Abstract

The objective of this paper is to introduce models to determine an effective, feasible, and cost-efficient strategy for the water system in Saudi Arabia so that it can meet its projected demand in 2025. This paper uses cost minimizing and production maximizing approaches to build the models. The water management system is divided into three processes: desalination, distribution, and wastewater treatment. For desalination and wastewater treatment, we use an economics Cobb-Douglas production maximization model. Through this model, the optimal levels of different inputs that maximize the production of usable water are determined, given the Saudi Arabia government's budget constraint. For the waterdistribution model, a cost function, which depends on the diameter of pipes and the hydraulic head, is utilized. The cost function is minimized with the 2025 demand constraint and is used to determine the optimal diameter of the pipes and hydraulic head. In the cost minimization model, the 2025 water demand is divided into three sectors–agricultural, industrial, and domestic–to meet their specific demand.

Using the desalination process model, the paper finds that the optimal level of input of electricity is 4.9 billion kWh and the maximized water output is estimated at 3.3 billion m^3. This value is about one-tenth of the projected demand of 2025(Seckler,Amarasinghe, Molden de Silva & Barker 1998). In addition, using the wastewater treatment model, the paper found that the optimal level of electricity input is 26.5 billion kWh annually and the maximized level of water production is 7.7 billion m^3. This value is greater than the estimated level of total sewage in 2025, a value of 1.6 million m^3. The water distribution model estimates that, given the 2025 water demand in Saudi Arabia, the set-up and operating cost of a distribution grid is approximately \$68.88 million. The model also estimates that a minimum pipe diameter of 5.37m and hydraulic head of 1186.14m is required to meet the demand of three sectors–agriculture, industry, and domestic.

The paper also provides suggestions to the Saudi Arabia government so that their water management system maximizies production and becomes more cost efficient. Using renewable energy for desalination and wastewater treatment, along with a reduction in the size of the agriculture sector, will not only result in a fall in water demand, but also create a more sustainable method for the country to provide water to its residents.

Water, Water Everywhere: Meeting the Demands of Saudi Arabia's Water Needs

February 5, 2013

Contents

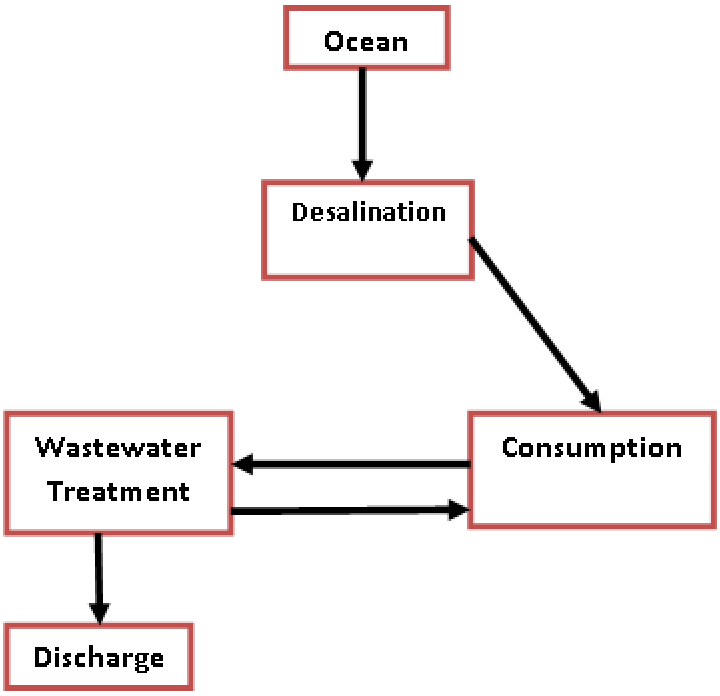
1 Introduction

Given that water is a limited resource and the world population and water usage is increasing drastically, the availability of water in the future is a major challenge we face today. A desert country like Saudi Arabia will face even greater difficulties as the population of the country grows and it continues to expand its agricultural and industrial sector. The Middle East is the largest desalination market in the world. Leading in this region is Saudi Arabia, where 70 % of the countrys drinking water supply comes from desalinated sea water (Rodriguez, 2012).In addition,as the water demand increases drastically along with population, there will be more wastewater to be treated. At present, only 37 % of the sewage is treated.(Kajenthira, Siddiqi& Anadon 2012). This paper presents three models that optimizes the efficiency of seawater desalination, water distribution and wastewater treatment. For the models of desalination and wastewater treatment, an economics cobb-douglas production maximization model is used to determine the optimal levels of inputs of electricity and other factors of production to maximize the total production of water. For the water distribution model, this paper models a cost function which is minimizd with the constraint of 2025 water demand. In addition, this model also estmates the optimal diameter of the pipeline and the hydraulic head, so that the capital and operation costs of the distribution grid can be minimized, given the demand constraint.Furthermore, this paper presents a point paper for the government of Saudi Arabia so that the water demand in the country can be met a cost-efficient and sustainable manner.

