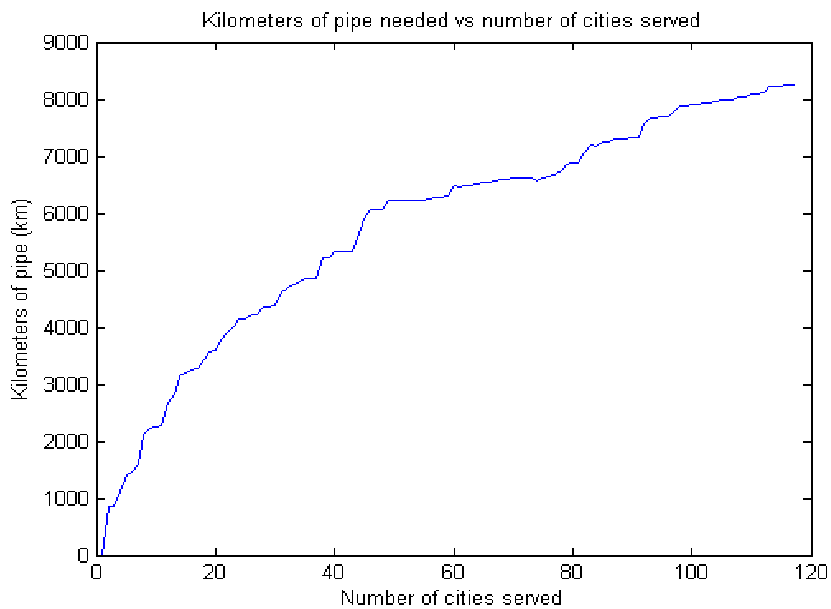

FIGURE 8: VARIANCE IN KILOMETERS OF PIPE WITH NUMBER OF CITIES SERVED

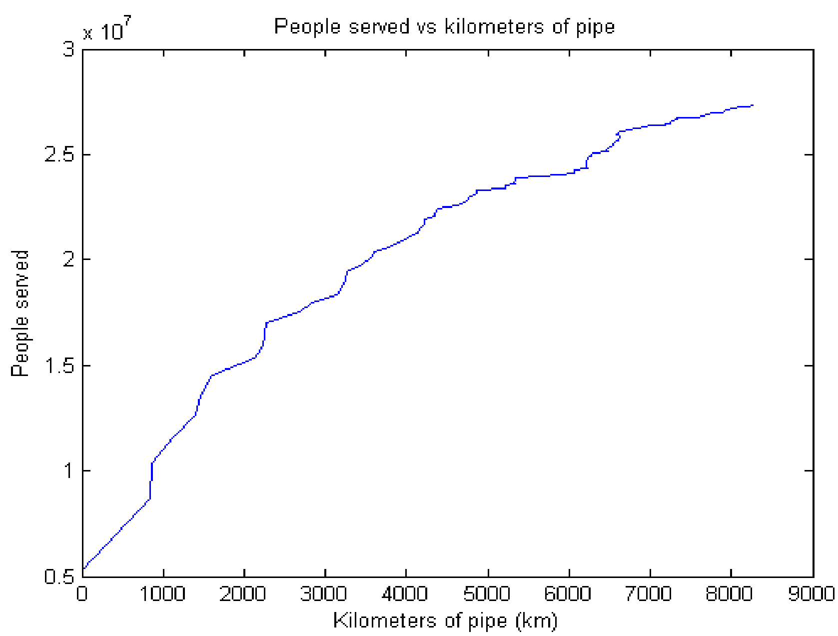

FIGURE 9: VARIANCE IN PEOPLE SERVED WITH KILOMETERS OF PIPE

So, by reducing the percentage of the population or number of cities that are served by this pipeline network, less materials need to be used, and construction costs can be lowered. The level of service can be used as an indirect proxy for cost, and can show the effects of reduction on the citizens of Saudi Arabia.

SUMMARY

This paper addressed the design of a water plan for Saudi Arabia. This plan has two separate main parts: The distribution of municipal water, and the distribution of agricultural water. The distribution of the municipal water is a strong and feasible plan, whereas the distribution of agricultural water is less rigid and may not provide better results right away.

MOTIVATION

The motivation for redesigning the water system of Saudi Arabia is the possible water supply issues that will occur in the coming years. Much of the water that is currently being used is coming from fossil aquifers deep beneath the ground. This itself is not a problem, however this water is not renewable. When these aquifers are depleted, there will be a shortage of water across the country. Current models show that the supply of water in these aquifers is on the downward slope of its supply curve.

