**Make wise use of every drop**

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**Abstract**: **We attributed water scarcity to uneven distribution in space and time and imbalance between supply and demand. We solved the former by transferring water across regions and storing water for future use, and for the latter we considered supply augmentation and demand constraint methods. We first used a grey model to predict gap between demand and supply in 2015. Results are that there will be 15 provinces in short of water. Jiangsu province, the most severe case, will be faced with 58.32 billion of water shortage. Next we developed four models to address water transfer, water storage, desalinization and water conservation. A transportation model was applied to determine an optimal transfer strategy. Results suggested that we transport 12.32 billion of water from the Songliao Region to the Haihe Region, and 5.2 billion of water from the Long River to the Yellow River. We applied a news-vendor model to determine optimal amount of water needed. A case study of Three Gorges Reservoir revealed that 84.1 billion of water should be stored now to satisfy water demand in 2025. A NPV analysis of desalinization projects indicated that 4 desalinization plants should be built in Shanghai, and several more in other provinces in need of water. A Ramsey pricing model was used to determine an optimal pricing strategy. A case study of Shaanxi province revealed that increasing block tariffs achieves a demand reduction of 17.8 per person per year. Finally, we provided a guide for government to make decisions and propose specific measures for four representative regions. Our models are conceptual ones and solutions are based on mathematical optimization. So with more precise data we are able to modify our results without much burdensome repetitions.**

**1 Introduction**

Recent changes in population and geography, from urbanization to climate change, have increased the demand for water and, at the same, degraded water supplies. The issue is even more severe in China. The Dow’s report (2011) [1] pointed out that among 661 cities in China, 33% are short of water, and 17% are regarded as badly in lack of water. Feeding the world's 20% population with the world's 6% total water resources poses a great challenge for China, which is now plagued by uneven distribution of water in space and time. Home to 40% of the population of China, northern regions hold only 5% of the nation’s water resources. Over-withdrawals of surface water and groundwater has led to depletion of water resources and environmental damage in some regions (Oelkers et al., 2011) [2], further exacerbating the issue. So it is urgent for us to take actions to deal with water shortage, reflected both in quantity and quality.

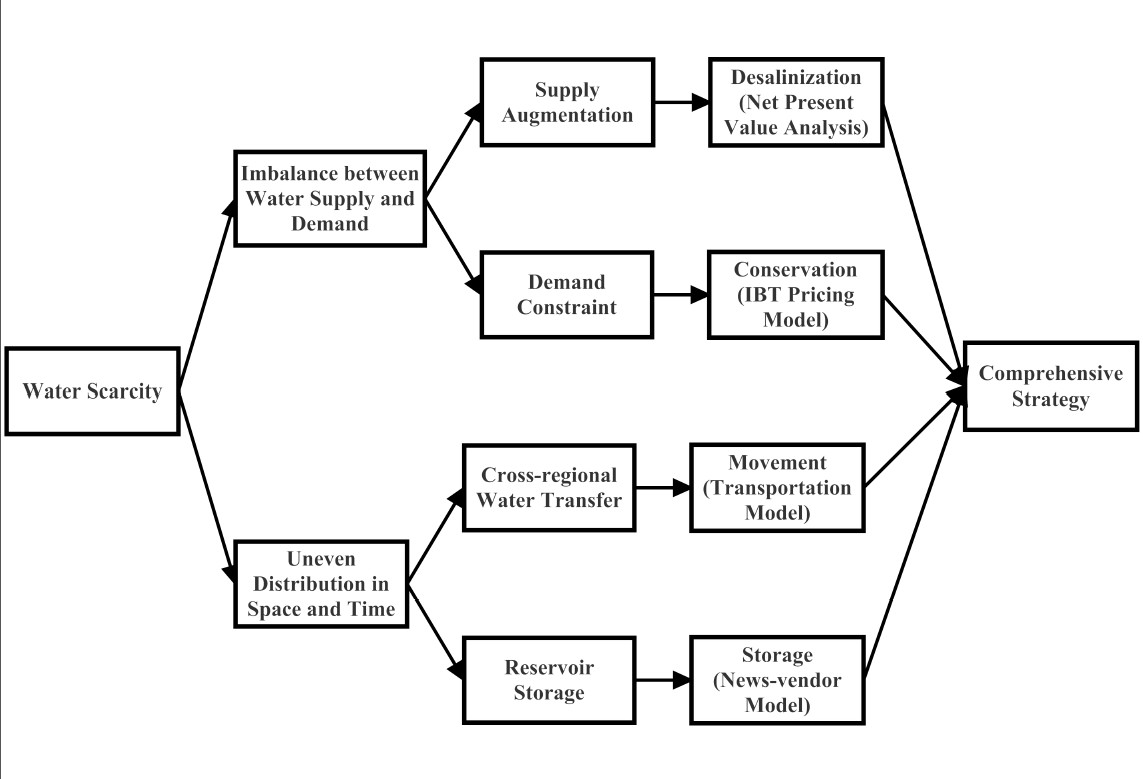
The purpose of the paper is to meet the challenge of sustainable water management in China. We regard the problem as composed of two major kinds, namely imbalance between water supply and demand, as well as uneven water distribution in time and space. First we separately consider four strategies: movement, storage, desalinization and conservation using a transportation model, a stock model, a NPV analysis and an IBT pricing model respectively (see **Figure 1**). Then we synthesize these four strategies from the perspective of decision makers in China. In particular, we answer the following questions:

**1. What is the estimated water demand and available water supply in 2025?** The answer will lead us to the gaps between demand and supply across China. Based on this gap, we can further analyse the problem.

**2. How to solve the predicted problem of water shortage?** Based on the logic of four strategies, we come up with four models tackling with water shortage seperately, and then a comprehensive model will be used for decision makers of China.

For the rest of our paper, we take every province in mainland China, as well as big municipalities like Beijing, into consideration. For simplicity, we will refer to all of them as "provinces" of China, and there are 30 provinces in our case. Hainan province, Hongkong SAR, Macao SAR and Taiwan district are omitted since they are more isolated to water management system of mainland China.

Figure 1: Basic Logic of Our Model



**2 Water Demand and Supply Prediction**

Many methods can be used to predict such time series data as water demand and supply, including auto regression, moving average, Box-Jenkins models, grey models, neural network and so on. As superiority to conventional statistical models, grey models require only a limited amount of data to estimate the behavior of unknown systems (Deng, 1989; Zhang and Liu, 2001) [3] [4]. Therefore, considering limited data available in China, we use a grey model to predict water demand and supply.

**2.1 Data Description**

The original province level data are adapted from 1999 to 2011 by National Bureau of Statistics of China [5].

**We use water usage (in 100 million ) as water demand,** including agriculture, industry, urban consumption and ecological protection. Note that data for year 2004 data are unavailable due to unknown reasons. For consistency, we take the average demand of 2003 and 2005 to substitute for that of 2004.

**We use 40% of total water resource (in million ) as a proxy for water supply.** The total amount of water resource is the sum of surface water resources and groundwater resources less the overlap between the two. There are various hierarchies for the quality of natural water resources, a small portion of which is fresh water, and an even smaller portion of fresh water is available for us [1]. Based on the statistics done by National Bureau of Statistics of China, we take a value of 40% as the average portion of natural water resources as available for usage[5].

**2.2 The Grey Model**

We use the GM(1,1) model to predict water demand and supply in 2025. For every province, denote historical water demand and supply by:

where represents water demand or supply in 1999, and represents historical data of water demand or supply in 2011. Under the rule of accumulated generation operation, we get:

Averaging the sequence, we get a vector with 12 elements:

where Establishing the grey differential equation:

(1)

yields the albino differential equation for Eq.(1):

(2)

Solving for Eq.(2) yields:

The method is given in the book Application of MATLAB in mathematical Modeling (Zhuo and Wei, 2011) [6].

After getting estimated water demand and supply for each province in 2025, we calculate the water gap as:

and use water gaps for our further study.