2 Terminology

- Hydraulic Head - is a measure of liquid pressure such as that of water flowing through pipelines
- Volumetric Flow Rate - the volume of water that passes through a given surface per unit time.
- Level of Loading- is the changing demand for the consumption of water during a day or year.

3 Models for Water Management in Saudi Arabia



Water Management Process in Saudi Arabia

The figure above illustrates a simplified system to manage the water demands of Saudi Arabia. Saudi Arabia has sea water on both eastern and western coast of the country (see Figure 1 below). Since most of the water supply of Saudi Arabia comes from desalinated water, the figure illustrates this process as the primary water supplier. Desalinated water goes for consumption through a water distribution system. After the used water is treated, it is either discharged or used for consumption again. This figure, thus, provides a layout for the three models that are explained below. These include a model for the desalination process, the water distribution process, and the water treatment process.

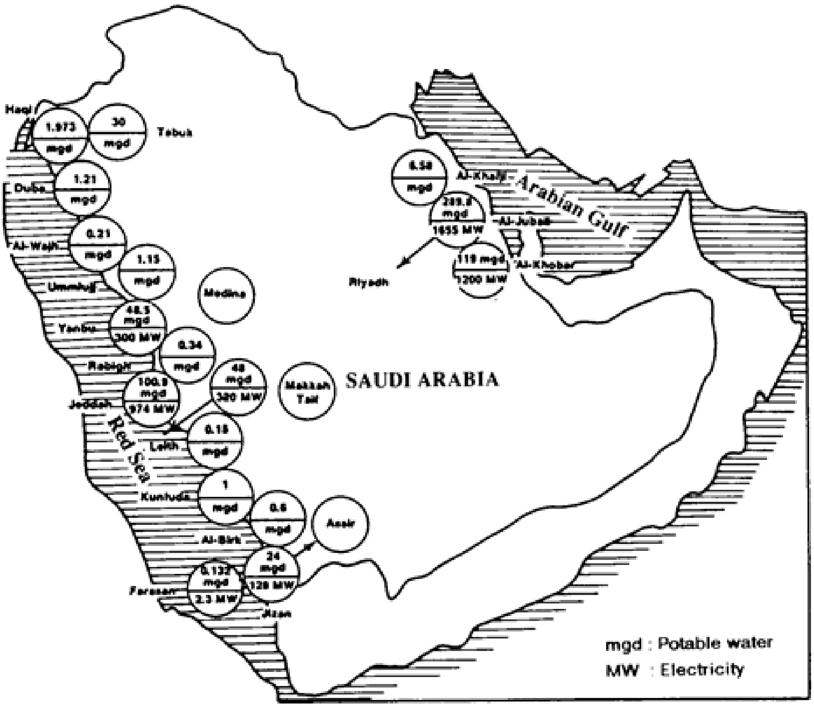


Figure 1: Desalination Plants in Saudi Arabia (Source: SWCC (1998))

4 The Models

4.1 A model for maximizing de-salted water production in desalination plants

4.1.1 Desalination - background

In todays scenario of depleting sources and increasing demand, Desalination provides alternative fresh water sources by making saline water from oceanic or underground sources usable for irrigation, municipal or industrial purposes. This is crucial since out of the vast majority of the Earths water which is located in the lakes and oceans, only about one percent is considered usable freshwater for human consumption. It provides a key strategy to tap into the vast available sources to meet water demands especially in coastal areas and areas with large brackish or underground water sources. Desalination consists of methods to reduce the amount of dissolved salt and other impurities such as biological or organic chemical compounds in saline water by using various separation processes such as thermal and membrane based desalination. Thermal desalination methods have been used for a longer time and involve evaporation and condensation to separate salt from water while membrane based methods use techniques where water diffuses through a membrane. The most widely used thermal and membrane based desalination processes are Multi-stage flash distillation (MSF) and Reverse Osmosis (RO) respectively. Although desalination has huge potential benefits for regions with water scarcity, the economic costs, energy consumption and the lack of regional and resource compatibility along with environmental impacts remain major deterrents in the way of its wide commercialization.

4.1.2 Saudi Arabia - the largest producer of desalinated water

Currently, the Persian Gulf islands, with limited local supplies, and some selected other areas in the region, where water options are limited and the public is willing to pay high prices, have the most significant seawater desalination capacities. The Middle-East is the largest desalination market in the world with Saudi Arabia leading the worldwide production of desalinated water. Seventy percent of Saudi Arabias drinking water demand is met by seawater desalination performed by over thirty operating plants which distribute the desalinated water to major urban and industrial areas through an extensive water distribution system. In 2010, more than 1,103 million cubic meters of desalinated water was produced. MSF and RO are the most commercially important and extensively used desalination processes with the future trend leaning more towards RO because of its lower cost and simplicity.

