# Water, Water, Everywhere


## Summary

A feasible and cost-efficient water strategy need determining for Chinese projected water needs in 2025.

Firstly， China was divided into seven zones to focus on the water-scarce regions. Prediction model was built after adding up the statistical data, namely performing multivariate regression on regional water consumption and GDP, water demand, irrigation, then the function about the three and time was fitted by MATLAB. After obtaining the function of water consumption and time, the supply-demand balance was analyzed. It was found that the water-scarce zones are zone B,C,F and G，and the water shortage in 2025，is respectively $352.83\times10^8m^3$ $316.42\times10^8m^3$，$229.65\times10^8m^3$，$281.85\times10^8m^3$.

To solve the water crisis， four models--storage、mobilization、desalination、and sewage treatment were established. In desalination and sewage treatment model, processing costs and environmental effects were calculated quantitatively. In the storage model, storage capacity of underground reservoirs was acquired by idealizing the aquifer. While in mobilization model, the various diversion routes were linear programmed by means of LINGO, four routes were found to have the lowest cost-- AB、CD、FD、CE. And sensitivity analysis was done.

The priority of the above measures is assessed by AHP, which showed the mobilization is optimal, followed by desalination. Then in that order the measures are combined to make up water. For the Internal water allocation, freshwater optimal allocation model is built to maximum the economic benefits. Then The final best water strategy is as follows: For C zone, CD、CE two routes need building with the total costs 72.78 billion yuan. For F zone, FD with the costs 5.43 billion yuan and 100 desalinators

in Shandong, Tianjin need building. For B,F zones, those measures can't completely work out, extras such as agricultural drip irrigation technology which can reduce the water demands should be adopted.

# Contents

## 1. Introduction

China is a seriously droughty and water-scarce country. The total freshwater resources of China is 2.8 trillion cubic meters, accounting for 6% of the world's freshwater resources, second only to Brazil, Russia and Canada, ranked fourth in the world. However, water resource per capita in China is only 2,300 cubic meters, which is only 1/4 of the world average, and China is one of the countries with the poorest water resources per capita in the global. What's more, China has the most water consumption in the world. In 2002, it’s national freshwater usage amount has already reached 549.7 billion cubic meters, accounting for about 13% of the world's annual usage amount, and it is about 1.2 times of freshwater supply---470 billion cubic meters the United States used in 1995.

Since the 1970s, China has begun drying out, which is not an alarmist, but an objective fact. Since the 1980s, China's water shortage has already begun to spread from the local gradually to the whole country, and the situation is more and more serious, which has a serious impact on agriculture and the national economy. So it is necessary to build a mathematical model for determining an effective, feasible, and cost-efficient water strategy for 2013 to meet the projected water needs of China in 2025, and the best water strategy should be identified as soon as possible.

## 2. Analysis of This Freshwater Problem in China

The requirements of the subject are to determine a feasible and effective, and cost-effective water strategy to meet the water demand in 2025, when it is 2013.

First of all, it is necessary to predict how large the water demand in China would be in 2015.Water demand is determined by the regional freshwater supply-demand balance, and therefore it needs to predict the amount of water consumption and water supply. Water resources data in recent years of each area in China can be found by the National Bureau of Statistics .With these data, the function about the both two and time can be fitted, and water consumption、water supply of various parts of China in 2025 could be obtained. Thus the dry zones and water shortage could be determined. With too many provinces and cities, and too much data, it is better to we split China into a few zones to study.

As to the problem of water shortage, it needs to raise solutions. In general, storage、mobilization、 desalination, sewage treatment and other measures are the common replenishment measures used by the government. In order to quantitatively study these programs, it needs to understand the specific process of each program, as well as each cost it produced. Among them, the diversion measures have been identified. To determine the water diversion route, taking the water mobilization costs into account, in view of the extremely uneven distribution of water resources in China, the best diversion route needs to be determined through the method of linear programming. In addition to water supply, reducing the demand for freshwater is also one of the ways, such as increasing the water prices, using agricultural irrigation drip technology, etc. They are all effective measures. On the other hand, the government should also improve the national water-saving awareness.

Each of these measures has its own costs, economic benefits and the environmental impact. When determine the water strategy, it is necessary to using priorities to make decisions. So it needs to use the analytic hierarchy model to assess and rank the various schemes. When determine the best solution combination, it also needs to considerate its local conditions and its feasibility.

Finally, it needs to fully compensate for the water shortage, and determine the best water strategy in 2025.

## 3. General Assumptions

In order to have a better study on this paper, we simplify our model by the following assumptions:

1. There is no additional artificial water supply except our determined water strategy from 2013 to 2025.
2. There are no droughts、floods and strong geological disasters from 2013 to 2025.
3. Water transfer line is straight, and water diversion costs per kilometer ignore the impact of the terrain and the environment.

4. Desalination plants are all offshore, without considering the seawater transportation costs.
5. Do not consider increased freshwater for greenhouse effect.
6. Do not consider the effect of price changes.

## 4. Symbols and Definitions

In this section, we will give some basic symbols and definitions in the following for convenience.

Table 1.Variable Definition

| Variable Symbols | Definition | Unit |
|---|---|---|
| $P$ | population | |
| $M$ | GDP | $\times 10^8$yuan |
| $N$ | Water demand of agricultural irrigation | $\times 10^4 m^3$ |
| $t$ | time | year |
| $W$ | Total water mobilization costs | yuan |
| $C$ | Desalination costs | yuan |
| $N$ | Pollution Equivalent | |

## 5. Mathematical Models

### 5.1. Prediction model

Water demand is determined by the regional freshwater supply – demand balance, before discussing the water demand in 2025, the water demand and water supply need to be predicted firstly.

#### 5.1.1. China partition according to the water resources situations

Partition principles：

I. Try to take care of the integrity of the administrative divisions, which is convenient for collection and statistics of the data.

II. Each partition has the same one level of annual precipitation, and each partition has a relatively consistent water shortage situation.

III. Try to ensure that the coastal areas could be divided together as much as possible, to be convenient for subsequent desalination processing.

China has 32 provinces and municipalities, which can be divided into the North China, East China, northeast of China, southern part of China and Northwest according to the geographical location. And the annual precipitation also showed a decreasing grading from southeast to northwest. With comprehensive considerations of location、climate、annual precipitation and other factors, China was divided into seven areas --A zone、B zone、C zone、D zone、E zone、F zone、G zone, for the convenience of our study. And we have studied respectively the water shortage situations of the seven regions： Specific dividing circumstances are as follows:


Figure 1：China partition

- A zone： Tibet、 Qinghai、 Xinjiang
- B zone： Gansu、Inner Mongolia, Shaanxi, Shanxi and Ningxia
- C zone： Sichuan、 Yunnan、Guizhou and Chongqing
- D zone：Hunan、 Hubei and Jiangxi、 Anhui、Henan
- E zone: Fujian, Zhejiang, Shanghai and Jiangsu, Guangxi, Guangdong and Hainan
- F zone: Beijing and Hebei, Shandong, Tianjin

G zone: Jilin, Liaoning and Heilongjiang

### 5.1.2.Analysis of water demand:

The demand of fresh water is constrained by the following several factors:

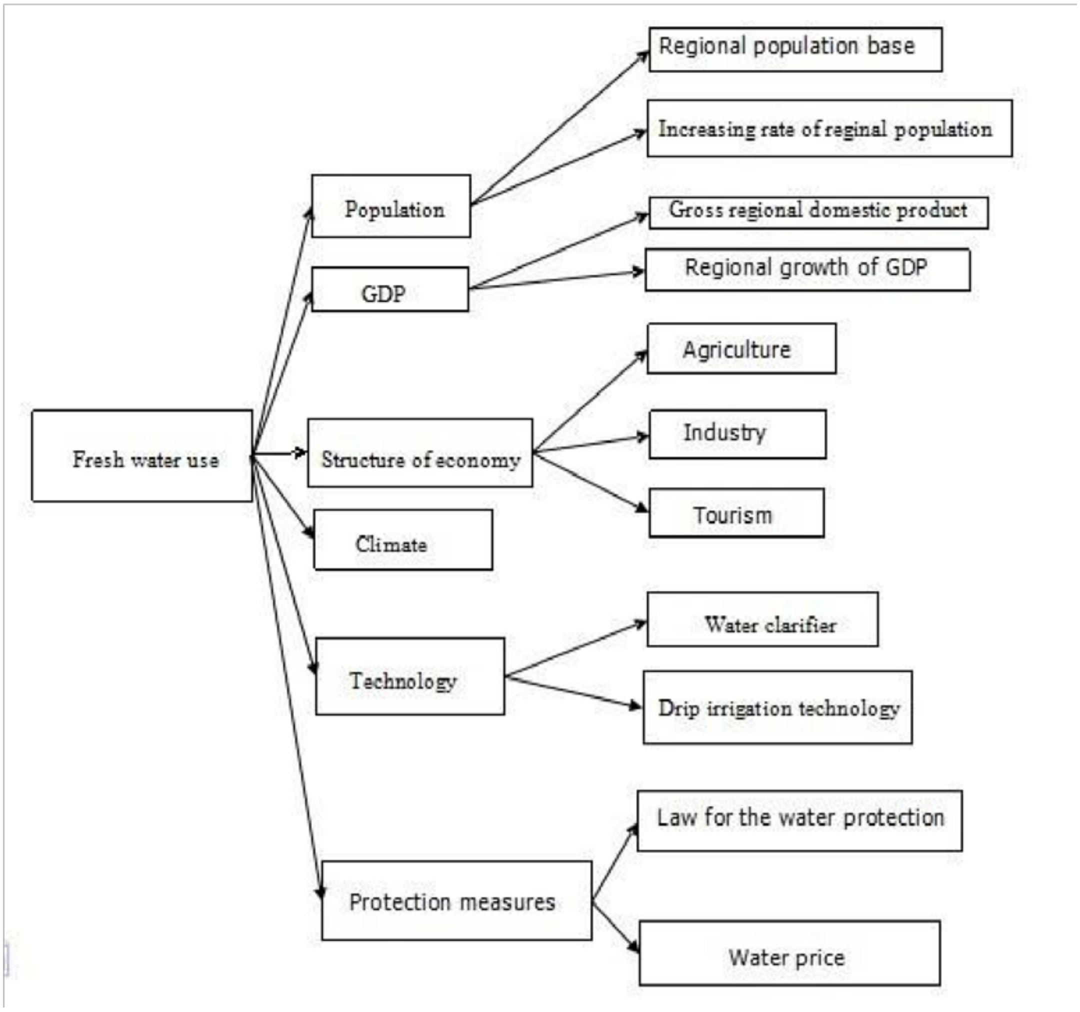


Figure 2: Influencing factors on water demand

Among them, population, GDP and agricultural irrigation have greater impacts. In view of those too much factors, it is hard to inquiry all the regional annual data of all those factors, so three important factors – population, GDP, the agricultural irrigation, have been chosen to research on the usage quantity of freshwater. Namely freshwater usage quantity is a function of such three factors – population、GDP and agricultural irrigation. Then their relationship can be explored using multiple regression analysis.

**1. Multivariate regression analysis**

Take A zone for example. Water resources data of each province and city can be found from National Bureau of Statistics. Integrating the data of all the provinces and cities in A zone by Excel（Tibet、 Qinghai、 Xinjiang），the statistics results can be gotten as the following table:

Table 2: Multivariate regression

| Year | G zone/ × $10^8 m^3$ | Population/× $10^4$ | GDP/× $10^8$yuan | Agriculture/× $10^8 m^3$ |
|---|---|---|---|---|
| 2003 | 554.9358 | 2738.00 | 2465.64 | 499.3 |
| 2004 | 555.21 | 2776.00 | 2895.53 | 504.5 |
| 2005 | 572.32 | 2830.00 | 3397.72 | 515.7 |
| 2006 | 580.6569 | 2881.00 | 3977.85 | 523.5 |
| 2007 | 585.5491 | 2934.00 | 4661.94 | 530.7 |
| 2008 | 600.11 | 2977.00 | 5596.68 | 542.5 |
| 2009 | 602.22 | 3012.93 | 5799.68 | 538.4 |
| 2010 | 608.04554 | 3049.30 | 7295.36 | 539.6 |

Assume that the freshwater demand of G zone is *A*， its population is *P*， GDP is *M*， the amount of water used by agricultural irrigation is *N*.

It can be obtained from doing multiple linear regression analysis on *A* about *P, M* and *N* by EXCEL：

| Regression | |
|---|---|
| Multiple R | 0.993634569 |
| R Square | 0.987309657 |
| Adjusted R Square | 0.9777919 |
| standard error | 3.070814168 |
| observed value | 8 |

Variance analysis

| | df | SS | MS | F | Significance F |
|---|---|---|---|---|---|
| regression | 3 | 2934.587673 | 978.1959 | 103.7334 | 0.000300679 |
| residual | 4 | 37.71959863 | 9.4299 | | |
| total | 7 | 2972.307272 | | | |

| | Coefficients | standard error | t Stat | P-value | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| Intercept | 98.35615954 | 136.8054362 | 0.718949 | 0.041193 | -281.477 | 478.1889 |
| population | 0.060931248 | 0.098613295 | 0.617881 | 0.00301 | -0.21286 | 0.334726 |
| GDP | 0.00282513 | 0.004147123 | 0.681227 | 0.021244 | -0.00869 | 0.014339 |
| agriculture | 0.561914512 | 0.361802245 | 1.553098 | 0.009838 | -0.44261 | 1.566439 |

It can be

$$G = 0.061P + 0.0028M + 0.56N \qquad (1)$$

Significance testing：

I.Combined effects testing （ F testing ）：

$$\text{Significance } F = 0.000301 < 0.05$$

So the Original assumption can be rejected. It indicates that the $r^2$ （Goodness-of-fit coefficient）is significant, thus it can be deduced that the established binary linear regression model is effective. II. Single variable inspection（T testing）

$$P: P - \text{value} = 0.041193 < 0.05$$

$$M: P - \text{value} = 0.00301 < 0.05$$

$$N: P - \text{value} = 0.009838 < 0.05$$

All the three reject the original assumption. The three regression coefficients are statistically significant.

$$\text{So } G = 0.061P + 0.0028M + 0.56N$$

**II.Curve fitting of P、M、N**

To explore the relationship between water demand and time, it is necessary to find the time function of population, GDP, the agricultural irrigation respectively. Now the regional annual data, about population、GDP and the water quantity used by agricultural irrigation, have been gotten. Then their function relationship about time t can be fitted by Matlab.