**2.3 Prediction Results**

**Figure 2** shows the results by running MATLAB. Fifteen provinces will suffer from water shortage in 2025, namely Jiangsu, Xinjiang, Anhui, Shanghai, Henan, Hebei, Heilongjiang, Ningxia, Inner Mongolia, Gansu, Shanxi, Shandong, Hunan, Beijing and Tianjin, most of which are located in northern areas of China, except Shanghai and Hunan Province. The result is in agreement with the fact that water issue is more severe in northern China than in southern China, due to less precipitation, drier climate and more demand by agriculture, industry and urban consumption. More specifically, with additional 58.324 billion needed, Jiangsu Province ranks top for water shortage, followed by Xinjiang Province and Anhui Province, with 36.05 billion and 34.93 billion respectively (see **Figure 3**).

As can be seen in **Figure 2**, nearly half of China will be endangered by water shortage in 2025. Based on this prediction, in the following four sections, we propose four strategies to solve the problem.

Figure 2: Predicted gaps between water demand and supply across China in 2025

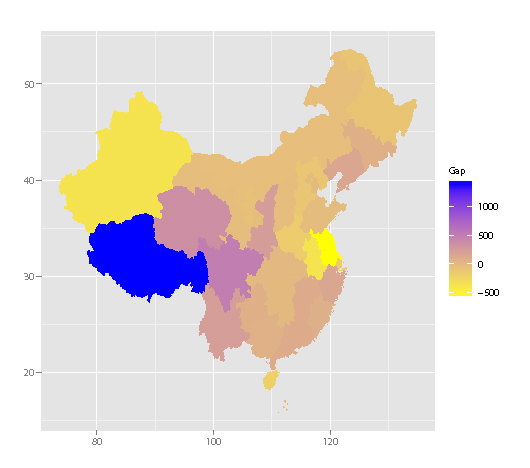
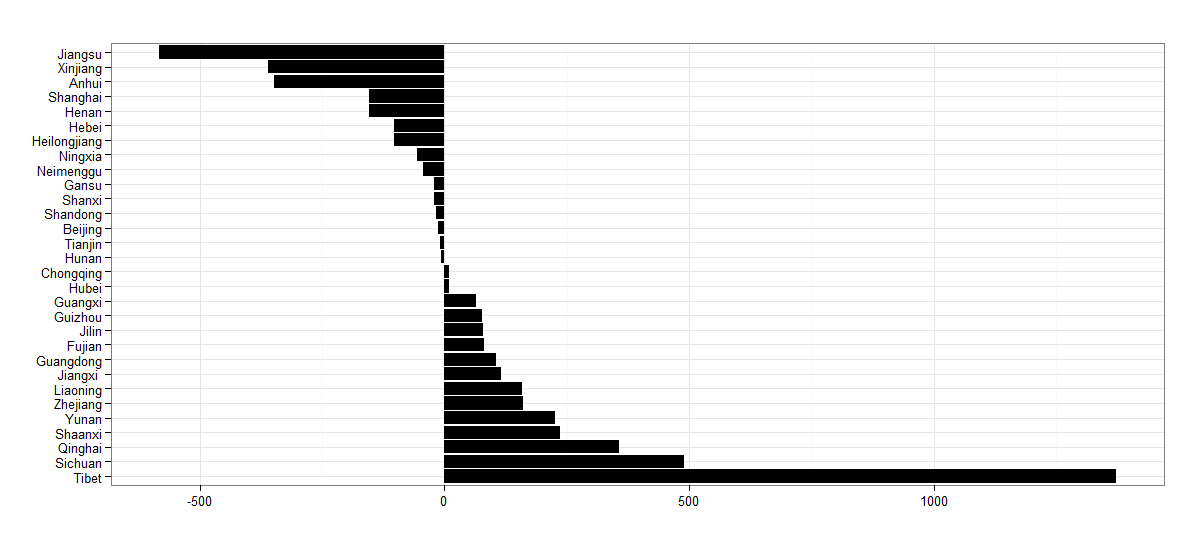


Figure 3: Predicted gaps water between demand and supply across China in 2025

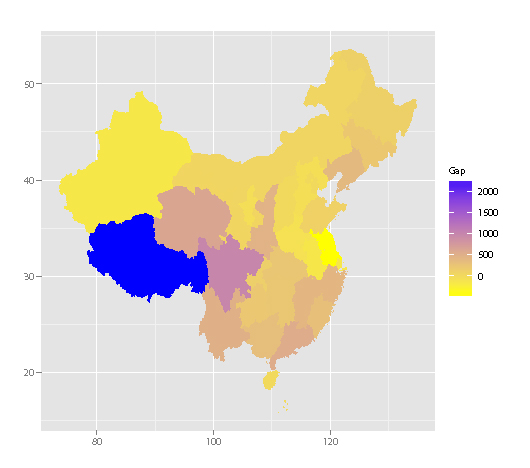
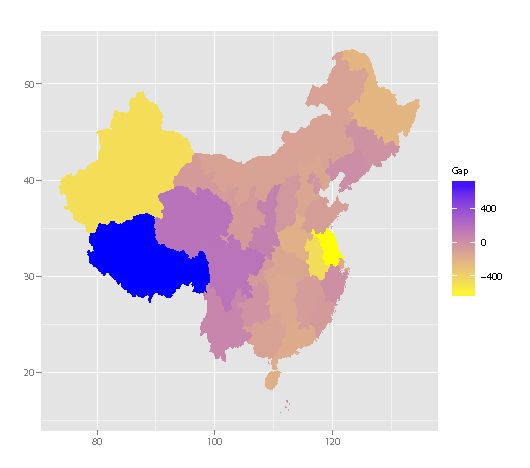


**2.4 Sensitivity Analysis**

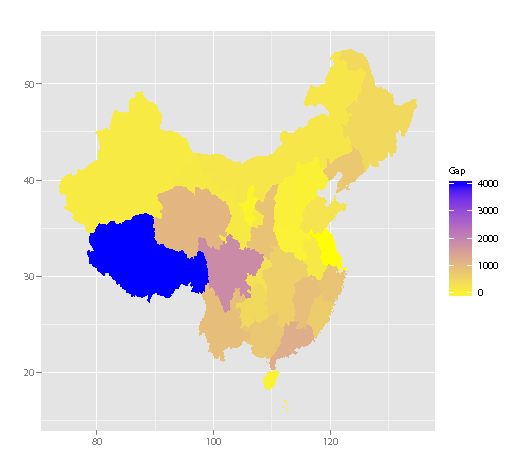
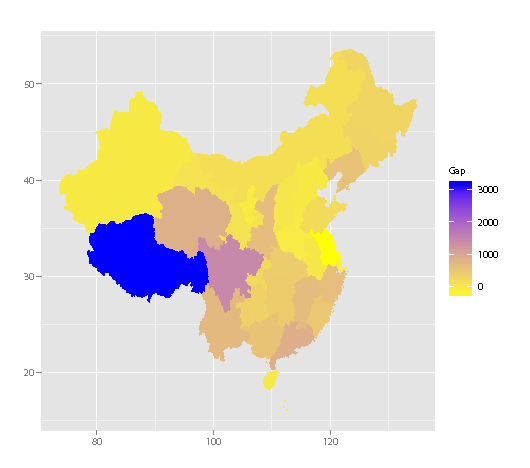
In our assumptions, we mentioned that a portion (40%) of water resources is available for usage. In this part, we try to test the model's sensitivity to changes in this number. **Figure 4** illustrates results of the analysis. It is suggested by the figure that the change barely affects our predicted water distribution across the country. The value of water gaps, however, changes to some extent with different portions (absolute values of water gaps is shown by the legends in the figure).

One flaw of the grey methods, as well as several models we mentioned before, is that we base the prediction on historical data trends and the assumption that this trend will continue in the future. It is never possible to accurately evaluate whether the assumption holds, so our model is still subject to possible error. A conceptual mode is offered by David et al. (1998)[7], which acknowledge the difficulty in quantifying water shortage prediction and base itself on dynamic system of water supply and demand and only requires a set of data in one single year. The authors discussed the precision of the model in their report. However, due to lack of required data, we give up on using their model. When related data are available, we suggest considering their model. More issues of data precision are discussed in the part of strengths and weaknesses of model.

Figure 4: Predicted Water Distribution on Different Portion of Available Water Supply



(a) 20% (b) 60%



(c) 80% (d) 100%

**3 Strategy 1: Water Transfer**

Given the estimated water conditions in 2025, we use a mathematical model to come up with a strategy for water transfer.

There are several major rivers in mainland China, and scholars often partition China into regions around these rivers. These regions are often referred to "river basins". An illustration of this partition is shown in **Figure 5**. For simplicity, we refer to river basins as "regions" for the rest of this part.