Reverse Osmosis is a pressure driven process where the impure saline feed water is pressurized against a membrane that rejects dissolved constituents to produce drinking water.The amount of desalinated water that can be produced ranges between 30 to 85 percent of the volume of the input water depending on the initial water quality, the quality of the product needed, and the technology and membrane involved. The development of improved membranes and energy recovery systems have and are continuing to reduce the cost of the RO process and have made it the most significant and viable desalination process.

4.1.3 Previous work in modelling Desalinated Water Production

Given the importance of desalination as a water resource for Saudi Arabia, a desert country with a rapidly growing economy and increas-

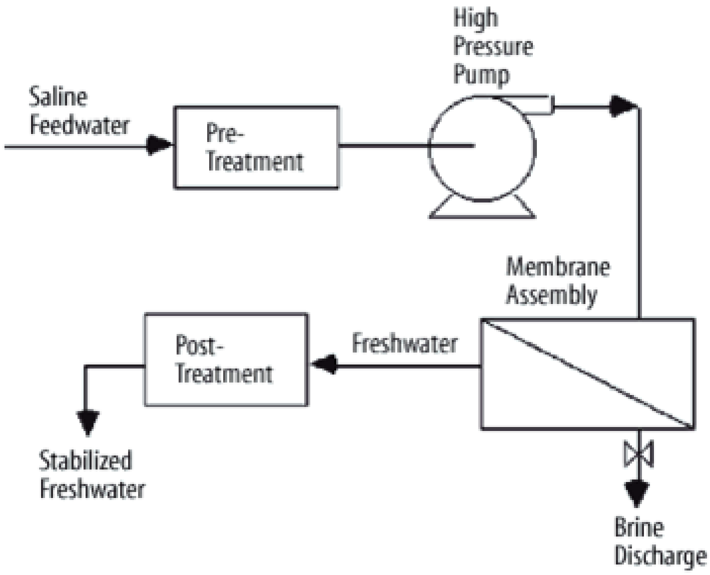


Figure 2: Flow Diagram of Reverse Osmosis System (Kahn, 1986)

ing resource demands, the continuous development of high productivity resource collection and distribution models is vital for ensuring sustained development. Previous studies have carried out statistical and econometric analysis of the costs and operations of a desalination plant and identified the underlying economic production function to be of the Cobb-Douglas form.(Production and Cost Functions of Water Low-Temperature Solar Desalination, Applied Economics 21 (September 1989)) Data from the model were obtained and evaluated under the condition that the plant operates under maximum loads continuously throughout the year except for maintenance periods. This analysis in terms of complementarity and substitution among the different factors of production and inputs led to the formulation of a production function:

$$W = F^{0.6} H^{0.4}$$

where W represents cubic meters of desalted water produced, F represents factors of production (an aggregation of evaporating pumps, maintenance of those pumps, and labor) and H represents the level of heat used for the evaporation process.

The analysis in terms of the average desalination costs and different production levels led to the formulation of a long term average cost function as well

According to the authors of the study:

"The technical inputs of water desalination can be classified into two groups: those for which the cost per unit of desalted water is increasing when the technical index of the number of effects is increasing, and those for which this cost is decreasing under the same circumstances. This classification permits us to express production of desalted water as a function of two aggregates of inputs, corresponding to the above substitutional groups. Thus a production function is extracted for the general case of full-load annual operation of the desalination plant."

Hence the production of desalinated water can be optimized by maximizing the production function under the budget constraint i.e. the total cost for inputs should not exceed the allocated government budget for desalination.

4.1.4 Model Assumptions

We will assume that the Cobb-Douglas model can be extended specifically to apply to Reverse Osmosis plant production, similar to how it was applied to the more traditional Thermal Desalination Plant in the above study. The model constructed assumes that the entire budget allocation will be directed towards one desalination facility which represents the aggregate production of all the plants that make up the desalination industry in Saudi Arabia. It will then be optimized to arrive at a maximum level of water output per year, represented by the output variable W (in terms of cubic metres of desalted water produced per year) under the budget constraints:

$$B = P_F F + P_H H$$

where P_F represents the price per unit of the aggregate factors of production, P_H represents the price per unit of level of heat used(in terms of price of electricity) and B represents the allocated budget for the Reverse Osmosis sector.

The following assumptions are made in terms of the variable inputs and constraints in the model:

- The desalination plants have constant returns to scale.
- The variable F is an aggregate input variable that represents the level of all the factors of production that go into the process of desalination.
- The input for the level of heat H is considered to be equivalent to the input for electrical energy, and hence will be interpreted as the required amount of electrical energy that needs to be supplied for optimum production. (in kWh)

- The price per unit variables P_F and P_H are taken to be the most recent aggregate cost per cubic meter of production (\$0.46/m^3) and cost of electricity required per cubic meter of desalinated water production (\$0.21/m^3) respectively. The cost of electricity was found using the price of electricity per kWh in Saudi Arabia (\$0.03/kWh) and estimates for the average electrical consumption per cubic meter production of desalinated water (7kWh/m^3).
- The constraint provided by the budget B, is assumed to be a percentage of Saudi Arabias 2013 national budget towards water related projects. We assume forty percent to be directed towards desalination projects, thus giving us a budget of \$2.56 billion.