MUNICIPIAL WATER

The first goal was to supply clean water to all of the citizens of Saudi Arabia. The proposed solution was to build a pipeline network that supplied water to all of the cities in the country. This network was designed to be of a minimum distance and a minimum cost. This network was supplied entirely by coastal desalination plants. When this network was spread across the 20 most populous cities, 72% of the population was supplied water, and when it was spread across all 117 cities of Saudi Arabia, then 97% of the population was supplied water.

AGRICULTURAL WATER

The majority of agricultural areas draw their water from two sources. The fossil aquifers provide the majority of the needed water along with surface water such as rivers and shallow wells. The former is a nonrenewable water source, while the latter is replenished naturally. The ideal situation would be to constrain all agricultural water use to the surface water sources. However, seeing as farming is one of the most water intensive acts, this may not be entirely possible. What we did was to determine a list of crops that provide the best profit to water use ratio. By making governmental recommendations to the public, this water use can hopefully be reduced.

COSTS AND PLANNING

The cost of the ideal 2 source desalination system is $17.46 billion (without all of the associated labor). This equates to a cost of $ 1.5 billion per year if the costs are distributed evenly. While this is a lot, it can be mitigated with higher water tariffs. Currently, Saudi Arabia has some of the cheapest water worldwide, despite having one of the scarcest supplies. Furthermore, if a reduction in service to the people is acceptable, then the size of the network can be reduced (see Figure 8 and Figure 9).

STRENGTHS AND WEAKNESSES

As with any model, assumptions are made, imperfections exist, and deviations from reality will occur. Here, we attempt to examine where the strengths as well as potential shortcomings of the model exist.

MUNICIPIAL WATER

The plan for our design of a municipal water system is very effective. The design of the spanning tree itself is a guaranteed minimum distance, and it provides connection redundancy in the case that one of the desalination plants fails. We designed our system by first looking at distances between cities, then looking at the diameter of pipe needed. We made the assumption that length of pipe dictates cost much more than the diameter of pipe needed. This is usually a fair assumption to make based off of data that we have seen, however it could in some cases (especially with extremely large pipes) become inaccurate. Finally, the pipe diameter calculations were based off of current population information. However, the population of Saudi Arabia is increasing [9] and could eventually outstrip this design.

AGRICULTURAL WATER

The agricultural water recommendations were not based off of many assumptions. The recommendations were entirely based off of historical production and economic data. Assuming that the data is accurate and stays consistent over the next few decades, the crop recommendations should be valid. Where the model falls apart is when economic theory comes into play. By only growing the foods that are listed at the top of this list, the supply of these foods will outstrip the demand, profits will be reduced, and effort will be wasted. So, the most effective way to use this information is to use these crops as guidelines, nothing more, for crop growth.

COST ANALYSIS

Where most of our potential errors exist is in the cost predictions for this distribution system. We used historical data [19] to predict the cost of the desalination plots, but the plants that we are planning to build (at least in our two source design) are much larger than any other desalination plant built. We also neglect labor costs in the construction of any pipelines, which could be considerable, especially when considered over a 12 year time frame. There are many other costs which were also not considered such as the cost of pumping stations, any possible maintenance costs, efficiency costs, etc.

APPENDIX A – DATA USED

CROP PRODUCTION DATA [20]

Crop	Cultivated area (hectares)	Production (metric tonne = 1000 kg)	Price (US$ per metric tonne)	Water requirements (mm)
wheat	744422	3463585	347.89	550
barley	56907	361900	243.36	410
sorghum	153056	199908	283.96	550
tomato	21558	462964	226	500
watermelon	18533	460725	350	500
onion	2038	13554	400	450
potato	2298	47700	250	600
citrus	4882	35233	350	1050
grapes	5764	99799	277	400

RAINFALL DATA (mm) [21]

Location:	Tabouk	Hail	Dahran	Riyadh	Medina	Yanbu	Jiddah	At Taif	Gizan
Jan	34	22	15	15	9	3	5	12	0
Feb	6	6	15	6	1	2	2	13	4
Mar	9	23	9	22	5	0	2	12	0
Apr	1	16	15	30	7	0	2	31	6
May	7	9	2	10	4	0	2	27	0
Jun	0	0	0	0	0	0	0	10	0
Jul	0	0	0	0	1	0	2	5	5
Aug	0	0	0	1	0	0	2	7	2
Sep	0	0	0	2	0	0	2	5	4
Oct	2	2	1	0	1	9	2	7	4
Nov	21	26	4	8	6	24	25	48	11
Dec	0	8	9	10	4	8	30	18	0