Since water transportation within a region is relatively easy and costless compared to across regions, we now only consider water transportation across regions. That is, we calculate water gap of every region by summing up that of every province belonging to the region.

Firstly, for every region, we take its water supply and demand as given, and figure out a model to determine an optimal transportation strategy satisfying the demand of every province. Based on this model, we input related data and get the desired strategy.

Figure 5: An illustration of river basins in China. Source: *Atlas of Natural Disaster System of China* (Shi et al., 2003) [8]



**3.1 Assumptions**

**Cost of transportation is proportional to the volume and the distance of water transported.** That is, the more and the longer distance water is transported, the more it costs for the government. It is unrealistic to transport a very small amount of water across regions, so we assume that the volume of water transported is large enough to ignore economies of scale.

**Transportation is accomplished at the beginning of a year.** We simplify a continuous water transfer to an event accomplished at the beginning of a year. After transportation, water demands in China are met to the largest extent.

**There exists a water transportation channel (or other water transfer projects) between every pair of regions.** There are several cross-regional water transfer projects built in China. A famous example is the South-North Water Transfer Project. We assume that under the help of these water transfer projects we are able to transport water between regions.

Notations used in the model are listed as follows:

Table 1: Notations Used in the Transportation Model

|  |  |
| --- | --- |
| Notation | Explanation |
|  | Region i. There are at total M regions involved. |
|  | Water supply of region i at the beginning of a year. |
|  | Water demand of region i for the year. |
|  | Water gap of region i. |
|  | Cost of transportation for per unit of water from region i to region j. |
| *E* | The set of net water suppliers, i.e., regions with water excess. |
| *S* | The set of net water demanders, i.e., regions with water shortage. |
| *m* | Number of elements in E, i.e., number of net water suppliers. |
| *n* | Number of elements in S, i.e., number of net water demanders. |
|  | The volume of water transported from region i to region j. |
| *C* | Total cost of water transportation. |

**3.2 The Transportation Model**

We first decide upon the set of regions with water excess or shortage by checking their gaps 's. We let if and let if . For legibility, we rename a positive gap from to and negative ones from to . We discuss below different cases corresponding to different values of total gap .

*In the case of G=0, total water excess equals to total water shortage.* The optimization problem can be listed as follows:

s.t.

*In the case of G>0, total water supply exceeds total water demand.* Therefore, everything else being equal, the first constraint changes to:

*In the case of G<0, total water demand cannot be satisfied by water supplies inside the country*. Therefore the second constraint changes to:

**3.3 Solution**

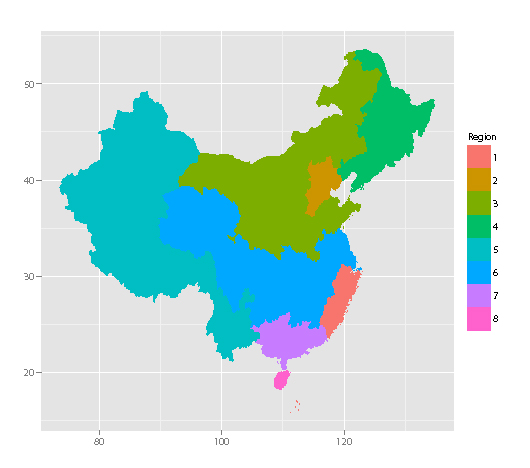
3.3.1 Parameter Estimation

*Regions.* As is shown in Figure 6, we use one of the mainstream partitions which divides mainland China into 7 major regions. We specify them in the Table 2 below.

Table 2: Classification of Provinces

|  |  |  |
| --- | --- | --- |
| Notation | River Basin | Provinces |
|  | The Southeast River Basin | Fujian, Zhejiang |
|  | The Haihe River Basin | Beijing, Hebei, Tianjin |
|  | The Yellow River River Basin | Gansu, Henan, Inner Mongolia, Ningxia, Shaanxi, Shandong, Shanxi |
|  | The Songliao River Basin | Heilongjiang, Jilin, Liaoning |
|  | The Southwest River Basin | Tibet, Xinjiang, Yunnan |
|  | The Long River River Basin | Anhui, Chongqing, Guizhou, Hubei, Hunan, Jiangxi, Jiangsu, Qinghai, Shanghai, Sichuan |
|  | The Perl River River Basin | Guangdong, Guangxi |

Figure 6: The 7 Regions We Use in the Model (Note that the region in the graph is Hainan Province, which we ignore in our model.)



*Supplies and demands.* We get from section §2.3 the projected water condition in 2025. According to our estimation, two regions will face water shortage, namely (12.32 billion ) and (5.21 billion ), and the rest 5 regions have water surplus (26.18 billion for , 15.90 billion for , 128.68 billion for , 53.37 billion for , 19.70 billion ). Total water gap in China will sum up to G=179.27 billion . The predicted net supplies and demands are also available, using the data above. In this case, we have E={, , , , }, and S={, }.

*Cost of transportation per per km.* We first determine the distances between regions. Since shapes of regions are irregular, there is no way to accurately capture the intrinsic distances, which leaves us to estimate such values. We take mean distance between provinces of each region as a measurement of region distances. To approximate this measurement, we choose a central city in each region and take the distance between these cities. We take cities Wenzhou, Beijing, Yan'an, Changchun, Lasa, Chongqing and Foshan to represent the center of from to , respectively (see Fig. 7). The distances calculated are listed below in Tab. 2. For example, the element in the first row and the first column stands for the distance between and . For simplicity, we arbitrarily assume that transporting water 1 km costs 0.1 yuan, then the unit cost equals to 10% of the distance between regions involved.

Figure7: Cities Standing for Centers for Regions and an Illustration of Water Channeling Network

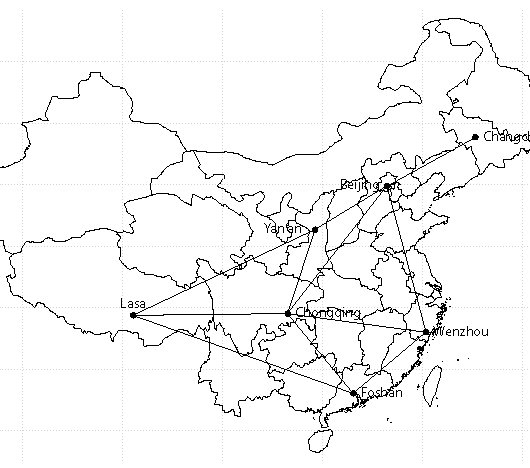


Table 3: Distance Matrix for Regions

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Distance (in km) |  |  |  |  |  |  |
|  | 1382 |  |  |  |  |  |
|  | 1420 | 710 |  |  |  |  |
|  | 1809 | 858 | 1564 |  |  |  |
|  | 2880 | 2564 | 1872 | 3400 |  |  |
|  | 1390 | 1460 | 828 | 2300 | 1490 |  |
|  | 940 | 1904 | 1550 | 2570 | 2310 | 980 |

The problem is a linear programming problem, or more, a typical transportation model. With costs, supplies and demands available, we specify the model and solve for the problem. The result is shown in Tab. 4.

3.3.2 Conclusion of Results

Based on the solution given by solving for the problem, we have a water channeling strategy to deal with water shortage in the year of 2025:

Transport 12.32 billion water from (The Songliao River Basin) to (The Hehai River Basin), which costs 1057.30 billion yuan;

Transport 5.21 billion water from (The Long River River Basin) to (The Yellow River River Basin), which costs 431.46 billion yuan.

The total cost sums up to 14.88 billion yuan.

Table 4: Water Channeling Strategy

|  |  |  |  |
| --- | --- | --- | --- |
| From | To | Volume | Cost |
|  |  | 12.32 | 1057.30 |
|  |  | 5.21 | 431.46 |
|  |  | Total Cost (C) | 1488.76 |

**3.4 Sensitivity Analysis**

The model uses a lot of estimated data as parameters, in addition to the estimated water gaps given by the prediction model. Therefore, we should carefully examine the model's sensitivity to changes in estimated results. Using the data given above as a basis, we look into the effect of partial changes of data. From **Table 5** we see that the total cost does not change more than estimation. But still, our model is to some extent reliant on the values of estimations. However, the optimality of our result is not negated by this sensitivity, since the model yields an analytic optimal result. In other words, our model always produces the best transportation path given that the related data are correct.