4.1.5 Final Optimization Model

With the above assumptions, we have the final optimization problem:

Maximize

$$W = F^{0.6}H^{0.4}$$

Subject to

$$0.46F + 0.21H \leqslant 2.56 \times 10^9$$

where

- W = Cubic meters of desalted water produced per year using Reverse Osmosis
- F = A measure of the level of input factors of production per year (an aggregation of plant equipment, maintenance, and labor)
- H = Amount of electrical energy used (in kWh) in the reverse osmosis process per year.

4.1.6 Optimization Results

Using *Mathematica* to optimize the above problem, we obtain following optimum levels of output, the input factors of production and heat input levels:

Maximum volume of water production per year $W = 3.9\times 10^9 m^3/year$
Level of input aggregate factors of production $F = 3.3\times 10^9 units/year$
Level of heat/electrical energy input $H = 4.9 \times 10^9 kWh/year$

4.1.7 Sensitivity Analysis

The robustness of the model can be examined by analyzing the sensitivity of the model's output to changes in input. We will test our model using several variable inputs and observing the resulting outputs and the level of variations.This is summarized in the table below:

% Budget	Max Output (billion m^3)	F (billions)	H (kWh)
34	3.30	2.84	4.14
36	3.50	3.01	4.34
38	3.69	3.17	4.63
40	3.86	3.34	4.88
42	4.08	3.51	5.12
44	4.27	3.67	5.36
Price/F ($)	Max Output (billion m^3)	F (billions)	H (kWh)
0.40	4.22	3.84	4.88
0.42	4.10	3.66	4.88
0.44	3.99	3.49	4.88
0.46	3.86	3.34	4.88
0.48	3.79	3.20	4.88
0.5	3.70	3.07	4.88
Price/H ($)	Max Output (billion m^3)	F (billions)	H (kWh)
0.15	4.44	3.34	6.83
0.17	4.23	3.34	6.02
0.19	4.04	3.34	5.39
0.21	3.86	3.34	4.88
0.23	3.79	3.34	4.45
0.25	3.62	3.34	4.10

Table 1: Sensitivity Analysis for Desalination Production Model

We can observe from the above table that changes in the constraints and inputs lead to changes in output as expected - higher budget causes output to increase while increases in the prices per unit of the input factors causes the output to decrease. If we examine the effect of variable changes on the input factors, we see that an increase in the budget is associated with higher levels of input factors as expected. However,although increases in prices per unit of production factors is associated with a lower input level of the factor whose price was increased, the input level of the other factor remains constant throughout. This is contrary to our expectation that higher prices per unit of one factor of production would have some impact on the use of other production factors. This could possibly point to some weaknesses in the estimation of the portion of the cost of water production that arises due to electrical energy costs and the portion that comes from other production factors. The price per unit used for the aggregate factors of production F might already account for energy costs. Another possibility is that the model tries to keep the input for the other production factors constant and only adjusts the input for the factor whose price changed, which could in practice ensure that the overall quality of production does not change significantly.

4.1.8 Strengths and Limitations of the Model

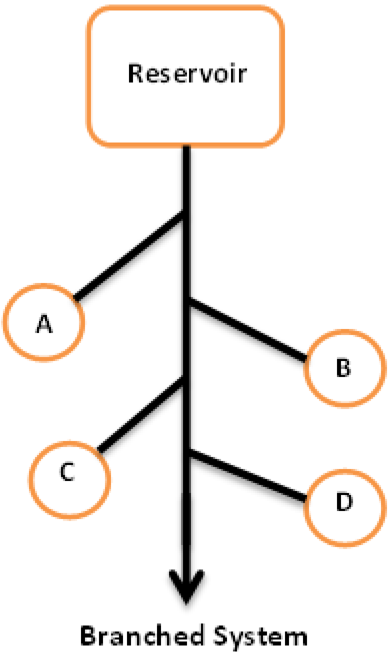
One of the strengths of the model is the wide applicability and simplicity of the Cobb-Douglas production function for the Desalination which allows us to easily examine optimal input allocations for maximized output. Another important feature of the model is that it separates input factors of production into an aggregate input factor and an energy factor. This is useful given that energy input forms one of the most important aspects of the water resource area in Saudi Arabia. This model can thus allow for a distinctive analysis of the level of investment that needs to be directed into energy sources.