POPULATION DATA [22] [23] [24] [25] [26]

City	Population	Longitude	Latitude
Al-Riyadh	5,254,560	46.724167	24.71167
Jiddah	3,456,259	39.172989	21.54349
Makkah Al-Mokarramah	1,675,368	39.816667	21.41667
Al-Madinah Al-Monawarah	1,180,770	39.62019	24.4609
Alahsa	1,063,112	49.486481	25.28558
Al-Taif	987,914	40.417068	21.27066
Ad Dammam	903,597	49.977714	26.39267
Tabouk	791,535	36.5732	28.39041
Buraydah	614,093	43.966667	26.33333
Alkhubar	578,500	50.2	26.28333
Alqatif	524,182	49.995689	26.55905
Khamis Mushayt	512,599	42.733333	18.3
Ha'il	412,758	41.683333	27.51667
Hafr Albatin	389,993	45.9753	28.43415
Aljubayl	378,949	49.658128	27.01256
Alkharj	376,325	47.305	24.14833
Abha	366,551	42.50816	18.22022
Najran	329,112	44.13229	17.49173
Yanbu Albahar	298,675	38.19851	23.993
Al-Qunfudhah	272,424	41.078739	19.12814
Sakaka	242,813	40.205009	29.97087
Muhayil	228,979	49.486481	25.28558
Sabya	228,375	42.625923	17.14899
Adduwadimi	217,305	44.394279	24.50452
Bishah	205,346	42.251837	18.77304
Samtah	201,656	42.943889	16.59722
Abu Arish	197,112	42.8325	16.96889
Ar'ar	191,051	41.025009	30.98083
Unayzah	163,729	43.994301	26.08476
Jazan	157,536	42.549751	16.89192
Alquryyat	147,550	37.366667	31.31667
Arrass	133,482	43.51289	25.86834
Almajmaah	133,285	45.35886	25.91053
Al-Lith	128,529	40.26685	20.15051
Alquwayiyah	126,161	45.265612	24.04634
Ahad Rufaydah	113,043	42.85056	18.15722
Ahad Almasarihah	110,710	42.955	16.70972
Wadi Addawasir	106,152	45.574444	20.45972
Almajardah	103,531	46.75077	24.56574
Al-Baha	103,411	41.441251	20.27227

Alghazalah	102,588	41.334888	26.7831
Al-Jmumum	92,222	39.7	21.61667
Rabigh	92,072	39.033333	22.8
Sharurah	85,977	47.116667	17.48333
Rafha	80,544	43.510929	29.6333
Afif	77,978	42.920278	23.91
Baysh	77,442	42.53625	17.374
Alaridah	76,705	43.08	17.05
Alkhafji	76,279	48.5	28.41667
Balqarn	74,391	40.880781	20.45253
Addiriyah	73,668	42.52	26.22
Damad	71,601	42.777481	17.10638
Al-Mukhwah	70,664	41.436246	19.75604
Azulfi	69,294	50.203735	26.27078
Addarb	69,134	42.251541	17.72728
Alaflaj	68,201	46.722483	24.73203
Sarat Abidah	67,120	43.1333	18.0933
Rijal Alma	65,406	42.270757	18.19305
Biljurashi	65,223	41.57123	19.85806
Alula	64,591	37.92284	26.6127
Badr	63,468	38.790556	23.78
Dahran Aljanub	63,119	46.825796	24.73693
Almahd	62,511	46.748293	24.68017
Umluj	61,162	37.265108	25.05001
Alaydabi	60,799	42.6876	17.4991
Ras Tannurah	60,750	50.049573	26.70186
Alhinakiyah	59,326	40.508018	24.85995
Tathlith	59,188	43.503658	19.56527
Qilwah	58,246	46.685855	24.53249
Albukayriyah	57,621	43.69088	26.12642
Albadai	57,164	43.733409	25.98118
Khulays	56,687	39.367279	22.15302
Annamas	54,119	46.765504	24.60005
Buqayq	53,444	49.666667	25.93333
Annuayriyah	52,340	48.481171	27.47234
Dhuba	51,951	39.864444	24.22778
Dawmat Aljandeal	49,646	39.868198	29.8182
Turayf	48,929	38.656399	31.67419
Khaybar	48,592	39.2925	25.69861
Annabhaniyah	47,744	43.068049	25.85791
Al-Aqiq	47,235	41.66544	20.26405
Ranyah	45,942	42.85404	21.26274
Alwajh	44,570	36.469059	26.22879