Table 5: Sensitivity Analysis of the Transportation Model

|  |  |
| --- | --- |
| Changes in distance between and | Change in total cost |
| 20.00% | 14.20% |
| 10.00% | 7.10% |
| -10.00% | -7.10% |
| -20.00% | -14.20% |

**4 Strategy 2:Water Storage**

Unlike water channeling, water storage is mainly used to deal with uneven water distribution in time, where water is stored for later use. Methods range from natural water stores, such as groundwater aquifers, to reservoirs behind major dams. In this section, we examine how reservoirs can be best used to resolve the future shortage.

Determining the volume of water needed for later use is similar to an inventory problem, which looks to solve for an optimal order quantity at a certain time point to satisfy the stochastic demands in the future. Therefore, we apply a classic news-vendor inventory model to solve the problem. For the convenience of modeling and consistency with jargon commonly used, we use the word "demand" as water gaps derived above.

For the rest of this section, we build up a theoretical inventory model and then study the case of the Three Gorges Reservoir in China for application of our model.

**4.1 Assumptions and Notations**

*Reservoirs store water from both its upstream and precipitation.* There are two main water sources for reservoirs. The order quantity from its upstream should exclude precipitation;

*Reservoirs store water to satisfy local and downstream demands.* It is impossible or too expensive for reservoirs to transport water to the areas upstream. The amount needed equals to demand less normal storage, which is the existing storage in the reservoir;

*We allow stock-out costs and holding costs to occur*. In the former case, areas in the downstream suffer from water shortage, thus incurring economic loss. In the latter case, excess water lead to opportunity cost lost by upstream areas;

*Downstream demands are normally distributed*, whose cumulative distribution function is F(x) and probability density function is f(x).

Notations used in the model are listed as follows:

Table 6: Notations Used in the Transportation Model

|  |  |
| --- | --- |
| Notation | Explanation |
|  | Downstream demand, which is stochastic. |
|  | Order quantity by reservoir. |
| s | Stock-out cost, reflected by the economic loss in the downstream when gaps cannot be met. |
| c | Holding cost, reflected by the opportunity cost lost in the upstream when order quantity exceed gaps. |
| TC | Total cost for the whole system. |

**4.2 The News-vendor Inventory Model**

We aim to determine the optimal order quantity to minimize the total cost. So the target function can be written as follows:

To solve the problem, we set the first order derivative of TC(q) equal to zero and get:

(3)

Since the second order derivative of TC(q) is nonnegative:

the optimal solution exists for the problem. Solving the Eq. (3), we get the optimal order quantity when:

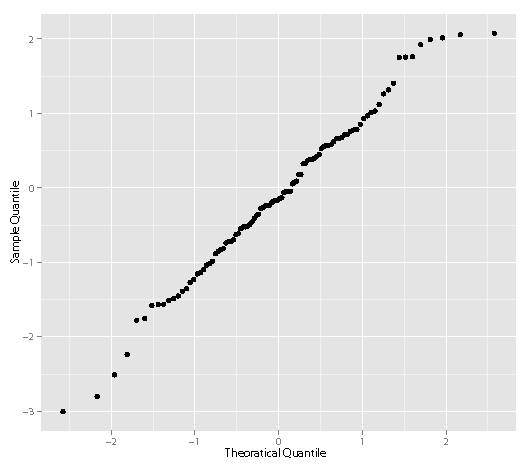
**4.3 Case Study: the Three Gorges Reservoir**

We apply theoretical model to the *Three Gorges Reservoir*, which is the largest reservoir in China. Located in Yichang city and spanning the Yangtze River, the reservoir is the main water supplier to its downstream areas, including Jiangsu, Anhui, Shanghai and Hunan. Both the representativeness and the strategic significance lead us to use the Three Gorges Reservoir as a case to study.

4.3.1 Normality Test for Historical Demands

We take historical data of total water demands of provinces around the downstream of the Three Gorges Reservoir to test our assumption of their normality. A Q-Q plot of data (see Fig. 8) suggests that they behave quite well in terms of normality. A Shapiro-Wilk test also confirms our hypothesis (W = 0.9885, p = 0.5429), which means that under the hypothesis of normality of sample data, the possibility of getting a W statistic more extreme than or as extreme as the observed one (W = 0.9885) is 54.29%. Therefore, our data supports the hypothesis and we accept the normality assumption.

Figure8: The Q-Q Plot for Historical Data



4.3.2 Parameter Estimation

We define the stock-out cost as the economic loss suffered by downstream areas due to inadequate water supply, since water shortage has a direct negative impact on agricultural production, industrial output and urban consumption, further influencing the local GDP. Water consumption per 10 thousand yuan of GDP is an official method to measure the contribution of water to the total GDP. So we use the GDP each of water can generate to quantify the stock-out cost.

We define holding cost as the opportunity cost, in which case upstream areas can use excess water for other uses, such as agricultural production, industrial output and urban consumption. Accordingly, we also use the GDP each of water can generate to quantify the holding cost. We ignore negative environmental effects for simplicity.

As for the Three Gorges Reservoir, its downstream areas include Hubei Province, Hunan Province, Jiangxi Province, Anhui Province and Shanghai and its upstream areas include Qinghai Province, Sichuan Province, Guizhou Province and Chongqing. Stock-out cost of each province is calculated by local GDP divided by water consumption, and the total stock-out cost, denoted by s, is the average of the stock-out cost in its downstream area, and so is the total holding cost, denoted by c. Original data are adapted from National Bureau of Statistics [5] and through simple computation, we get s=53.44 yuan/ and c=222.43 yuan/.

Taking into account the precipitation and normal storage in the reservoir, which is the minimal requirement of the reservoir, we define net demand as:

where gap is the average of respective provinces in downstream or upstream, which equals to 154.48 billion . Precipitation is calculated by:

where data are adapted from Wikipedia, from which we also get the normal storage equaling to 393 .

So we can get the net demand of 115.16 billion . Since we treat precipitation and normal storage as constants, standard deviation of net demand equals to that of gap, that is, 440 .

4.3.3 Solutions and Simulation of the Model

With known normal distribution of net demand and parameters of s and c, we can solve for the theoretical results for the news-vendor problem. The optimal order quantity is 84.1 billion (see Fig. 9). We use the Matlab symbolic computational methods to come up with the expected total cost of every possible order quantity. Fig. 10 shows that the best order quantity is 84.1 trillion We randomly generate 500 random water demands of downstream of the Three Georges Dam according to a Gaussian Distribution (mean = 1152, standard deviation = 440) and then compute the total cost given the optimal order quantity 84.1 trillion (see Fig. 11).

Considering 2025 as the next stock period, we suggest that the Three Gorges Reservoir store 84.1 billion water to satisfy the future water gap by downstream areas. The case study also verifies that the news-vendor inventory model is a strong theoretical model to tackle with realistic problems. With more precise data, governments will be able to make wise decision on order quantity by getting more accurate normal distribution of demand, stock-out cost and holding cost.