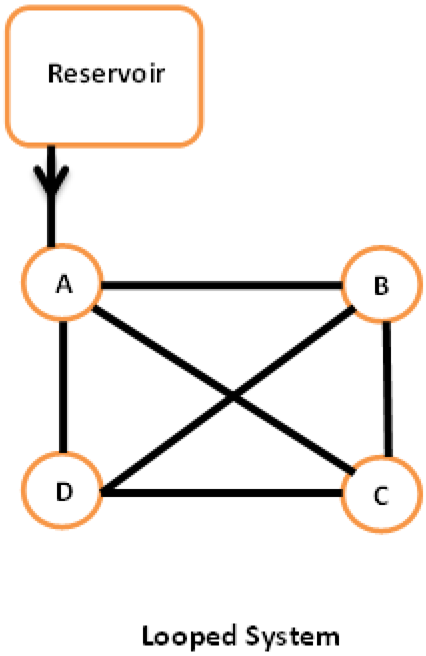
Although the model does provide a valuable tool for optimizing the desalination process, the above maximization process has a number of limitations due to the lack of availability of exact figures for prices per unit of inputs and government budget allocations to desalination projects. In this light, several assumptions were made which might make our results quite unrealistic in terms of pratical application to the water management scenarion in Saudi Arabia keeping the 2025 projected demands in mind. Better data would make the model more extendable to applications in the desalination industry situation in Saudi Arabia.

4.2 A model for Minimizing Distribution Costs of Water

4.2.1 Water Distribution-A Background

Once the water is stored in a reservoir from different supply streams, the water is distributed to agricultural sector, industries, and households. There are two ways by which water is usually distributed. In The branched method, each node,representing a water consumption body, has only one pipeline or link connected to it. In this system there is one main pipeline and smaller pipelines connect the main pipe to the individual nodes (see diagram below). Another method for water distribution is a looped method where more than one pipeline is connected to each node. In this system, thus, every node can receive water from at least two sources (see diagram below).





4.2.2 Model Assumptions

- The model illustrates the water distribution system for both branched and looped system.
- There are two factors, diameter of piping and hydraulic head, that affect the cost of distribution of water.
- The topography of Saudi Arabia is plain like a 2-D surface and does not include any contours, mountains, and valleys.
- There is no resistance or friction of water in the pipes or at the nodes.
- The distance between nodes or the length of the linking pipes is given, along with the level of consumption at each node.
- The model does not have a valve system to stop the water flow in the pipes i.e. once the water is released from the reservoir, it will continue to flow through the pipe in the grid of nodes and links.
- The model assumes that the consumption of water at each node is known.

4.2.3 The Model

The model seeks to minimize total cost, including the fixed or capital costs and variable or operational costs, in the water distribution system. The total cost function is minimized given the constraint that the total demand of water in Saudi Arabia is met. Thus, the model seeks to optimize the cost of supply of water while meeting the demands of the three main sectors-agriculture, households, and industries (Shamir, 1974).

The fixed cost in the model is a function of the length L, the distance bewteen each node of consumption, and the diameter d of the piping network. The length of the pipes is given in the model becasue usually the distances between existing industries and households cannot be changed. The diameter of the pipes, on the other hand, is a variable calculated by solving the optimization problem. Both length and diameter of the pipe are directly proportional to the capital cost in the water distribution system as more material and labor costs are required when the piping system is longer and bigger.

The variable cost is a function of the amount of consumption C of water at each node, the diameter d of the piping, and the hydraulic head h of the water flowing through the pipes. The diameter of piping is directly proportional to the operating cost because the greater the diameter of the pipe, larger are the maintaing costs, especially when the pipes break or there are leakages. Additionally, the greater is the diameter of a pipe, the larger is the volumetric flow rate i.e. greater are the costs as more energy is required for a larger flow rate. Hydraulic head, which is a measure of liquid pressure, is also directly related to the operating cost. Greater the liquid pressure with which water flows in the pipes, greater pumping energy is required, resulting in higher costs. In addition, the variable cost also depends on the level of loading l that occurs at any given point of time during a period of time (Heaney et al, 2000). Loading l takes into account that water consumption may be higher during mornings or the tourist season of the year. Given the changing level of consumption of water in a given period of time, the operational cost also varies. Thus, a distribution system may have a higher loading i.e. higher consumption during 30 percent of a day and lower loading for the rest of the day.

When the capital and operational costs are added, a total cost function is created. The function includes a fixed cost constant α and a variable cost constant γ which are determines using the data available. The total cost function is given by the following.

TotalCost (d,h)=Fixed Cost + Variable Cost

$$TotalCost(d,h) = \alpha \sum_{i=1}^{n} L_i d^{\beta} + \gamma \sum_{l=1}^{L} \sum_{j=1}^{p} (c_P)^l d^{l\theta} h^{l\phi}$$

$$Minimize(TotalCost(d,h))$$

$$s.t.$$

$$Q = 3.5d^2\sqrt{h}$$

- α=fixed cost constant
- β=economies of scale factor for diameter in fixed cost
- γ=variable cost constant
- l=loading level
- θ=economies of scale factor for diameter in variable cost
- ϕ=economies of scale factor for hydraulic head

The constraint is calculated using th following equation, where Flow rate Q is given by the ratio of total demand of water and unit time, g is the gravitational constant, and h is the hydraulic head.