As zone A，the fitted curve of population and $x$($x$=$t$-2000)can be shown as figure 3:

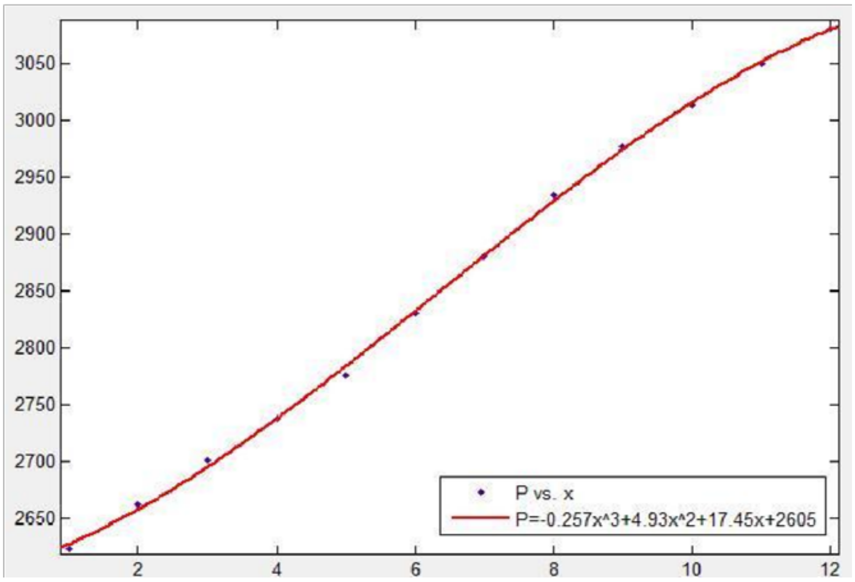


Figure 3 relationship between population and time Its

function relationship:

$$P = -0.257x3 + 4.93x2 + 17.45x + 2605;$$ （2） In a similar way, the fitted curve of zone GDP and $x$($x = t - 2000$)、the fitted curve of the water quantity used by agricultural irrigation and

*x*(*x*=t-2000)are respectively shown as Figure 4、5:

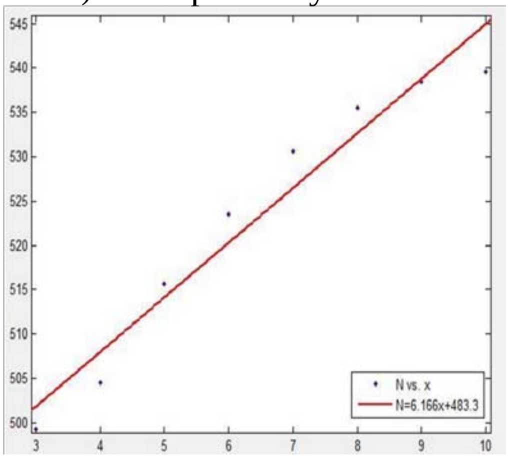


Figure 4 GDP and *time*

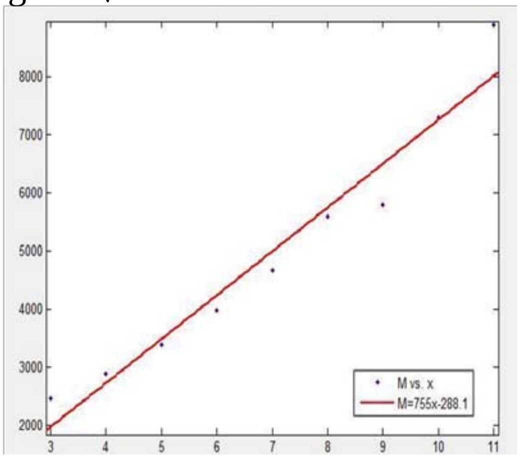


Figure 5 irrigation and time

Its function relationship:

$$M = 755.0x - 288.1 \quad (3)$$

$$N = 6.166x + 483.3 \quad (4)$$

Take（2）（3）（4）into type（1），then it could be gotten that the relational expression about the water demand of zone A and time:

$$A = -0.0156(t-2000)^3 + 0.\,(t-2000)^2 + 6.9\;2(t-2000) + 428.75 \quad (5)$$

When t=2025，it could be calculated that the water demand of A zone is A=537.535<601.05. That is to say, water supply in 2025 is more than water demand, and A zone will have water about 601.05-537.535=63.52 $\times 10^8 m^3$in 2025 for mobilization.

In a similar way, using ternary regression analysis, the relationship curve, about annual water consumption of the other zones and time t, can be fitted by Matlab. (x = t− 2000 )，and the fitting results are shown as the following table:

Table 3: Data collection and statistics

| Zone | Consumption | P |
|---|---|---|
| A | A = 0.061P + 0.0028M + 0.56N | P = −0.257x3 + 4.930x2 + 17.45x + 2605 |
| B | B = 0.018P + 0.001M + 1.27N | P = 0.532x3 − 7.803x2 + 82.18x + 12255 |
| C | C = 0.033P + 0.0024M + 0.26N | P = −0.252x3 + 3.224x2 + 27.29x + 18986 |
| D | D = −0.039P + 0.0026M + 1.09N | P = 1220x0.2587 + 30690 |
| E | E = 0.014P + 0.0009M + 1.26N | P = −1.67x3 + 41.24x2 + 115.0x + 31118 |
| F | F = 0.011P − 0.00015M + 0.76N | P = 0.854x3 − 3.008x2 + 110.8x + 17921 |
| G | G = 0.02P + 0.00085M + 0.96N | P = −0.159x3 + 4.228x2 − 3.317x + 10680 |
| Zone | M | N |
| A | M = 755.0x − 288.1 | N = 6.166x + 483.3 |
| B | M = 4304. x − 6299. | N = −1.885x + 405.7 |

| | | |
|---|---|---|
| C | M = 4074.x − 3671 | N = −3.308x + 316.4 |
| D | M = 8434x − 7973 | N = 16.61x + 627.0 |
| E | M = 16133x − 3483 | N = 0.030x3 + 0.079x2 − 8.592x + 1017 |
| F | M = 8601.x − 3003 | N = 0.057x3 − 1.55x2 + 10.8x + 310.2 |
| G | M = 3938.x − 2029 | N = 12.42x + 286.9 |

### 5.1.3.Analysis of freshwater supply：

Water supply contains two aspects, one is the natural water supply, and the other is artificial water supply. Natural water supply depends on some uncontrollable natural factors like climate、rainfall and so on, While artificial water supply can provide more freshwater by improving or increasing the water-supply measures.

In order to determine water strategy of 2025 in 2013, assume that except the water strategy we developed, there is no additional artificial water supply. So it is necessary to analyze the water supply of 2025 by freshwater supply in 2013.

Statistical data indicate that the water supplies of each zone in 2013 are respectively shown as the following table:

Table 4: the water supplies of each zone in 2013

| Zone | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| Output | 601.05 | 523.27 | 565.58 | 1370.64 | 1898.92 | 473.83 | 588.71 |

**5.1.4Analysis of supply-demand balances:**

According to the calculation method of water demand in A zone, water demands of other zones can be calculated, and the results are: Table 5 Analysis of freshwater supply

| Zone | Output | Consumption | D-value |
|---|---|---|---|
| A | 601.0455391 | 537.534695 | 63.52 |
| B | 523.2719044 | 876.1035 | -352.83 |
| C | 565.5787098 | 882.00135 | -316.42 |
| D | 1570.63796 | 1168.985791 | 401.65 |
| E | 2602.916324 | 2494.9068 | 108.00 |
| F | 473.8310362 | 703.47595 | -229.65 |
| G | 588.7133 | 870.56585 | -281.85 |

The above table indicates that, among the seven zones, only zone A、D、and E would have enough water supply in 2025，and their redundant water quantity are respectively $63.52\times 10^8 m^3$，$401.65\times 10^8 m^3$，$108\times 10^8 m^3$.

While zone B、C、F、G would be in water shortage in 2025, and the quantity of their water shortage are respectively$352.83\times 10^8 m^3$，$316.42\times 10^8 m^3$，$229.65\times 10^8 m^3$，$281.85\times 10^8 m^3$.

The water supply indicates that the water shortage situation of some zones is serious. In order to solve the water crisis, national water strategy need to be determined to face the challenge.