Almidhnab	44,043	44.228056	25.86278
Turubah	43,947	41.647301	21.22264
Hawtat Bani Tamim	43,300	39.2506	21.47456
Al-Khurmah	42,223	41.7	18.01667
Ashshinan	41,641	37.466667	31.41667
Shagra	40,541	40.423994	21.27006
Baqa	40,157	38.716667	24.21667
Almuzahimiya	39,865	46.25576	24.48147
Assulayyil	36,383	45.574444	20.45972
Tayma	36,199	38.56012	27.62774
Al-Mandag	35,629	41.492164	20.23079
Riadh Alkhabra	34,497	43.55	26.05
Al-Qara	31,480	43.771252	26.41014
Rumah	28,055	47.160584	25.56371
Haqil	27,856	41.683333	27.51667
Uyun Aljiwa	26,544	43.687891	26.52607
Alasyah	26,336	42.565833	28.74611
Qaryah Alulya	24,634	50.043465	26.47018
Duruma	24,429	46.129167	24.60667
Khubash	22,133	46.741752	24.65589
Al-Kamil	21,419	39.785858	22.26971
Hubuna	20,400	44.0165	17.8332
Arrayth	18,961	46.724167	24.71167
Alharth	18,586	39.248577	21.47622
Farasan	17,999	42.120984	16.7019
Thadiq	17,165	46.727616	24.69044
Yadamah	16,851	44.2105	18.5321
Thar	16,047	39.223153	21.55895
Huraymila	15,324	46.10403	25.1158
Alhariq	14,750	46.522099	23.61772
Alghat	14,405	44.960833	26.02667
Badr Aljanub	11,117	46.642955	24.61277
Ashshimasiyah	10,605	44.263056	26.31833
Alkhirkhir	4,015	50.070368	26.41747

APPENDIX B – CODE

DISTRIBUTION TREE (DISTRIBUTIONTREE.M)

```
%% Analysis of Water Pipelining and Distribution Techniques
% In Saudi Arabia, water supplies are extremely limited. In order to
% distribute water among the entire population, water from a limited number
% of soruces must be transported to as many people as possible. This can be
% modelled using a spanning tree.

%% Finding the location of the sources and sinks
% The locations of the various sources can be found by taking inputs of the
% geographic coordinates of the city and then reading them into a matrix.

% Load the relevant data
[num, txt, ~] = xlsread('Sadi Arabia Cities 3.xlsx',3);
names = txt(2:118,1); % May have to adjust this if more cities are added
populations = num(:,1);
longitude = num(:,2);
latitude = num(:,3);
coastal = num(:,4);

% [num, ~, ~] = xlsread('Saudi Arabia Cities 2.xlsx');
% populations = num(3,:)';
% longitude = num(2,:)';
% latitude = num(1,:)';

% Clear unused variables
clear num txt;

%% Modelling connections between sources
% Now, we must find the distances between each point and assign each
% connection a certain weight. Mesh networking theory tells us that the
% total number of connections between n points will be n(n-1)/2.

% Preallocate the connections matrix
numNodes = length(populations);
numConnections = numNodes*(numNodes-1)/2;
DG = zeros(3,numConnections);

%% List Connections.
% Each column represents a different connection. Each row in the column
% has different meanings
%
% * Row 1: Weight of connection between the nodes
% * Row 2: One node of the connection
% * Row 3: Other node of the connection
%

% Generate the connection matrix
head = 1;
for i=1:numConnections
    DG(2,head:head-1+numNodes-i)=i;
```

```
    DG(3,head:head-1+numNodes-i) = i+1:numNodes;
    head = head+numNodes-i;
end

% Calculate the distance for each of the connections
DG(1,:) =
pos2dist(latitude(DG(2,:)),longitude(DG(2,:)),latitude(DG(3,:)),longitude(DG(
3,:)),1);

%% Create Spanning Tree
% Create the sparse matrix of the connections and form the matrix needed
% for the spanning tree algorithm
DG = sparse(DG(2,:), DG(3,:), DG(1,:),numNodes, numNodes);
UG = tril(DG + DG');

% Calculate the minimum weight spanning tree and view in Biograph Viewer
spanningTree = graphminspantree(UG);
%view(biograph(spanningTree,names,'ShowArrows','off','ShowWeights','on'));

%% Create map and background
% Create the bounding box and extract the bounding information
ax = worldmap('Saudi Arabia');
mstruct = gcm;
latlim = mstruct.maplatlimit;
lonlim = mstruct.maplonlimit;

% Load the ETOPO1 data to provide a geographic elevation background to the
% map
[Z, refvec] = etopo('C:\Users\Greg\Desktop\etopo1_ice_c_f4.flt', 1, latlim,
lonlim);
geoshow(Z, refvec, 'DisplayType', 'surface');
rivers = shaperead('worldrivers', 'UseGeoCoords', true);
geoshow(rivers, 'Color', 'blue');
demcmap(Z,256);
colorbar;

%% Plot spanning tree connections between cities
[city1, city2] = find(spanningTree);
distances = zeros(size(city1));
fullMatrix = full(spanningTree);
for i=1:length(distances)
   distances(i) = fullMatrix(city1(i), city2(i));
end

for i=1:length(city1)
   linem([latitude(city1(i)), latitude(city2(i))],[longitude(city1(i)),
longitude(city2(i))],'-y','LineWidth',2);
end

%% Plot Cities on map of Saudi Arabia
plotm([latitude longitude],'k.');
%% plotm([latitude(84) longitude(84)],
'rs','MarkerSize',10,'MarkerFaceColor','r');
%% plotm([latitude(104) longitude(104)],
'rs','MarkerSize',10,'MarkerFaceColor','r');
```

```
%% linem([latitude(33), latitude(75)],[longitude(33), longitude(75)],'-
r','LineWidth',4);
```