$$Q = Area * Velocity$$

$$Q = \frac{\pi d^2}{4} * \sqrt{2gh}$$

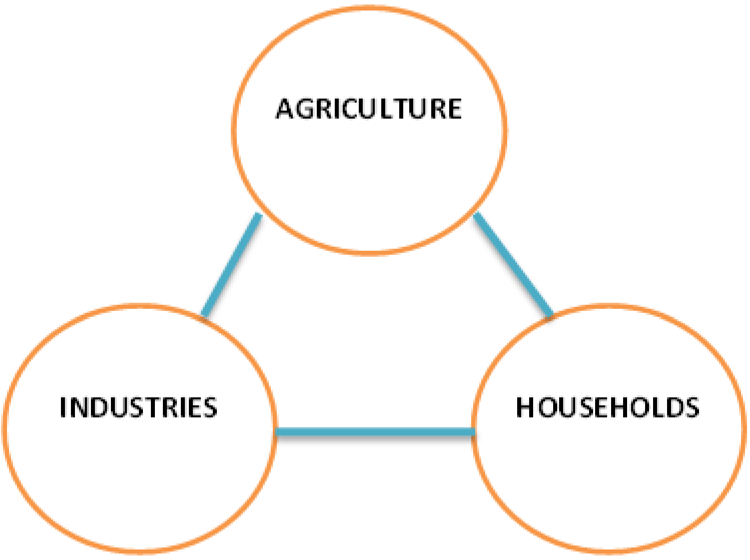
$$Q = 3.5d^2\sqrt{h}$$

4.2.4 Parameter Estimation

The parameters listed above are estimated using empical studies on water distribution systems in United States. Even though costs and factors of economies of scale are probably different in United States and Saudi Arabia, the emperical work on Saudi Arabia's water distribution system was lacking. Given that (Heaney et al, 2000) estimate the pipe construction cost per foot to be dollar 15 for an inch of diameter in the 1998 dollar terms, in 2012 terms the pipe construction cost per meter for a meter of pipe diameter is calculated to be dollar 827. Thus, α, the fixed cost constant, is estimated as 827. Heaney et al estimate the flow rate constant as 218. When calculated in conjuction with 2012 and the flow rate equation, γ, the variable cost constant is 763. According to this study, β, θ, and ϕ have values less than 1. This means that economies of scale is being achieved oth in fixed and variable costs i.e. water distribution system has cost advantages due to the large size. Thus, β is estimated as 0.6, θ is estimated as 0.8, and ϕ is estimated as 0.4385.

4.2.5 The Results

When the model is run using the software *Mathematica*, we get the following results. For this simulation, the total Saudi Arabia's water demand for 2025 is divided by into the three main sectors-argriculture, industries, and households, given that agriculture accounts for 88 percent water use in Saudi Arabia with 3 percent usage by industries and 9 percent usage by households (Abderrahman, 2006). Thus, there are three nodes representing agriculture, industry, and household with consumption of $876.41\frac{m^3}{s}$, $29.81\frac{m^3}{s}$, and $89.74\frac{m^3}{s}$, respectively. In this hypothetical example, the links or pipes are assumed to be of the length 490m, 485m, and 500m, respectively.



Three Sectors as Nodes for Water Distribution

After optimizing, the results indicate that the total cost for laying out and operating a water distribution system, given the hypothetical distances bewteen the nodes and the consumption by each of the main three sectors, is $68.88 million. This result also generates a minimzed pipe diameter of 5.37 m and hydraulic head of 1186.14 m. Thus, if there were only three nodes of consumption that are laid out at the distance mentioned above, then to meet the demand, $68.88 million will have to be spent on the water distribution system. In the simulation laid out in this section, it was assumed that there is only one level of loading, i.e. three nodes have a constant demand of water.

4.2.6 Sensitivity Analysis

The robustness of the model explained above is measured in this section.If the lengths of pipelines and the amount of water consumed is altered, we get the results as illustrated in the table below. The table illustrates that greater the length of pipeline or larger the level of consumption, greater is the cost for laying and operating the distribution system.

Total Length	Total Consumption	Cost	d	h
1475m	$996\frac{m^3}{s}$	68.88 Mil	5.37m	1186.14m
98m	$3.8\frac{m^3}{s}$	616,50	0.28m	17.23m
2450m	$27.41\frac{m^3}{s}$	221,743	0.32m	114m

Table 2: Cost, Diameter, and Hydraulic Head for a Given Length and Consumption

Additionally, the greater is the projected demand/consumption of water, the bigger is the minimized diameter of the pipes and the minimized hydraulic head. Thus, the model does not seem to be very sensitive to large and small input values of pipeline length and water consumption.

4.2.7 Strengths and Weaknesses of the Model

Even though the model presented above only takes into account the pipe diameter and hydraulic head as two inputs among many other inputs of a cost function, it generates robust results that align with emperical research. Additonally, this model also takes into account the differences in consumption that may occur at each node in the distribution grid. Furthermore, the model acknowledges that the distances between nodes (whether it be a residential or industrial area) is usually a given factor and cannot be changed. The level of loading adds another dimension to the model by taking into account the differing amounts of water consumption at any given period of time.