## 5.2. Water storage model

In the flood season of rainy year, a large quantity of water supply exceeds demand. Excess rainwater would be stored in the intake area, in order to be taken advantage of in the dry season. The excess water is usually stored in two ways: groundwater storage that makes the most of the hydrogeological conditions and the pre-existing groundwater extraction wells of the water-starved city to replenish groundwater; surface water storage that makes full use of the pre-existing reservoirs of water-starved city, the best of which supplements the surface water from the source region of the city's water supply (which can take advantage of the pre-existing water supply system).

The underground reservoir is a special reservoir, built with the natural underground water storage space, playing the roles of impoundment、regulation and utilizing groundwater flow. As shown in the following figure:

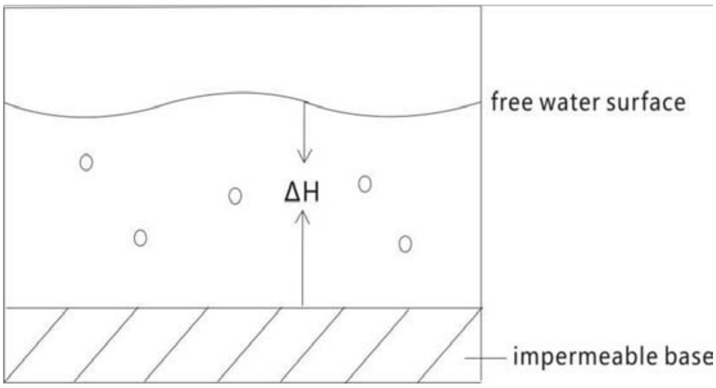


Figure 6: underground reservoir

According to the thickness of the aquifer, the distribution area and rock storage coefficient, it can be calculated that the maximum regulation and storage capacity of underground reservoir as:

$$V_{max} = SA\Delta H \qquad (6)$$

Where: $V_{max}$ refers to the regulation and storage capacity of underground reservoirs($m^3$);$S$ is storage coefficient of the underground water-bearing medium in reservoir storage layer, for the no pressure water-bearing body$S = \mu + \mu^*$, for the pressure water-bearing body$S = \mu^*$,where $\mu$ is gravity specific yield(dimensionless),$\mu^*$ is elastic storage coefficient(dimensionless);$A$ is reservoir area ($km^2$);$\Delta H$ is the maximum thickness the regulation and storage layer, that is, the water level difference value between the extreme high water level and the planning regulation and storage layer bottom interface(m)(Zheng et al. 2004).

Superiorities：

① Underground reservoir taking natural aquifer as water storage spaces, so it has relatively simple construction conditions and lower construction costs;

② Underground reservoirs has little effect on other ground buildings, relatively safe, low environmental impact;

③ Groundwater in reservoir regions has smaller evaporation loss, easy to conserve;

④ It provides the basis and conditions for the joint scheduling of surface water and groundwater, and it slows down the flood pressure.

Problems：It has relative larger errors to calculate the amount of resources of underground reservoirs; and it has a larger workload to survey, with higher costs and longer periods （Zhao 2002）.

Considering that the underground reservoir just saves the local region's water supply, rather than additional water source, it can be used to solve water supply-demand imbalance issues in the short term, so that in the dry season of the year, the residents can use the water of the flood season. However, it is not suitable as a long-term water strategy to resolve the regional water supply-demand imbalance situation.

## 5.3.Mobilization model

By the first prediction model, it can be found that the distribution of water resources in China is extremely imbalanced, with more Water in Southern, less Water in Northern. And the water resources are concentrated in the Yangtze River basin.

In order to solve the water shortage problem, it is feasible to transfer the water from the wet area to the water-poor areas, by the redistribution of water resources through a canal or aqueduct.

Statistics show that the water transfer costs in the south-to-north water diversion project center line is 2.6 $\mathrm{yuan/m^3}$ (Qiu 2000). The water transfer costs in western route of water diversion from South to North is 1$\mathrm{yuan/m^3}$( Tu 2001),and it is 3.4$\mathrm{yuan/m^3}$in the east route.

Here the diversion costs take the average value$(2.6 + 1 + .4) \div =$
$2.\ \mathrm{yuan/m^3}$

Abide by the principle of cost minimization, the determination of the water transfer schemes need linear programming to solve.

### Linear programming

As the figure shows, in order to simplify the transfer process, take one big city in each zone as a centralized point to study their water mobilization. Those centralized point turn to be respectively:

A:Xining(+63.52)
B: Hohhot(-352.83)
C: Chengdu(-316.42)
D: Wuhan(+401.65)
E: Guangzhou(+108)
F: Beijing(-229.65)
G: Harbin(-281.85)

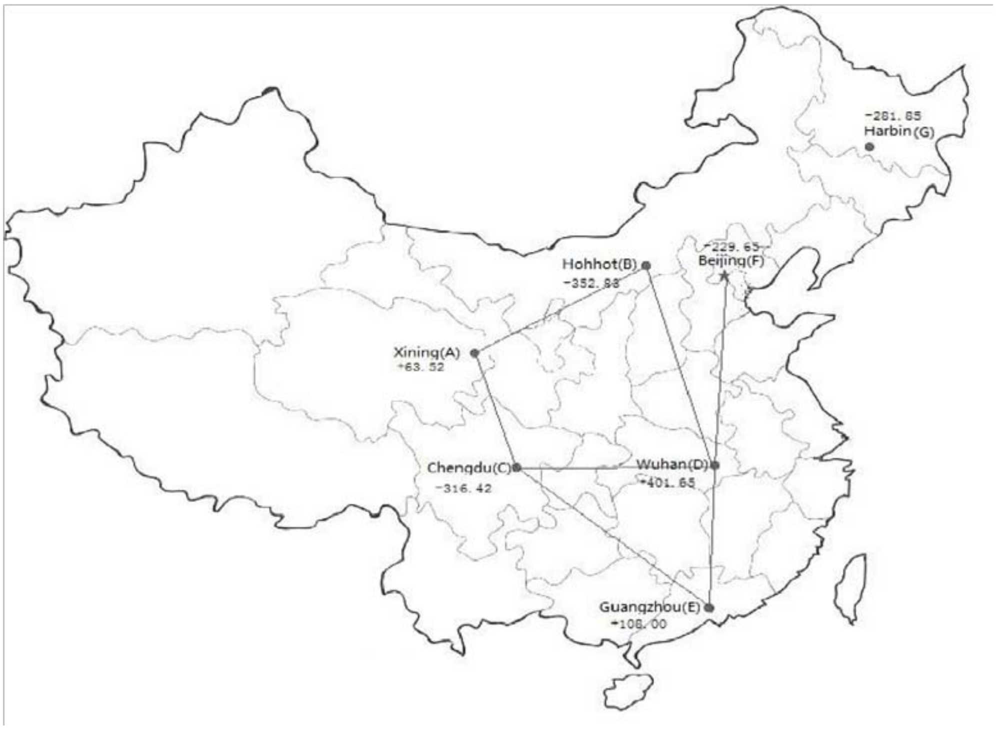


Figure 7: Mobilization model

①Point A、D、E are water supply points, B、C、F、G are water-poor points.

$$A+D+E=573.17$$

$$B+C+F=898.9>573.17$$

So A、D、E don't have enough water to meet the quantity B、C、F demand. While the distance between G and water supply points is the farthest， and the costs is the largest, so it can be ignored to transfer the freshwater to G zone.

②.It can be seen that D zone must supply water to B or F（$D>C$），in order to avoid the costs caused by route repeat, when E provides water to B、F, it can provide water to D firstly，then to B、F.

③.Because A zone had less water supply， and the distance between A and F is father than DF, and the distance between A and C is closer than CD and CE, so the routine AF can be excluded.