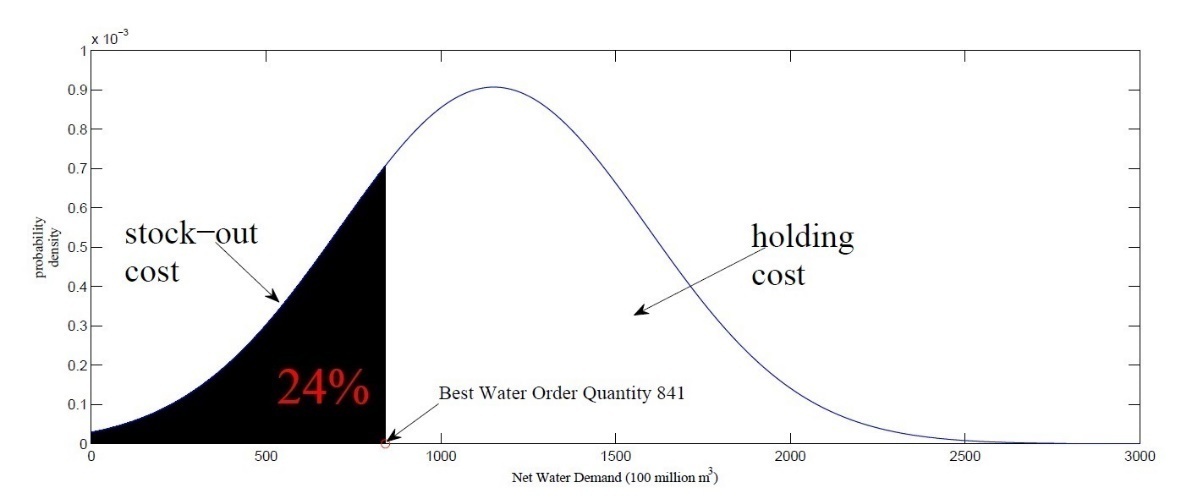
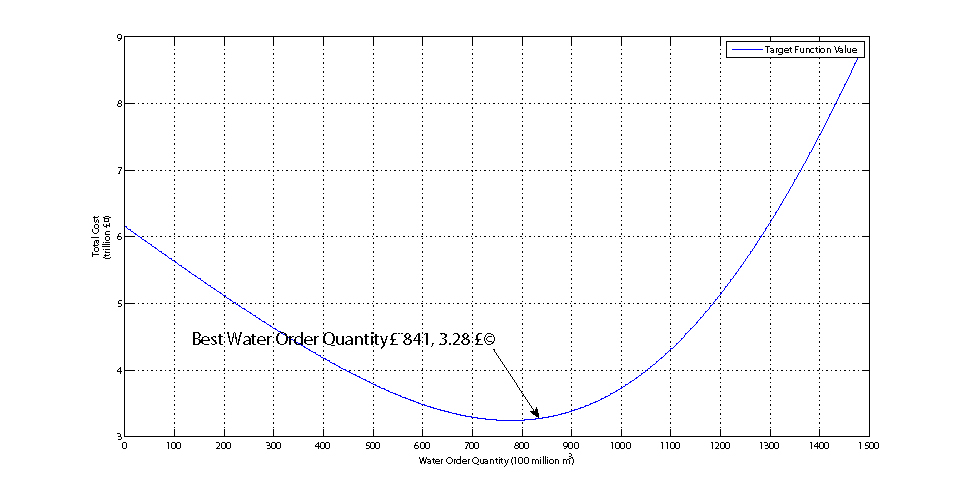
Figure9: Solution to the News-vendor Inventory Model

Figure10: The Target Function



**4.2 Sensitivity Analysis**

The minimum expected total cost calculated by our model can help decision makers better deal with future uncertainty. However, environmental or social factors are not considered in the cost: possible cost includes environmental damage and forced migration. Another limitation is that normality of demand's distribution must be strictly met. In our model, we use contributions of water to GDP in downstream and upstream as the estimation of stock-out cost and holding cost. Here, we test the impact of their fluctuation on total cost and order quantity (see Fig. 12).

Figure11: The Monte-Carlo Simulation of Water Demands

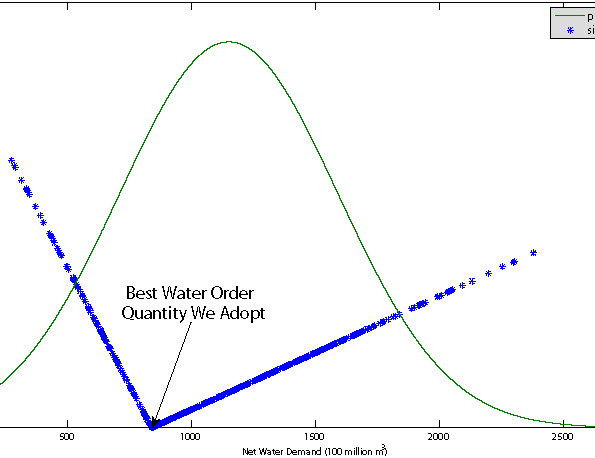
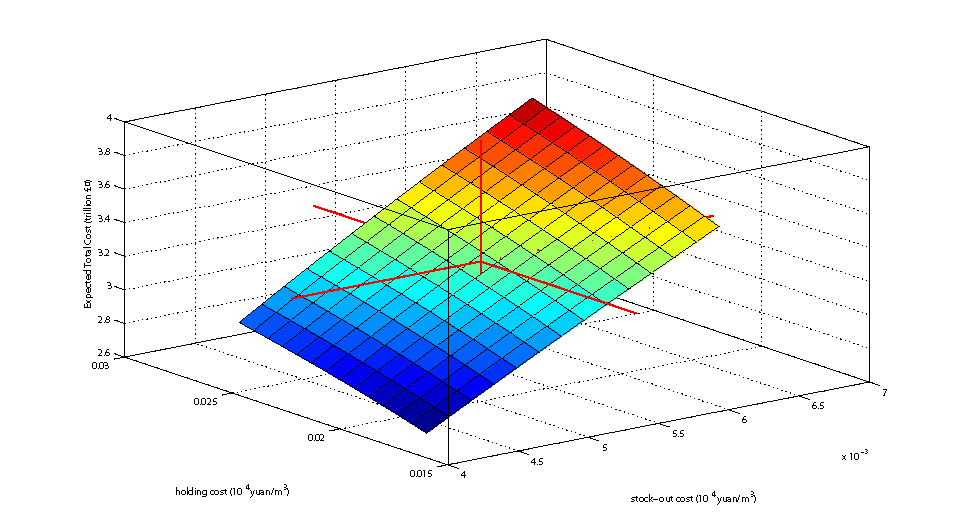


Figure12: Visualization of Sensitivity Analysis



**5** **Strategy 3: Desalinization**

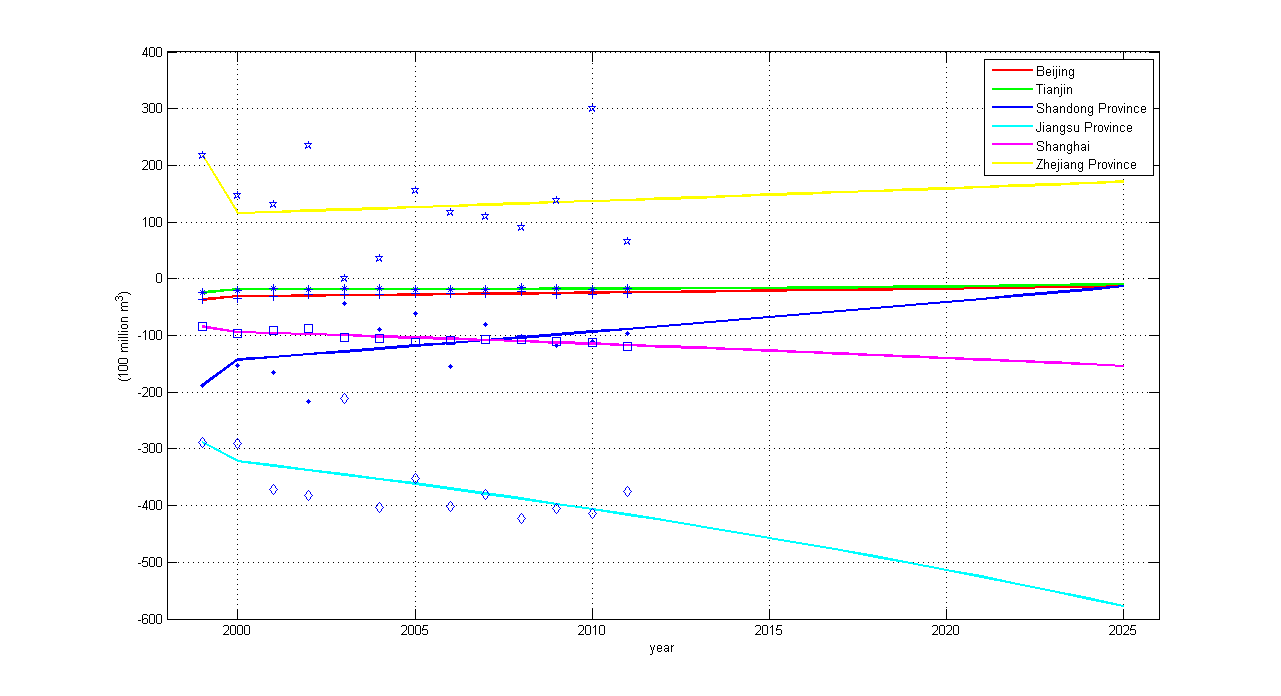
Desalinization refers to the process that removes some amount of salt and other minerals from saline water, thus providing fresh water for human use and irrigation. Saline water is no doubt a huge source of water supply, so some coastal regions have adopted desalination to solve water shortage, such as Saudi Arabia[9].