Nevertheless, the model does have some limitations. Firstly, since the number of pipes and nodes need to be modelled discreetly, the level of loading is also being modelled discreetly. This may not reflect the actuality of water distribution as the changes in level of loading happen continously. Secondly, the cost model does not take into account the water loss that may occur from leakages and pipe breaks, a common problem in Saudi Arabia. Thirdly, the model assumes that the a 2-D like distribution grid, discounting the affect gravity will have on the pressure (hydraulic head) of water.

4.3 A Model for Maximizing the Production in Wastewater Treatment Plants

4.3.1 Assumptions

- Constant returns to scale $a + b$=1
- Unfortunately there was no data found on the input of electricity and factors of production and outputs. If the data were present, the method of least square regression would be used to estimate a and b. we assume a and b to be 0.4 and 0.6 respectively.
- Both inputs of electricity and other factors of production are proportional to the output.
- Cost of electricity and other factors of productions are determined by the price of electricity times the quantity of electricity needed per m^3 and cost of other factors of production per m^3.
- p^f=$0.038 per m^3
- P^e=$0.46 per m^3[1]

  $6.4 billion dollars (SR24 billion) will be spent on water resources by building dams and desalination plants, using deep aquifers wells, expanding and improving water and water treatment networks.[2]Since there was no information found on the breakdown of this budget, the budget for the wastewater treatment would be assumed to be 30% of the total budget. Thus, B=$2.56 Billion

4.3.2 Model

$$Q = F^a E^b$$

Maximize the function where the constraint is C=$P^f P^e \leqslant$B

- Q=Total production
- F=Factors of Production

[1]Seckler,Amarasinghe,Molden & Silva 1998
[2]U.S-Saudi Arabian Business Council

- E=Electricity
- P^e=Cost of electricity per
- P^f=Cost of factor of production per m3water
- C=Total cost of water productions
- B=Governmetbudget

4.3.3 Results

The function was maximized with the constraint.The optimized values for the quantities of electricity and other factors of production are estimated

F=$3.339 \times 10^9 unit$
E=$2.65 \times 10^1 0kWh$
Q=$7.65 \times 10^9 m^3$[3]

4.3.4 Sensitivity Analysis

With Different Government Budget

As the budget increase, the total production increases, at faster rate

% Budget	F	E	G
0.1	0.83	6.64	1.91
0.2	1.66	13.28	3.82
0.3	2.50	19.90	5.74
0.4	3.33	26.56	7.65
0.5	4.17	33.20	9.56
0.6	5.00	39.8	11.48
0.7	5.89	46.48	13.30
0.8	6.67	53.10	15.30
0.9	7.51	59.70	17.22
1	8.34	66.40	19.10

Table 3: Optimal Level of Input for Electricity and Other Factors of production with Varying Budget

at the lower level of the budget at the higher level of the budget. When the fraction is budget is increased from 10% to 20%, there is 100 % increase in the maximum output while when the budget is increased from 90 % to 100 %, the increase in the maximum output is only 10

[3]Kajenthira, Siddiqi& Anadon, 2012

%. In addition, the optima electricity input grows a lot faster than other factors of productions. When the fraction of budget spent was increased from 10 /

4.3.5 Strengthes and Weaknesses of the Model

Since there was no information found on the breakdown of inputs for the wastewater treatment platns, the constants a and b could not be determined. This may have caused inaccuracy in the result. In addition, if there were more information available on the prices and quantities of labor, materials and other different factors of productions, the production function could be a product of more variables. This may give us the optimal level of labor, chemicals and other factors of production. Furthemore, when calculating the price of factors of productions per m^3 production of water, it was uncertain to determined if the data obtained included electricity cost. If it did include the cost, it may explain partially the reason why the change in government budget caused much greater increase in optimal input level for electricity than in other factors of production.

Dispite these drawbacks of the model, it can be practically applied with enough information on the inputs and the outputs. In addition, the model can be integrated with the one of desalination model to estimate the optimal fraction of the budget to be spent on the desalination and on the the wastewatertreatment.