So the feasible water supply line includes AC、AB、DB、DF、DC、EC、ED、（ED+DB）、（ED+DF）

It can be sought by measuring tape through Baidu map that $ED$=838 km，$EC$=1233km，$DF$=1056km，$DB$=1061km，$AC$=703km，$AB$=984 km，$CD$=992km.

It has been assumed that the water supply amount from A to B、C is respectively: $x_{12}$、$x_{13}$，the water supply amount from D to B、 C、F is respectively:$x_{42}$、$x_{43}$、$x_{46}$，from E to B、C、F is respectively$x_{52}$、$x_{53}$、

$x_{56}$. Transportation costs of the unit volume of water are a， the transportation costs are *W*.

So the Decision objective:

$$\min W=(703x_{12}+984x_{13}+992x_{43}+1061x_{42}+1056x_{46}+1233x_{53}+1899x_{52}+1894x_{56}\ a) \quad (7)$$

$$\text{Constraints}\begin{cases} x_{12}+x_{13}=63.52 \\ x_{43}+x_{42}+x_{46}=401.65 \\ x_{53}+x_{52}+x_{56}=108 \\ x_{12},x_{13},x_{43},x_{42},x_{46},x_{53},x_{52},x_{56}\geq 0 \\ x_{12}+x_{42}+x_{52}\leq 352.83 \\ x_{13}+x_{43}+x_{53}\leq 316.42 \\ x_{46}+x_{56}\leq 229.65 \end{cases} \quad (8)$$

After solving it by LINGO， the optimal solution has been obtained：

| Variable | Value | Reduced Cost |
|---|---|---|
| X12 | 63.52000 | 0.000000 |
| X13 | 0.000000 | 345.0000 |
| X43 | 208.4200 | 0.000000 |
| X42 | 0.000000 | 5.000000 |
| X46 | 193.2300 | 0.000000 |
| X53 | 108.0000 | 0.000000 |
| X52 | 0.000000 | 602.0000 |
| X56 | 0.000000 | 597.0000 |

Namely the water supply A to B is $63.52\times 10^8 m^3$. D to C is $208.42\times 10^8 m^3$. D to F is $193.23\times 10^8 m^3$.E to C all is $108\times 10^8 m^3$.

**Sensitivity analysis**

Obtaining the minimum value of the total cost of the diversion by the lingo software: 588622.1a.And the data obtained by the sensitivity analysis are as follows:

| Row | Slack or Surplus | Dual Price |
|---|---|---|
| 1 | 588622.1 | -1.000000 |
| 2 | 0.000000 | -703.0000 |
| 3 | 0.000000 | -1056.000 |
| 4 | 0.000000 | -1297.000 |
| 5 | 289.3100 | 0.000000 |
| 6 | 0.000000 | 64.00000 |
| 7 | 36.42000 | 0.000000 |
| 8 | 63.52000 | 0.000000 |
| 9 | 0.000000 | 0.000000 |
| 10 | 208.4200 | 0.000000 |
| 11 | 0.000000 | 0.000000 |
| 12 | 193.2300 | 0.000000 |
| 13 | 108.0000 | 0.000000 |
| 14 | 0.000000 | 0.000000 |
| 15 | 0.000000 | 0.000000 |

It can be drawn from the above data that the reduction of the third and fourth rows of data would make the total cost reduce more. 100 million $m^3$ water reduction of Zone D and Zone E would make the total cost reduce to 1056 a and 1297a respectively. In addition, 100 million $m^3$ water reduction of zone C would make the increase of 64 a in the total cost.

To sum up, just considering the economic cost of water diversion, water diversion can be changed as the follows: minimizing water diversion of D、 E zone or reducing its water transfer distance; as to zone C (Beijing, Tianjin, Shandong) ,the more the water demand proportion of the C zone (Beijing, Tianjin, Shandong), in the case of constant water demand of all zones, the less the total costs, which is in line with the actual situation, in which the costs of the south-to-north water diversion project center line are respectively low.

## 5.4.Seawater desalination model

Seawater desalination technology, that is using seawater desalination to produce fresh water, is the open source incremental technology, which realized the utilization of water resources, regardless of the impacts of time、space and climate. It can protect the drinking water needs of coastal residents.

The desalination methods used nowadays include seawater freezing method、 electrodialysis、 distillation and reverse osmosis. Thanks to its advantages of simple devices, easy maintenance and equipment modular, reverse osmosis, with the application of reverse osmosis membrane, occupied the market quickly and gradually replace distillation method to become the most widely used method. Then taking reverse osmosis as an example to calculate the external costs of desalination.

**Cost analysis of desalination:**

The costs of desalinated water are produced in various stages, including the economic and environmental costs, mainly the costs of the energy consumption, the costs of the effluent discharge to the environment and the value conversion of using seawater. Its cost analysis is shown as figure 8:

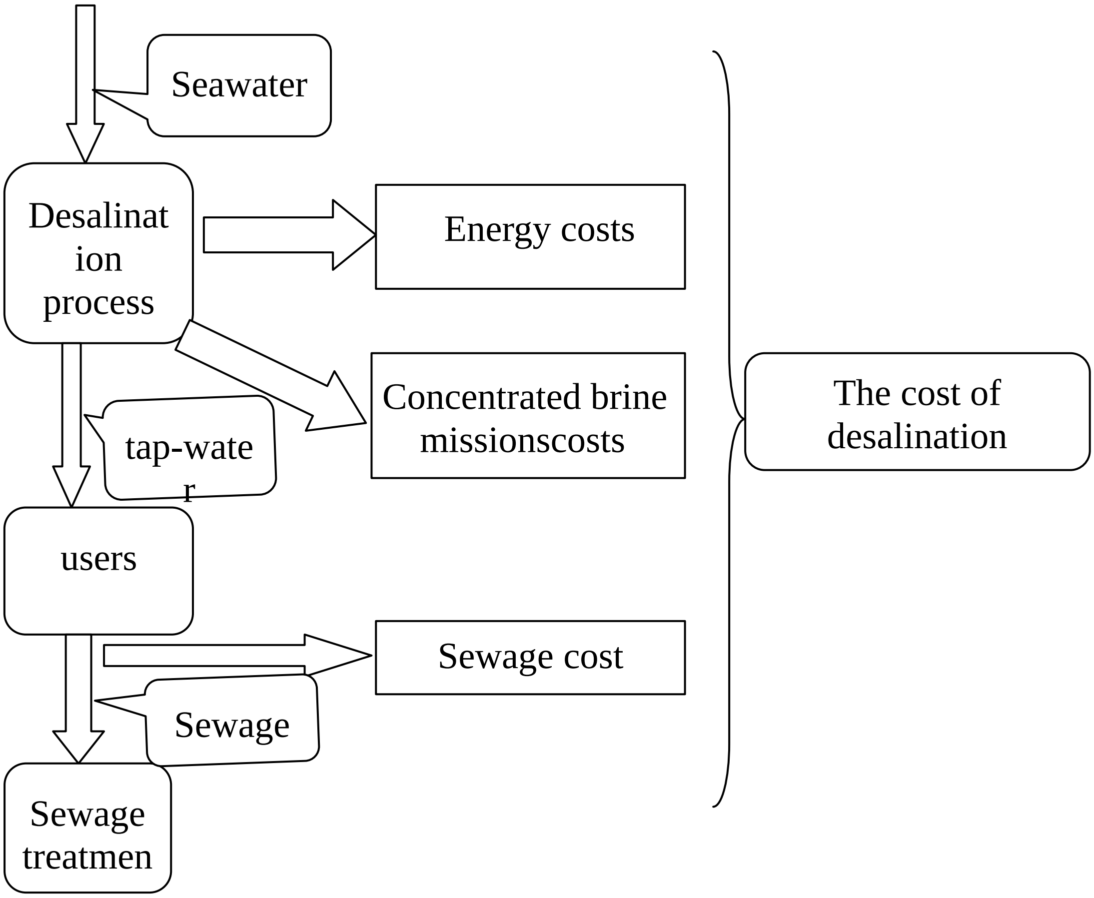


Figure 8External cost analysis of seawater desalination

**5.4.1.Analysis of energy consumption costs:**

Energy consumption cost is calculated in accordance with the quantity of the resources consumed by unit electricity, which is generated by general coal-fired power generation (Chen 2009). The formula is:

$$C_1 = R \times \sum P_i Q_i \qquad (9)$$

Where R is electricity consumption Per ton of desalination water (kW*h);$P_i$is the prices of resource (yuan); $Q_i$ indicates that the resources quantity consumed by unit of electricity is i (g/kWh).