POSITION TO DISTANCE CALCULATOR (POS2DIST.M) – SUPPORTING FUNCTION FOR SPANNINGTREE.M

```
function dist = pos2dist(lag1,lon1,lag2,lon2,method)
% function dist = pos2dist(lag1,lon1,lag2,lon2,method)
% calculate distance between two points on earth's surface
% given by their latitude-longitude pair.
% Input lag1,lon1,lag2,lon2 are in degrees, without 'NSWE' indicators.
% Input method is 1 or 2. Default is 1.
% Method 1 uses plane approximation,
% only for points within several tens of kilometers (angles in rads):
% d =
% sqrt(R_equator^2*(lag1-lag2)^2 + R_polar^2*(lon1-
lon2)^2*cos((lag1+lag2)/2)^2)
% Method 2 calculates sphereic geodesic distance for points farther apart,
% but ignores flattening of the earth:
% d =
% R_aver * acos(cos(lag1)cos(lag2)cos(lon1-lon2)+sin(lag1)sin(lag2))
% Output dist is in km.
% Returns -99999 if input argument(s) is/are incorrect.
% Flora Sun, University of Toronto, Jun 12, 2004.
if nargin < 4
    dist = -99999;
    disp('Number of input arguments error! distance = -99999');
    return;
end
if abs(lag1)>90 | abs(lag2)>90 | abs(lon1)>360 | abs(lon2)>360
    dist = -99999;
    disp('Degree(s) illegal! distance = -99999');
    return;
end
if lon1 < 0
    lon1 = lon1 + 360;
end
if lon2 < 0
    lon2 = lon2 + 360;
end
% Default method is 1.
if nargin == 4
    method == 1;
end
if method == 1
    km_per_deg_la = 111.3237;
    km_per_deg_lo = 111.1350;
    km_la = km_per_deg_la .* (lag1-lag2);
    % Always calculate the shorter arc.
    if abs(lon1-lon2) > 180
        dif_lo = abs(lon1-lon2)-180;
    else
        dif_lo = abs(lon1-lon2);
    end
    km_lo = km_per_deg_lo .* dif_lo .* cos((lag1+lag2).*pi/360);
```

```
    dist = sqrt(km_la.^2 + km_lo.^2);
else
    R_aver = 6374;
    deg2rad = pi/180;
    lag1 = lag1 .* deg2rad;
    lon1 = lon1 .* deg2rad;
    lag2 = lag2 .* deg2rad;
    lon2 = lon2 .* deg2rad;
    dist = R_aver .* acos(cos(lag1).*cos(lag2).*cos(lon1-lon2) +
sin(lag1).*sin(lag2));
end
```