5 Position Paper for the Ministry of Water and Electricity, Saudi Arabia

The Kingdom of Saudi Arabia is an excellent example of a nation that has overcome its harsh geographical setting and environmental scarcity of water, perhaps the most vital resource, and has made astonishing progress over the last several decades. The government has efficiently diverted its abundant natural oil resources to turn around the situation of water scarcity in the kingdom. Massive investments by the Saudi government in projects such as agriculture and desalination technologies has provided the citizens with the vital resources to grow individually and hence develop as an entire nation. However, as lifestyles improve and the infrastructure expands, the consumption of resources is multiplying more than ever before. In light of this rapidly increasing demand, there are rising concerns over whether the government will be able to sustain its current approach to the supply of water resources. Desalination and water reclamation processes are very expensive but form a crucial aspect of the water supply system in Saudi Arabia. Although the government is introducing measures and policy decisions to move towards more efficient allocations of water resources, illustrated by steps such as wheat subsidy cuts in the 1990s and the plan to phase out domestic wheat production entirely by 2016 (Water and National Strength in Saudi Arabia, March 2016), there is a need to assess and remodel existing processes to improve their economic and production efficiencies. Any strategic planning for supply systems must consider the above issues while designing appropriate mechanisms for the kingdom. Here we present our water management model which strives to cover all the critical aspects of the water supply scheme, with a special focus on ensuring that the current supply and consumption is sustainable and one that is line with meeting future projected water demands.

An Economic Approach to Water Management Strategy

Our Water Management Strategy tackles the following areas:

- Maximizing water production using Reverse Osmosis as a desalination process.
- Efficient Distribution mechanisms.
- Water Reclamation as a conservation tool - Maximizing wastewater conversion efficiency.

We believe that one of the best ways to think about the efficient management of any resource is to consider it as an economic resource. An economic approach allows us to apply models which target the maximum possible benefits with the most efficient use of resource inputs and this forms the overarching theme in our water strategy models. Since desalination forms the largest water source for the nations consumption, we have created an optimization model that maximizes the desalinated water output using the governments budget allocations in this field as its constraint. This will provide a very useful tool to project planers ant organizations to assess the level of inputs that need to be directed towards producing the optimum amount of desalinated water under the given monetary constraints. Using an approximate figure $2.56 billion (forty percent of the budget allocations on water resource projects for 2013) as the constraint, our model estimates an optimum water production of 3.9 billion cubic meters of water per year which is a significant portion of the projected demand for the year 2025. Similarly, our model for a cost efficient water distribution system optimizes a cost function for supply networks and determines the optimum design in terms of the pipeline diameters and the hydraulic pressure input. The supply area is conceptualized as the three main sectors - agriculture, industries and households and a minimum optimum cost of \$68.9 million was obtained under the consumption constraints projected for 2025. This would be quite feasible given the budget constraints. The distribution model can be easily extended to include more sectors or components of the economy which would make it more applicable to actual implementation.

Keeping an eye on ensuring the inclusion of conservation practices, we have applied a similar approach to optimize the functioning of waste water treatment plants using part of the 2013 government water resources budget allocation as in the case of desalination production. This would help assess the level of input (capital and energy) that needs to be directed towards water reclamation plants so as to achieve the maximum amount of recycled water that can be used for industrial and irrigation purposes. Again, using thirty percent of the allocated 2013 budget as an approximate constraint, we obtained a maximum yearly recycled water production of 7.65 billion cubic meters which would be a very significant contribution towards the projected water demands. This model is helpful in estimating the optimum level of energy input that needs to be invested in waste water treatment and hence achieve the goal of conservation in a cost-efficient way.

These models combined would provide a very effective tool for analyzing and determining the best way to manage and distribute Saudi Arabias water resources. Given the fact that the nation is already investing so much towards this area, our models can help improve input allocations decisions, most importantly that of energy use in water resources projects. While the kingdom is already leading in terms of harnessing its access to seawater for water consumption aided by energy from the vast oil reserves, the possibility of tapping into renewable energy production to carry out processes such as desalination and wastewater treatment provides a huge potential for investment. In this scenario, the models that we have proposed can also be used to estimate the optimum level of input investment that can be directed into harnessing renewable energy sources such as solar and wind power energy. Our economic models for water management can thus act as very practical stepping stones to approaching a wide range of production and distribution issues in the field of water supply systems in Saudi Arabia and moving towards achieving the goal of meeting future demands.

6 Conclusion

The final result of the desalination implies that $4.9 \times 10^9 kWh$ of energy should be used to maximize the output. The maximized output with the budget we have assumed is $3.9 \times 10^9 m^3$ of water annually. This is about one-tenth of the total projected demand in 2025 which is $3.14 km^3$(Kajenthira, Siddiqi& Anadon, 2012). However, considering the fact that 88% of the projected water demand for 2025 is designated for agricultural secor, if the agricultural activity could be reduced by two-thirds, the water production will be able to meet the demand for domestic and industrial use. The estimated optimal input of electricity and other factors of production for wastewater treatement plants are 2.265×10^{10}kWh and $3.33 \times 10^9 units$ and the maximized output is $7.65 \times 10^9 m^3$ which is far more than the 2025 projected wastewater of $1.75 \times 10^6 m^3$(Kajenthira 2011). This shows that if 40% of the budget is spent on the wastewater treatment, Saudi Arabia can easily reach 100% sewage rate in 2025. Finally, the distribution model estimated the optimal values for the diameter of pipelines to be 5.37m and the hydraulic head to be 1187.14m. The minimized cost of production is estimated to be $68.8 million.

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