**5.4.2. Analysis of environmental costs:**

When the sewage charges is calculated by pollution equivalent, according to the type and quantity of the emission pollutants, charged standard of each pollution equivalent is 0.7 Yuan. For each outfall, the type number of pollutants which are charged of sewage fees, in decreasing order of pollution equivalent amount, up to not more than 3.

Pollution equivalent amount of some certain pollutant *N* is:

$$N = \frac{Emissions\ quantity\ of\ pollutant}{Pollutant's \qquad value} \quad (10)$$

Environmental costs of unit desalinated water after utilization:

$$C_2 = 0.7Q_a \times \sum_{i=1}^{3} \frac{(\omega_i - \omega_i')}{1000D_i} \qquad (11)$$

Where $\omega_i$ is the concentration of pollutant i, which is produced after the usage of desalinated water,(mg/L)； $Q_a$ is the amount of sewage converted by unit freshwater； $\omega_i'$ is the concentration of pollutant i in the freshwater,(mg/L)； $D_i$ is the pollution equivalent value of pollutant i, (kg).

Among $Q_a = \frac{Q_1}{Q_2}$; $Q_1$ is the total amount of sewage emitted； $Q_2$ is the total water consumption.

In the similar way， the external impact of concentrated brine emissions on the marine environment, can also be calculated by method of estimating sewage charges , of which the formula is:

$$C_3 = 0.7Q_b \times \sum_{i=1}^{3} \frac{(\omega_j - \omega_j')}{1000D_j} \qquad (12)$$

Therefore， the costs of desalination can be calculated as:

$$C = C_1 + C_2 + C_3 \qquad (13)$$

where $C_i$ is the cost of factor i.

**Example** :solving of the desalination external costs：（taking desalination of Qingdao Baifa project as an example）

1.Calculation on the energy external costs：

The daily production of this plant is 100,000 $m^3$ desalinated water, and energy consumption per ton of water is 3.8kWh/$m^3$. Resources consumed by unitelectricity, which is generated by general coal-fired power, are shown in Table 2.

Table 2：Resources consumed by unit of combustion power generated electricity （g/kWh）

| resource | iron ore | raw coal | chalk | copper ore | crude oil |
|---|---|---|---|---|---|
| Price/(Yuan/t) | 400 | 672 | 30 | 600 | 5500 |
| Coal acquisition stage | 0.31 | 12.36 | 0.163 | 0.027 | 0.017 |
| coal transportation | 0.06 | 2.28 | 0.044 | 0.007 | 0.58 |
| production stages | 2.491 | 491.295 | 0.142 | 2.125 | 0 |
| total | 2.861 | 505.935 | 0.349 | 2.159 | 0.597 |

Notation: Take standard coal consumption of coal-fired power as 350g/kWh, and the resource consumption of coal mining and transportation stages is calculated by the National 122departments input-output table in 2002.

External costs of its resources can be calculated according to the formula: $C_1 = R \times \sum P_i Q_i = .8 \times (2.861 \times 400 + 505.9\ 5 \times 672 + 0.49 \times 0 + 2.159 \times 600 + 0.597 \times 5500) \div 10^6 = 1.\ 1$ *(yuan)* .Calculation on the Environmental external costs, the data are shown as the fllows:

Table 3 pollutantcontentsand their pollution equivalent value(2011)

| pollutant | Contents in the reverse osmosis brine/(mg/L) | Contents after usage/(mg/L) | pollution equivalent value/kg |
|---|---|---|---|
| SS | 1 | 280 | 4 |
| COD | 3 | 250 | 1 |
| $NH_4 - N$ | 0.02 | 30 | 0.8 |
| Tp | 0.97 | 0.97 | 0.25 |

The total water amount Qingdao used in 2010 is 943 million $m^3$, and its wastewater emissions amount is 381.56 million tons, then(2011):

$$Q_a = \frac{Q_1}{Q_2} = \frac{8156}{94300} = 40.46\%$$

Then it can be estimated that the environmental costs of used desalinated wateris:

$$C_2 = 0.7Q_a \times \sum_{i=1}^{3} \frac{(\omega_i - \omega_i')}{1000D_i}$$
$$= 0.7 \times 40.46\% \left(\frac{250-3}{1000 \times 1} + \frac{280-1}{1000 \times 4} + \frac{30-0.02}{1000 \times 0.8}\right)$$
$$= 0.101(\text{yuan})$$

Environmental costs of concentrated brine emission can be calculated according to table 4 :

Table 4: The chemical components' nature of pollutants

| Measuring Items | Original seawater (μmol/L) | Concentrated brine (μmol/L) | Pollution equivalent value(kg) |
|---|---|---|---|
| Mn | 4.35 | 8.04 | 0.2 |
| u | 0.74 | 2.14 | 0.1 |

| | | | |
|---|---|---|---|
| $NH_4-N$ | 4.48 | 29.53 | 0.8 |

Taking the current technology level into account, the efficiency of the desalination processing is approximately among 40% to 50%. Daily seawater requirement of BaiFa project is 260000t. It produces 100000 t freshwater every day, with the emission concentrated brine160000t every day, so the quantity of emissions concentrated brine for producing unit desalinated water Q is 1.6.Therefore the environmental costs of brine emissions are:

$$C_3 = 0.7Q_b \times \sum_{i=1}^{3} \frac{(\omega_j - \omega_j')}{1000D_j} = 0.7 \times 1.6 \times \left(\frac{8.04-4.35}{1000\times 0.2} + \frac{2.14-0.74}{1000\times 0.1} + \frac{29.53-4.48}{1000\times 0.8}\right) = 0.072(\text{yuan})$$

$$C = C_1 + C_2 + C_3 + C_4 = 1.\,1 + 0.101 + 0.072 = 1.49\text{yuan}$$

## 5.5.Sewage treatment model

Another idea to increase the available freshwater is recycle. After treatment of the sewage treatment plant, reuse the wastewater that meets the national emission standards.

Cost Analysis：

1. The cost of processing and its components

For municipal wastewater treatment plant, domestic wastewater is the main sewage source. And nowadays, its processing has been relatively mature, of which the core technology is biological activated sludge process.

$$X = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 \qquad (14)$$

Where $X$ is the month processing cost of the sewage treatment plant; $X_1$ is depreciation cost;$_2$ is personnel cost; $X_3$ is power cost ; $X_4$ is maintenance cost; $X_5$ is agent cost; $X_6$ is other costs, which can be estimated as 5% of the previous five costs.

2. Analysis of Processing cost

Take sewage treatment plant with the handling capacity of 30,000 t / d of North China as an example for analysis.

**a. Depreciation charges $X_1$**

Depreciation is a measure to recover the investment, which means extracting a certain amount of funds as a recovery of investment at the end of the year. According to the calculation method of the annuity, without extra consideration offinancial expense, the depreciation extracted every year is(Jin 2003)

$$X_1 = Z \times (1 - i)/(12 \times n) \qquad (15)$$

Where Z is total investment amount($\times\ 10^4$ yuan); i is the discount rate （%）, which is calculated generally based on the loan interest rate; n is depreciation life （year）.