SERVICE PLOTS GENERATION (SERVICEPLOTS.M) [27]

```
%% Pipe distance vs number of cities plots
% In the same manner as distributionTree, this script will create a plot
% that describes how the service and amount of pipe will change given

% Uses an iterative approach to determine the amount of pipe to connect the
% 1, 2, 3, ..., n most populous cities, then creates plots of
%
% * Amount of pipe needed vs number of cities served
% * Amount of pipe needed vs population served
%

% Load the relevant data
[num, txt, ~] = xlsread('Saudi Arabia Cities 4.xlsx',3);
names = txt(2:118,1); % May have to adjust this if more cities are added

totalPipe = length(populations);
for n=1:length(populations);
    populations = num(1:n,1);
    longitude = num(1:n,2);
    latitude = num(1:n,3);
    % Preallocate the connections matrix
    numNodes = n;
    numConnections = numNodes*(numNodes-1)/2;
    DG = zeros(3,numConnections);

    head = 1;
    for i=1:numConnections
        DG(2,head:head-1+numNodes-i)=i;
        DG(3,head:head-1+numNodes-i) = i+1:numNodes;
        head = head+numNodes-i;
    end

    % Calculate the distance for each of the connections
    DG(1,:) =
pos2dist(latitude(DG(2,:)),longitude(DG(2,:)),latitude(DG(3,:)),longitude(DG(
3,:)),1);

    DG = sparse(DG(2,:), DG(3,:), DG(1,:),numNodes, numNodes);
    UG = tril(DG + DG');
```

```
    % Calculate the minimum weight spanning tree and view in Biograph Viewer
    spanningTree = graphminspantree(UG);

    [city1, city2] = find(spanningTree);
    distances = zeros(size(city1));
    fullMatrix = full(spanningTree);
    for i=1:length(distances)
       distances(i) = fullMatrix(city1(i), city2(i));
    end
    totalPipe(n)=sum(distances);
end

figure;
plot(totalPipe);
xlabel('Number of cities served');
ylabel('Kilometers of pipe (km)');
title('Kilometers of pipe needed vs number of cities served');

figure;
populations2 = cumsum(populations);
plot(totalPipe, populations2);
xlabel('Kilometers of pipe (km)');
ylabel('People served');
title('People served vs kilometers of pipe');
```

RAINFALL VS RETURN PERIOD PLOT GENERATOR (RESERVOIR.M)

```
%% Storage Distribution

%% Load in rainfall data
data = xlsread('../DATAAAAAAA/rainfall.xls');
data = data(1:9,2:13);
data = [data(:,1:5) data(:,10:12)];

%% Calculate the means and standard deviations for each station
meanRain = mean(data,2);
stdRain = std(data,0,2);

%% Calculate the various coefficients
alpha = 1.282./stdRain;
beta = meanRain - 0.5772./alpha;
beta = beta*12;
%% Calculate the reservoir stores
T = 1:.001:100;
xt = zeros(length(alpha),length(T));
for i=1:length(alpha)
    xt(i,:) = 1/alpha(i)*(log(-log(1-1./T)))+beta(i);
end

%% Plot results
plot(T,xt);
xlabel('Return period (months)');
ylabel('Rainfall (mm)');
```

```
title('Rainfall vs return period');
```