In China, Tianjin operates a desalinization plant to alleviate local critical water shortage. But desalination has not been extensively used across China. Here, we apply a NPV (net present value) method to examine the costs and benefits of establishing desalination plant and further decide whether to implement desalination.

**5.1 Potential Locations for Desalination**

Due to the nature of desalinization, target locations are restricted to coastal regions. We first choose potential locations along cost according to the extent provinces are in water shortage. Based on our prediction in Section 2, we narrow down our target to 5 provinces that will be in severe water shortage in 2025, including Bejing, Tianjin, Shanghai, Jiangsu province and Shandong province(see Figure 13). Priority should be given to Jiangsu province with a predicted gap of 58.324 billion .

Figure 13: Comparison of water gaps in 6 provinces



Assume that it is feasible to establish desalination plants, both technologically and geologically, we next focus on its economic and social implications to see whether the potential social benefits exceed economic cost.

**5.2 Assumptions**

* **Desalination plant aims to fully satisfy the predicted water gap in each province.**
* **No difference exists among desalination plants.**Each plant has the same capacity, initial investment, unit cost and operating cost.
* **It takes 2 years to construct a plant, which is the average time needed.**
* **We use contribution of water to local GDP as benefits of desalination plant.** Water is critical to agricultural production, industrial output and urban consumption, which further influence local GDP.

**5.3 Notations**

* : Cash flow of the province in period t.
* : Water contribution to GDP in province i.
* : GDP for province i in period t.
* : Water supply for province i in period t.
* : The number of plants that each province need to establish to satisfy the water gap.
* : Initial investment for each plant. We assume it to be 2 billion yuan.
* : Operating cost for each plant. We assume it to be 147 million yuan.
* : Capacity for each plant. We assume it to be 5 billion yuan.
* : Unit cost of dealing saline water for each plant. We assume it to be 1.5 million yuan.
* Discount rate. We set it to be 5.12%.

Note thatthe estimation are based on*the prospectus for desalinization plant in Taoyuan, Taiwan.*[10]

**5.4Cost-Benefit Analysis**

As we can see, costs include initial investment, operating cost per year and cost of dealing saline water per year, while benefit is definedas the contribution ofwater to local GDP. In each period, cash flow of establishing a desalination plant equals to:

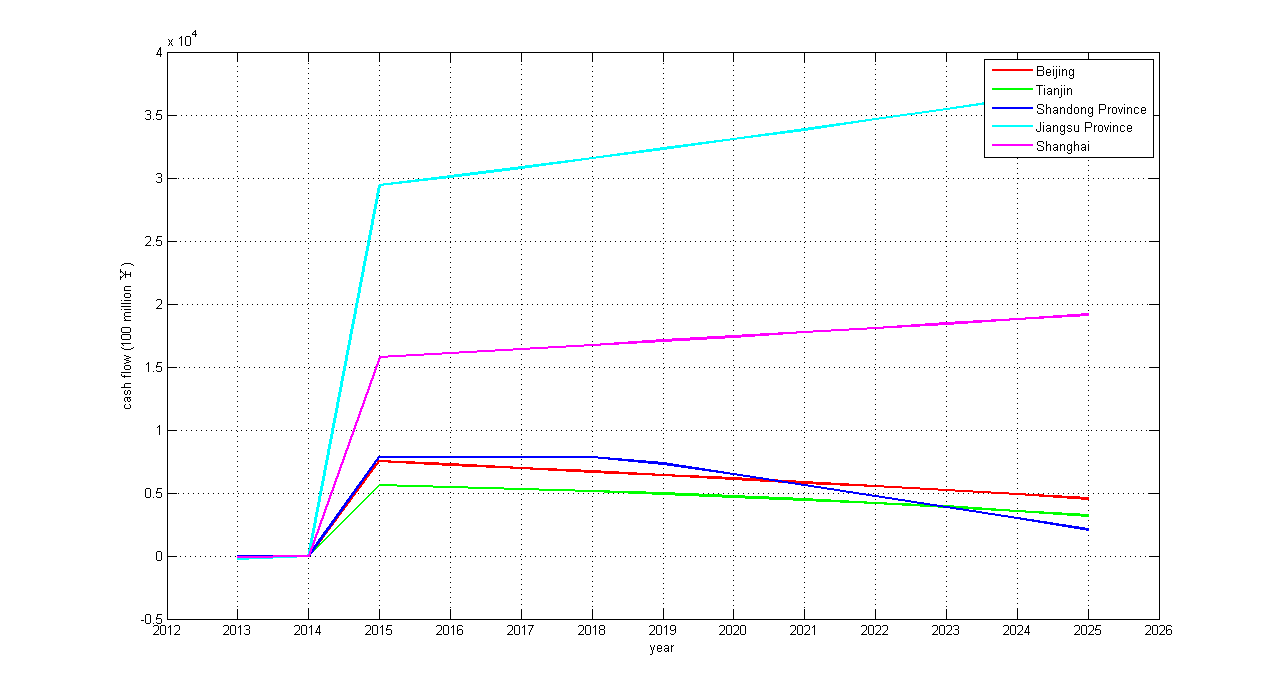
Where, and are the average of the past three year's data for each province. Dividing water gap by the capacity, we can get the number of plant needed for each province, which is 1 for Beijing, 1 for Tianjin, 4 for Shanghai, 12 for Jiangsu and 1 for Shandong.

Taking discount rate into account, we get the calculation of NPV, which is:

where we use benchmark interest rate as our discount rate, which is 5.12\%. \\

The results show that it is profitable to establish desalination plant for each five province (see Figure 14). In particular, Jiangsu enjoy the highest profit implementing such a project, with a NPV of 24.46 trillion yuan.

Figure 14: Cash flow of desalination plant in 6 provinces



**5.5Strategy**

Without other strategies, we highly recommend coastal regions to adopt desalination if it is technologically and geographically feasible to resolve the water shortage problem in 2025. However, it should be noted that capacity of existing plant in Tianjin is mostly hampered by poor local infrastructure and the low demand for drinking water[11]. So when implementing desalination, the government should pay attention to better infrastructure construction and promote the desalinized drinking water.

**6 策略4：节水方案**

节流和开源同样重要。为了鼓励市民节约用水减少浪费，政府最近引入了诸如阶梯性水价政策，它的理论基础源于Ramsey定价策略。通过对陕西省的实地调查 [12]，刘和顾发现阶梯性水价策略每人每年能节约大约15立方米水。因此，该项目很可能在未来为了解决缺水问题而得到广泛的应用。本文主要关注如何确定水价策略的阶梯，包括水价和阶梯的幅度。

Ramsey定价理论的核心在于，分界的价格应当和需求价格弹性互为倒数关系，并乘以一个小于1的常熟 [13]。大量学者已经将这一理论应用于公共服务部门，比如政府希望在水部门最大化公共福利而不是利润 [14, 15]。因而，我们同样运用Ramsey定价模型来提出我们的最优水价策略。

**6.1 假设**

* **我们将各个省划分成农业部门，工业部门和生活部门，并在各部门内单独考虑最优的定价策略。**农业，工业和生活用水是水资源需求的主要组成部分，它们所占比重分别为61%,24%和13% [5] .
* **在每一部门中，根据消费者不同的收入水平，我们划分低收入群体，中等收入群体和高收入群体。**三阶梯无论是在理论上还是实践中都被大量使用，因为过多的阶梯难以操作，而过少的阶梯效率低下[16]。
* **对于不同的人群，需求是内生的，受到水价格的调节。**古典经济理论提出，价格是影响需求的有力武器。
* **我们假设政府是水资源供应商，因此边际成本和固定成本在不同部门中，对于不同的群体都是相同的。**
* **政府只要总收入等于总成本。**不像企业，政府更关注社会福利。即便它的确产生利润，利润也通常非常低 [17]。
* **定价方法在三个部门中是相同的。**为了简便起见，我们接下来所展示的模型只针对一个部门，该模型可在另两个部门中得到拓展。