Assume that the total investment amount is 3000$\times\ 10^4$yuan, the loan interest rate is5%, depreciation life is 20years, then the depreciation every mouth is:$X_1$= Z(1-i)/(12n)=118750 (Yuan)

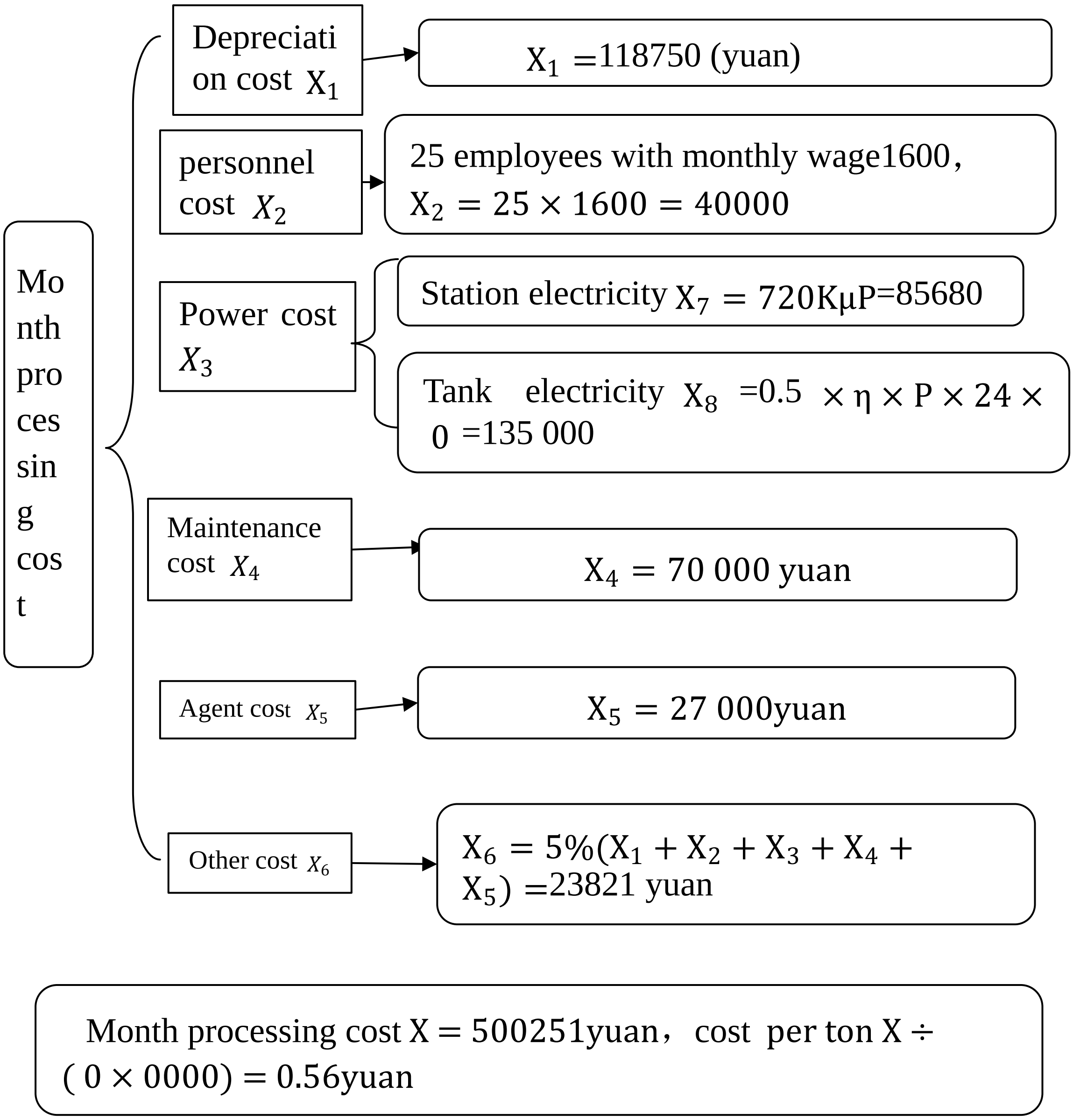


Figure 9: sewage treatment cost

**b. Power costs $X_3$**

i. Pumping station electricity bills$X_7$：

$$X_7 = 720 \times K \times \mu \times P \qquad (16)$$

Where:$X_7$ is pumping station electricity bill, Yuan; K is electricity bills per kilowatt per hour, Yuan/(kWh) ;μ is the utilization efficiency of the pump, kW;P is the power of the pump, kW;720 is the runtime of pump per month.

For the 30000 t/d sewage treatment plant, the power of 4 lift pumps is $4 \times 60\text{kW} = 240\text{kW}$, the power of 5 sludge and reflux pumps is$5 \times 20$ kW = 100 kW, and electric charges 0.5 Yuan/(kWh), the utilization efficiency of the pump is 0.7, then the pumping station electricity bills one mouth is: $X_7$ =85680( yuan).

ii.aeration tankelectric fees $X_8$：

The power of aeration equipment is among 450~ 550 kW, taking the middle value500 kW. The utilization efficiency of the pump is about 75% .Monthly electricity bills is : $X_8 = 500 \times 0.5 \times 0.75 \times 720 =$ 1 5000(Yuan) 。 power cost is : $X_6$ = $X_7$+ $X_8$= 220680(Yuan) (17)

**c.Maintenance cost $X_4$**

Maintenance fees and instrument calibration fees are generally accrued annual 5% of the amount of investment in equipment. Equipment overhaul costs and pipeline maintenance fees are generally only one time among a few years, with the annual provision for 2% of the amount of investment in equipment.

The investment in equipment is generally about 1 200× $10^4$yuan. In accordance with the situation that one equipment overhaul every five years, the monthly maintenance fee is:

$X_4$= 70 000( yuan)

**d. Pharmacy fees $X_5$**

Pharmacy fees included various chemical reagents, flocculants and disinfection fees.

The operating costs of sewage disinfection is 0.025 yuan/t.

The dosage of chemical reagents and flocculant is relatively small, and the pharmaceutical fees for processing sewage is 0.03 yuan/t, so the pharmacy fees every month is: $X_5$= 27 000 Yuan.

So processing cost every mouth:

$X = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 = 500251$(yuan)

Processing cost per ton is: $X \div (\ 0 \times 0000) = 0.56$(yuan).

Water Strategy

The predictionmodel has confirmed the water shortage areas and wet areas in 2025. In order to solve the water shortage problem, four water supply schemes were introduced: storage, movement, seawater desalination and sewage treatment

To determine the best water strategy, it is necessary to evaluate the strengths and weaknesses of those four schemes, before the permutation and combination of them.

Because underground reservoirs just save the regional water, rather than provide additional water, it can just solve water demand-supply imbalances in the short term, so that in the dry season of the year can also use the water of the flood season, but is not suitable as a long-term water strategy.

Therefore, it is feasible to evaluate the mobilization、 desalination and sewage treatment by analytic hierarchy process models firstly.