ECONOMIC OPTIMIZATION (ECONOMICS.M)

```
clear all
close all
clc

tic

% Load the data for the pipes and their distances.
load('spanningTree.mat');

% Find the connections, the number of connections for each city, and the
% identies of the pipes.
[city_connections,num_connections,pipes] = find_connections(fullMatrix);

% Set the cost in dollars dollars per kilometer per diameter meter.
cost_rate = 81000/1.609/2.54*100;

% Find the daily water consumption of one person in cubic meters per day.
yearly_water = 2.1*1000^3;
total_population = 28082541;
water_per_capita = yearly_water/365/total_population;

% Set the baseline for the flow rate-to-diameter ratio.
diameter1 = 72*2.54/100;
flow_rate1 = 990000;
area1 = pi*(diameter1)^2/4;

% Find the minimum cost for one desalination plant.
total_cost1 = 1e+15*ones(length(populations),1);

% Increment through every city.
for i = 1:length(populations)

    % See if the city is coastal.
    if coastal(i) == 1

        % Determine the population served by each pipe.
        pipe_pops =
population_counter(populations,i,city_connections,num_connections,pipes);

        % Determine the fow rate needed for each pipe.
        flow_rate = water_per_capita*pipe_pops;

        % Determine the necessary diameter for each pipe.
        diameter = sqrt(flow_rate/flow_rate1*area1*4/pi);

        % Determine the cost of each pipe.
        cost = cost_rate*diameter.*pipes(:,1);
```

```
        % Determine the total cost for the configuration.
        total_cost1(i) = sum(cost);
    end
end

% Find the minimum cost for one desalination plant.
[min_cost,i] = min(total_cost1);
disp(min_cost);
disp(i);

% ---------------------------------------------------------------------------
% Use two desalination plants.

% Find which cities are coastal cities.
j = 1;
for i = 1:length(populations)
    if coastal(i) == 1
        coastal_cities(j,1) = i;
        j = j + 1;
    end
end

% Perform a test run for a given pipe and two given port cities.

j = 94;
% Determine the two cities connected by the pipe.
citya = pipes(j,2);
cityb = pipes(j,3);

% Eliminate that pipe.
pipes2 = [pipes(1:j-1,:); pipes(j+1:length(pipes),:)];

% Eliminate that pipe's connections.
city_connections2 = city_connections;
num_connections2 = num_connections;
city_connections2(citya,cityb) = 0;
city_connections2(cityb,citya) = 0;
num_connections2(citya) = num_connections(citya)-1;
num_connections2(cityb) = num_connections(cityb)-1;

i = 2;
k = 8;

% Find the two source cities.
source1 = coastal_cities(i);
source2 = coastal_cities(k);

% Find the populations served by each pipe.
pipe_pops1 =
population_counter(populations,source1,city_connections2,num_connections2,pip
es2);
pipe_pops2 =
population_counter(populations,source2,city_connections2,num_connections2,pip
es2);
```

```
% Add the two vectors together.
pipe_pops_total = pipe_pops1 + pipe_pops2;

if ~isempty(find(pipe_pops_total == 0,1))
    pipe_pops_total = 1e+18*ones(length(pipe_pops1),1);
end

% Add the two vectors together.
pipe_popstotal = pipe_pops1 + pipe_pops2;

% Find the total cost.
total_cost2 = zeros(length(pipes),3);



% Increment through every pipe.
for j = 1:length(pipes)

    % Determine the two cities connected by the pipe.
    citya = pipes(j,2);
    cityb = pipes(j,3);

    % Eliminate that pipe.
    pipes2 = [pipes(1:j-1,:); pipes(j+1:length(pipes),:)];

    % Eliminate that pipe's connections.
    city_connections2 = city_connections;
    num_connections2 = num_connections;
    city_connections2(citya,cityb) = 0;
    city_connections2(cityb,citya) = 0;
    num_connections2(citya) = num_connections(citya)-1;
    num_connections2(cityb) = num_connections(cityb)-1;

    total_cost2b = 1e+15*ones(length(coastal_cities),length(coastal_cities));

    % Increment through each coastal city for the two sources.
    for i = 1:length(coastal_cities)
        for k = 1:length(coastal_cities);

            if i ~= k
            % Find the two source cities.
            source1 = coastal_cities(i);
            source2 = coastal_cities(k);

            % Find the populations served by each pipe.
            pipe_pops1 =
population_counter(populations,source1,city_connections2,num_connections2,pip
es2);
            pipe_pops2 =
population_counter(populations,source2,city_connections2,num_connections2,pip
es2);

            % Add the two vectors together.
            pipe_pops_total = pipe_pops1 + pipe_pops2;
```

```
            if ~isempty(find(pipe_pops_total == 0,1))
                pipe_pops_total = 1e+18*ones(length(pipe_pops1),1);
            end

            % Determine the fow rate needed for each pipe.
            flow_rate_total = water_per_capita*pipe_pops_total;

            % Determine the necessary diameter for each pipe.
            diameter_total = sqrt(flow_rate_total/flow_rate1*area1*4/pi);

            % Determine the cost of each pipe.
            cost = cost_rate*diameter_total.*pipes2(:,1);

            % Determine the total cost for the configuration.
            total_cost2b(i,k) = sum(cost);

            end

        end
    end

    % Find the minimum cost for this pipe cut.
    [col_mins,min_inds] = min(total_cost2b);

    [min_val,min_index] = min(col_mins);
    total_cost2(j,1) = min_val;
    total_cost2(j,3) = min_index;
    total_cost2(j,2) = min_inds(total_cost2(j,3));

    % Display the minimum cost for removing this particular pipe.
    disp(total_cost2(j,1));
    disp(total_cost2(j,2:3));

end

% Find the absolute minimum cost among all the options for removing a pipe
% and choosing cities for desalination plants.
[absolute_min,pipe_min] = min(total_cost2(:,1));
min_citya = total_cost2(pipe_min,2);
min_cityb = total_cost2(pipe_min,3);

% Display how long running the code took.
time = toc;
disp(time)

% Display the minimum for two desalination plants.
disp(absolute_min);
disp(min_citya);
disp(min_cityb);
disp(pipe_min);
```