**6.2 标识**

* : 不同群体的需求，i可以是低，中和高。
* : 针对不同群体的水价，i可以是低，中和高。
* : 不同群体的需求弹性，i可以是低，中和高。
* : 不同群体需求函数中的截距项，i可以是低，中和高。
* : 政府所面临的总成本。
* : 政府所面临的边际成本，这在每个部门中都是相同的。
* : 政府面临的固定成本，这在每个部门中都是相同的。
* : 政府面临的总收入。
* : 不同收入群体的边际社会福利，i可以是低，中和高。
* : 每个部门的总社会福利。

**6.3 模型**

Bailey[18]用线性回归和双对数线性回归来描述基于价格的用水量，结果发现后者拟合得更好。鉴于Bailey的研究结果，我们同样采用双对数显性回归，需求函数如下：

这里，ε, 代表了某个部门内各个群体的需求弹性。

对于政府，总成本为：

总收入为：

增加一单位用水量，消费者支付，政府支付MC。所以，边际社会福利可以表示为：

我们的目标是得到最大化总社会福利的最优用水需求。因此，问题可以表述为：

为了得到最优需求量，我们使用拉格朗日乘子法，先得到每个消费群体的最优价格。从而，最优化问题转变为：

使（6）式的一阶导数为零，我们得到：

因此，对于每个消费群体，我们可得：

用来表示和 ，我们得到：

将(7)式和(8)式带入(4)式和(5)式，并如我们假设的那样，是总收入等于总成本，我们得到：

这里，。通过解等式（9），我们可得到在不同用水量下的最优价格，并进一步得到最优的用水量，后者可作为阶梯水价的用水量划分。

**6.4 算例分析和策略**

农业部门占了总用水量的绝大部分，但直到最近才有部分省市，比如湖南省，开始收取灌溉费用，因为在农村地区执行收费非常困难。因此，我们认为在农业部门使用阶梯性水价策略还为时过早。

自从在生活部门得到使用后，阶梯型水价策略得到了广泛的讨论。为了能提出一个具体的最优策略，我们使用算例分析来验证该模型的可信性。

根据基本的微观经济理论，需求弹性大约位于-1到0之间。贾和康 [19]发现在中国，需求弹性为-0.346。所以，我们将-0.4赋给。在我们的模型中，低消费群体的用水需求量可视为对水的基本需求，弹性为-0.7。这一逻辑同样适用于高消费群体的用水量，我们将-0.1赋给。对于其它参数，我们主观赋值（具体见表6-1）。

**表6-1 参数赋值**

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |
|  |  |  |

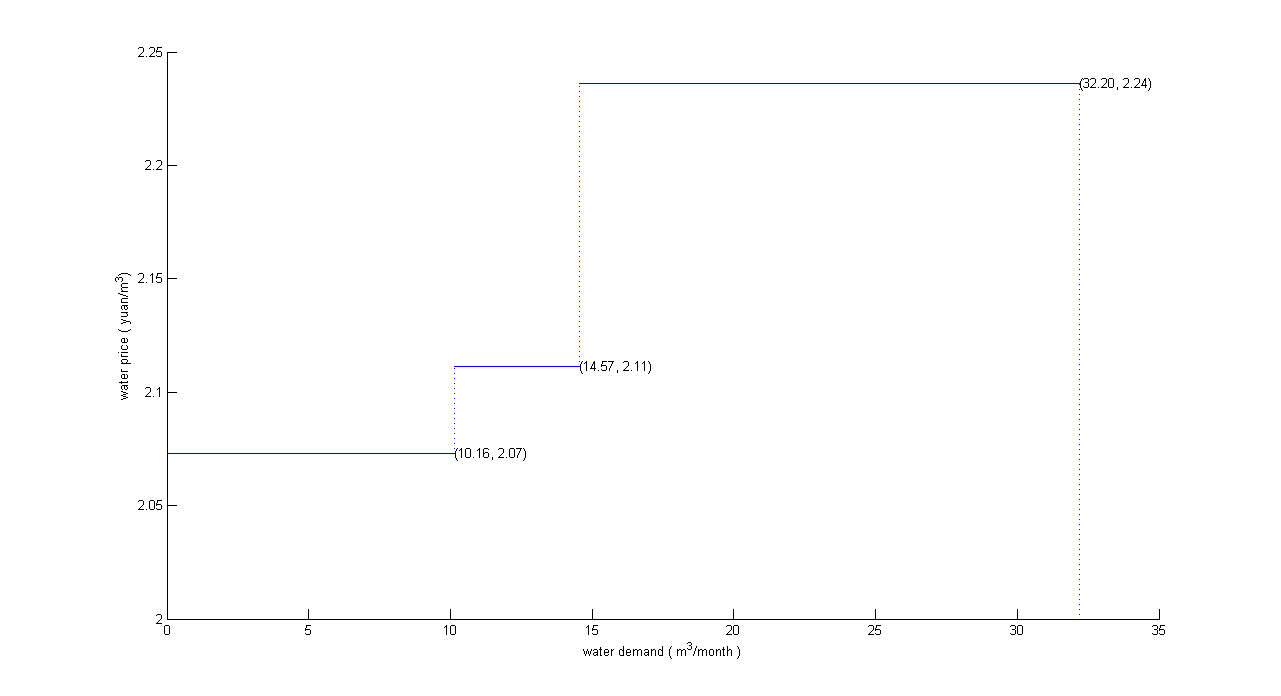
从表6-2和图6-1的结果来看，当用水量低于大约时，最优价格应设为。当用水量介于和时，价格应设为。当用水量超过时，价格应设为2.24元/。 结果符合常识，但是我们需要更全面的调查来获得更准确的参数值，这对最终的定价策略是必须的。

**表6-2 算例分析和最优定价策略**

|  |  |  |  |
| --- | --- | --- | --- |
|  | 第一阶梯 | 第二阶梯 | 第三阶梯 |
|  | 10.16 | 14.57 | 32.2 |
|  | 2.07 | 2.11 | 2.24 |

基于刘和顾 [12]提供的数据，我们将上述结果应用于西安市，结果发现平均每人每年能节约17.8立方米的水资源，比现有计划更加有效，这展示了我们模型的优势。然而，我们需要更全面的调查来获得更准确的参数值，这对最终的定价策略是必须的，但是我们相信该模型是政府制定好政策的有力武器。

**图 6-1 算例分析和最优定价策略**



**7综合策略**

现在，我们希望整合上述四种策略，为决策者提供一个综合提案。我们认为每个策略都有各自的优势及劣势（具体见图7-1），当面对缺水时，政府应当因地制宜地调整策略。

**水资源调度**在紧急情况下很有优势，尤其是解决水资源在地里分布上的分布不均匀。然而，水资源调度工程需要大量的资金和时间投入。**水资源存储**方便执行，因为水库通常位于主要河流附近。然而，水库的位置同样会带来负面效应，比如给生态环境施加过多压力。当下游需求相对稳定时，即很少会发生无法预测的紧急事件，该策略的适用效果最好。**去盐碱化**能产生更高质量的水资源，对于那些缺乏干净可用的水资源地区非常有用。虽然该策略拥有几乎无限的水资源，也能产生诸如盐的副产品，它的成本主要取决于相关技术。去盐碱化只能应用于沿海地区，我们建议在发达城市应用去盐碱化，因为它需要相应地基础配套设施和饮用水市场。**阶梯性定价**可在城市大量应用，执行起来方便且成本相对较小。但是市场的反馈，反映在需求的减少，可能有一定的时间差。

根据两大标准，内陆VS沿海以及不确定用水需求VS确定用水需求，我们对四种策略进行划分（具体见图7-2）。我们将历史数据的波动程度定义为需求的确定性，而前者可通过相关部门获得。