PIPE SERVICE POPULATION COUNTER (POPULATION_COUNTER.M) – SUPPORTING FUNCTION FOR ECONOMICS.M

```
function pipe_population =
population_counter(population_data,source,connections,num_connections,pipes)

% Create dupliclates in case recursion is needed.
connections_duplicate = connections;
num_connections_duplicate = num_connections;
population_data_duplicate = population_data;

% Find the number of cities.
[num_cities,~] = size(connections);

% Create a vector to hold the population supplied by each pipe.
pipe_population = zeros(length(pipes),1);

% Loop indefinitely.
while(1)


% Exit the fucntion if there are no zero pipe populations left (that do not
% lead to unserviced, zero-population cities).
check = 0;
for k = 1:length(pipes)
    if (pipe_population(k) ~= 0) || ((population_data(pipes(k,2)) == 0) &&
(population_data(pipes(k,3)) == 0))
            check = check + 1;
    end

end

% Exit if all of the pipes either have a population number or serve a city
% that has zero population.
if check == length(pipes)
    return
end



% Create a temporary matrix of connection data.
temp_num_connections = num_connections;

% Look at each city.
for i = 1:num_cities

    % See if the city has only one connection and is not the source.
    if temp_num_connections(i) == 1 && i ~= source

        % Find the city that the city connects to.
        j = find(connections(i,:) ~= 0,1);

        % If the connection can't be found, this is a flawed tree, so set
        % the cost at maximum and exit.
```

```
        if isempty(j)
            pipe_population = 1e+15*ones(length(pipes),1);
            return
        end

        % First ensure the current city has a population.
        if population_data(i) ~= 0

            % See if the city is connected to an isolated city or a city
            % with a population of zero.
            if (temp_num_connections(j) == 1 && (j ~= source && i ~= source))
|| population_data(j) == 0

                % If so, set the populations of both cities to zero.
                population_data_duplicate(i) = 0;
                population_data_duplicate(j) = 0;

                % Then call the function again with those two cities having
                % populations of zero, so that pipes to those cities will
                % serve no populations (that is, the source doesn't reach
                % those cities).
                pipe_population =
population_counter(population_data_duplicate,source,connections_duplicate,num
_connections_duplicate,pipes);
                return
            end

            % Find the pipe between those two cities.
            temp = ((pipes(:,2) == i) & (pipes(:,3) == j)) | ((pipes(:,2) ==
j) & (pipes(:,3) == i));

            % Find the pipe.
            pipe_num = find(temp == 1,1);

            % Add the population to that of the connecting pipe and that of
the
            % city connected to it.
            pipe_population(pipe_num) = population_data(i);
            population_data(j) = population_data(j) + population_data(i);

            % Eliminate the connection between those two cities.
            temp_num_connections(j) = temp_num_connections(j) - 1;
            temp_num_connections(i) = temp_num_connections(i) - 1;
            connections(i,j) = 0;
            connections(j,i) = 0;

        end

    end
end


% Update the connection data.
num_connections = temp_num_connections;
```

```
end

end
```

CONNECTION LOCATIOR (FIND_CONNECTIONS.M) – SUPPORTING FUNCTION FOR ECONOMICS.M

```
function [city_connections,num_connections,pipes] =
find_connections(distance_matrix)
% Labels the connections each city has to the other cities.

%Find the size of the distance matrix.
[rows,cols] = size(distance_matrix);

% Create the connection matrix.
city_connections = zeros(rows,cols);

% Set an incrementer.
k = 1;

% Look at each row and column.
for i = 1:rows
    for j = 1:cols
        % Determine if there is a connection between the two cities.
        if distance_matrix(i,j) ~= 0

            % If there is a connection, note the connection for both
            % cities.
            city_connections(i,j) = 1;
            city_connections(j,i) = 1;

            % Label the pipe between the two cities.
            pipes(k,1:3) = [distance_matrix(i,j), i, j];
            k = k+1;
        end
    end
end

% Set up a counter of the number of connections each city has.
num_connections = zeros(rows,1);

% Look at each city.
for i = 1:rows
    % Find all connections.
    temp = find(city_connections(i,:) ~= 0);
    % Find the number of connections and store them.
    [~,num] = size(temp);
    num_connections(i) = num;
end

end
```

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