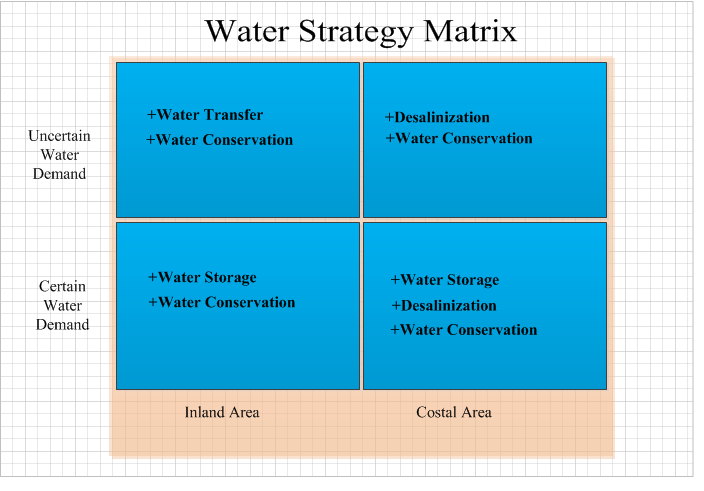
结合对用水缺口的预测，我们提出四大计划来应对2025年的用水问题。

1. 应当优先考虑**江苏省**的情况，因为它缺水最为严重。江苏是一个相对发达的省份，所以我们建议**进行水资源存储，建立5个去盐碱化工厂和采用阶梯性水价策略**江苏省拥有大量水库，相关部门应当根据我们的报童模型制定储水策略。在采用其它策略的情况下，要弥补用水缺口，5座去盐碱化工程师恰当的。事实上，阶梯性水价策略已经在南京市和南通市应用，我们高度建议在我们模型的基础上，在全省范围内推广该策略。要执行全面的调查来精确地预测参数值。
2. 鉴于其在中国战略性地位，**上海**也应当受到重视。和江苏省一样，上海是高度发达的沿海城市，所以我们建议**建立5个去盐碱化工厂和采用阶梯性水价策略。**考虑到上海的高购买力，我们预计水价应当高于其它城市，前提是我们的模型被正确使用。
3. **河南**是典型的内陆城市，主要依靠农业，因此我们建议**进行水资源存储**来解决缺水问题，因为黄河流经河南省。决策者需仔细决定为了今后的用水缺口，需储水多少。我们相信我们的报童模型能帮助政府做到这一点。
4. 对于**北京**，**天津**和**山东省**，我们建议**分别建立1个去盐碱化工厂，采取水资源调度和阶梯性水价策略。**三个相邻省份能产生极大的协同作用。中国北方地区是典型的水源性缺水，因此水资源调度工程将对北方的地区产生直接的益处。

**图 7-1 不同模型的优势和劣势**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 水资源调度 | 水资源存储 | 去盐碱化 | 水资源节约 |
| 优势 | 1、满足紧急的用水需求 | 1、易操作  2、为当地动物建造生态环境 | 1、充足的海水供给  2、产生其它副产品  3、提供高质量的水资源 | 1、低成本  2、易操作 |
| 劣势 | 1. 建设成本高 2. 建设时间长 | 1. 可能会引起地震 2. 运营成本高 | 1、技术要求高 | 1、水资源需求的改变存在时滞 |
| 适用条件 | 1、不确定的用水需求 | 1、下游确定的用水需求  2、水库容量大 | 1、沿海地区  2、发达地区 | 1、城市地区 |

**图 7-2: 四种策略的划分**



**8结论**

**Q1: 到2025年，预计水资源的需求和供给分别是多少？**

根据灰色模型，我们估计到2025年，中国会15个省份处于缺水状态，大多数位于中国北方。其中，江苏省情形最为严重，缺水量达5.8千万立方米。

**Q2: 如何填补预计的缺口？**

在考虑空间上的分布不均时，我们通过运输模型来实现水资源调度方案。将全中国划分成七大流域，将每个流域内各省的用水缺口相加得到整个流域的用水缺德口，我们发现到2025年，海河流域和黄河流域将面临缺水问题。假设运输成本与距离成正比，我们得到以下最优调度方案：松辽流域向还和流域运水，龙河流域向黄河流域运水，总成本为14.89亿元。

在考虑时间上的分布不均时，我们通过报童模型来实现水资源存储方案。将水库看成向上游订购水量的分销商，以满足下游的用水需求，我们旨在找到水库为了满足未来的需求所需存储的最优水量。三峡大坝的案例分析表明为了满足下游的需求，三峡大杯需储水8.4千万立方米，其下游包括安徽和上海。

在考虑增加供给时，我们通过NPV分析来决定是否建立去盐碱化工厂。我们首先将选择范围缩小到5个在2025年面临缺水的沿海城市，进而得到需建立几个去盐碱化工厂。我们假设用水缺口必须得到满足。基于成本和收益的适当假设，我们发现去盐碱化工程在每个省内的净收益都是正的，说明该方案在经济上和社会效应上都是有效的解决缺水问题的工具。

在考虑减少需求时，我们通过Ramsey定价模型来实现水资源节约。基于不同的用水量，我们旨在提出一个最优的阶梯性水价方案。通过一个相对主观的算例分析，我们证明了我们模型的可信性，但是为了得到最终结果，我们需要更精确的参数估计。

**Q3: 怎样恰当地使用四种策略？**

四个策略各有优势和劣势，所以我们应当因地制宜地采取措施。为了给政府制定决策提供一个简洁和清晰的指导，我们根据两大标准对四项策略进行划分，标准分别为内陆地区VS沿海地区以及不确定用水需求VS确定用水需求。去盐碱化和阶梯性水价应当在城市里实施，而不是农村地区。

对于一些将在2025年缺水的地区，我们提出了详细的方案。具体来讲，我们建议江苏省采用水资源存储，去盐碱化以及阶梯性水价，上海采用去盐碱化和阶梯性水价，河南省采用水资源存储，北京、天津和山东省联合采用去盐碱化和水资源调度。

**9优点与不足**

一个主要的问题在于数据的精确性。不同来源的数据遵循不同的标准，因此可能会产生整体的不一致性。另外，虽然我们的数据来自官方，比如国家统计局，但这些数据仍然可能受到操纵。在另一方面，对数据的不同解释也会导致不同的结果。我们模型中参数估计的数据有些很难得到，比如水资源调度的单位成本，建立去盐碱化工厂的成本等等，如果这些参数估计偏离了本质的数值，我们的最终策略将发生极大的改变。

然而，得到理想的数据不是简单的事情，这往往需要长期的调查和研究，以及相关领域专家的帮助。在短短的几天时间里，不可能准确地获得这些数据。面对这一事实，假设我们的数据都是精确的，我们试图用逻辑性和数学计算来建立概念模型（灰色模型是一个例外，使用灰色模型的理由详见第二部分）。这样一来，只要我们获得更精确的数据，比如官方的内部数据，我们就能够不费力地调整我们的最终方案。

**10 A Non-technical Position Paper to Governmental Leadership**

To Whom It May Concern,

We are writing this position paper to suggest a best strategy which combines desalinization, conservation, movement and storage to help you tackle with projected water shortage facing China in 2025.

We estimate that situation will be quite severe in 2025. There will be about 15 provinces whose water needs cannot be covered by local water supplies. Jiangsu province, in particular, will be faced with 58.32 billion of water shortage. Beijing, Shanghai and several other provinces also will be short of fresh water.

We suggest that in year 2025, the best water transfer strategy is to transport 12.32 billionof water from the Songliao Region to the Haihe Region, and 5.2 billion of water from the Long River to the Yellow River. On the other hand, our study on the Three Gorges Dam suggests that the Dam should store 84.1 billion of water from upstream to satisfy water needs in its downstream. For cities desalinization plants should be built in Shanghai, and several more in other provinces in need of water. The example of Shaanxi province tells us that an increasing block tariff pricing policy can well constrain water demands.

More specifically, in order to tackle with the severe water shortage in Jiangsu province, we suggest an increasing block tariff pricing policy combined with construction of 5 desalinization plants. Using more efficient storage strategy in water reservoirs can significantly generate stable water supplies to meet the demand in the province.

Our methodology combines four strategies together to deal with water shortage in a complicated environment in China. Jointly, these strategies cover demands of different degree of urgency, and different geographical distribution. We are confident that under various situations, our strategy will yield an optimal solution for you.

However, a major problem we encounter in our study is the precision and creditability of data. Since our models are conceptual ones using logical reasoning and mathematical computation, we are able to modify our final strategies as soon as we obtain more accurate data. Therefore, if you are interested in our study and provide us with field expertise and more credible results, we are more than happy to determine an even more detailed and effective strategy. We hope that with our joint effort, we can best alleviate water shortage and fight for a bright for the Country.

Best regards,

Team #17444

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