## 5.6. AHP model

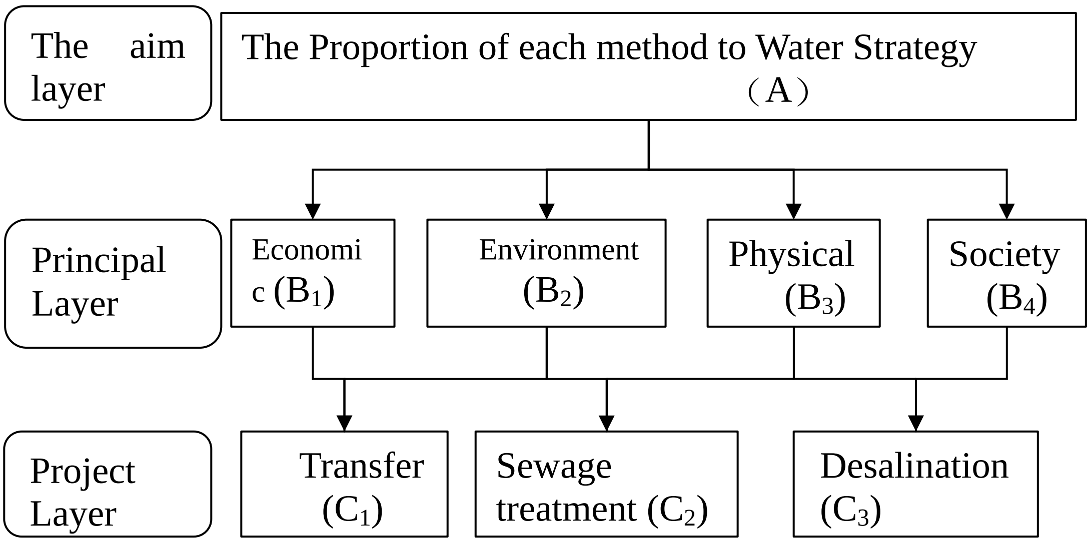


Figure 10: analytic hierarchy process modes The weighing result is as follow:

| A | B1 | B2 | B3 | B4 |
|---|---|---|---|---|
| B1 | 1 | 3/2 | 9/8 | 5/4 |
| B2 | 2/3 | 1 | 2 | 7/5 |
| B3 | 8/9 | 1/2 | 1 | 3 |
| B4 | 4/5 | 5/7 | 1/3 | 1 |

| B1 | C1 | C2 | C3 |
|---|---|---|---|
| C1 | 1 | 3 | 2 |
| C2 | 1/3 | 1 | 3/2 |
| C3 | 1/2 | 2/3 | 1 |

| B2 | C1 | C2 | C3 |
|---|---|---|---|
| C1 | 1 | 3/2 | 7/5 |
| C2 | 2/3 | 1 | 1/2 |
| C3 | 5/7 | 2 | 1 |

| B3 | C1 | C2 | C3 |
|---|---|---|---|
| C1 | 1 | 3 | 7/4 |
| C2 | 1/3 | 1 | 1/2 |
| C3 | 4/7 | 2 | 1 |

| B4 | C1 | C2 | C3 |
|---|---|---|---|
| C1 | 1 | 3 | 2 |
| C2 | 1/3 | 1 | 3/2 |
| C3 | 1/2 | 2/3 | 1 |

After the standardization of eigenvector, the vector of weighing can be acquired by:

$$W_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{kl}} \quad (18)$$

Coherence Check:

Firstly, calculate the C.I. （consistency index）

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (19)$$

Secondly, calculate R.I. （random index）: n=3, R.I.= 0.90 n=4, R.I.=0.58

Thirdly, calculate C.R. （consistency ratio）

$$CR = \frac{CI.}{RI.} \quad (20)$$

When CR < 0.1, the consistency of judgment matrix is acceptable, otherwise, it should be corrected.

Using Matlab, the weight vector and test results can be gotten as follows:

| $B_2$ | weight | $B_3$ | weight | B4 | weight |
|---|---|---|---|---|---|
| $C_1$ | 0.3752 | $C_1$ | 0.3726 | $C_1$ | 0.4215 |
| $C_2$ | 0.2531 | $C_2$ | 0.2768 | $C_2$ | 0.2917 |
| $C_3$ | 0.3717 | $C_3$ | 0.3506 | $C_3$ | 0.2868 |
| λ | 3.07 | λ | 3.04 | λ | 3.02 |
| CR | 0.06 | CR | 0.05 | CR | 0.05 |

According to above tables, the results can be obtained as follow:

| Method | Weight | Importance sequence (High to Low) |
|---|---|---|
| Mobilization | 0.4683 | 1 |
| Desalination | 0.3284 | 2 |
| Sewagetreatment | 0.2033 | 3 |

When determine the best water strategy, it should mobilize the water firstly, namely the redistribution of water resources.

It can be found from the mobilization model : C zone solved its water shortage; B zone need more water 52.8 − 63.52=289.31 $\times 10^8 m^3$, F zone need more water229.65 − 193.23=36.42× $10^8 m^3$ , G zone need more water 281.85× $10^8 m^3$.

Implementation of desalination needs offshore environment. Based on the principle of local conditions, F zone should adopt desalination strategy.

B zone belongs to inland, so it should adopt sewagetreatment strategy.

G zone has some parts offshore, so it would be better to adopt joint strategies of desalination and sewagetreatment.

**Costs Analysis**

Nowadays, the daily average processing capacity of desalinator is $1.0 \times 10^5 m^3$, while the sewage treatment plant is $8.0 \times 10^4 m^3$,as the following table shows:

| Poor-water zones | Water shortage $\times 10^8 m^3$ | Amount of desalination plants | Amount of sewagetreatment plants | costs/ $\times 10^8$yuan |
|---|---|---|---|---|
| B | 289.31 | 0 | 990 | 147.5 |
| F | 36.42 | 100 | 0 | 54.3 |
| G | 281.85 | 50 | 903 | 161.6 |

The water strategy costs of each zone:

| Zone | Mobilization costs/$\times 10^8$yuan | Desalination costs/$\times 10^8$yuan | Sewage treatment costs /$\times 10^8$yuan | Total/$\times 10^8$yuan |
|---|---|---|---|---|
| B | 146.1 | 0 | 147.5 | 293.6 |
| C | 727.8 | 0 | 0 | 727.8 |
| F | 444.4 | 54.3 | 0 | 498.7 |
| G | 0 | 27.2 | 134.4 | 161.6 |
| Total/$\times 10^8$yuan | 1318.3 | 54.3 | 147.5 | 1520.1 |

The results show that, in order to solve the water shortage, F zone needs to build at least 100 desalinators in Shandong、 Tianjin before2025, with the costs 54.3× $10^8$yuan;

B zone needs to build at least 990 desalinators before 2025, with the costs 147.5× $10^8$yuan。

G zone needs to build at least 50 desalinators in Liaoning before 2025, and 903 sewage treatment plants before 2025, with the respective costs $27.2\times 10^8$yuan、$134.4\times 10^8$yuan.

**5.7.Model for intra-regional optimal allocation of water**

In addition to replenishing the water shortage, the optimal water strategy also needs to ensure that the increased freshwater resources within the zone could bring the maximum economic benefits.

The families within the zone are seen as minimum units. Along with the increase in the amount of freshwater allocated, other means of production would be fully utilized, and the economic efficiency would increase. However, when the allocation amount is increased to a certain degree, the economic efficiency would decrease because the increased water costs and the decreased productivity growth. To simplify the model, assume that the economic benefits, J and water consumption, q satisfy the quadratic function. As the figure shown.

*Set* $J = aq^2 + bq$, a  0, q is the water consumption amount, J is actual benefits.

When water consumptionq = 0 , the economic benefitsJ = 0 ; When water consumption q = Q, the maximum economic benefitsJ = J'.

Solving equations $\begin{cases} -\frac{b}{2a} = Q \\ J = aq^2 + bq \end{cases}$,

then it can be gotten: $\begin{cases} a = \frac{J}{q^2-2Qq} \\ b = \frac{2QJ}{2Qq-q} \end{cases}$

2

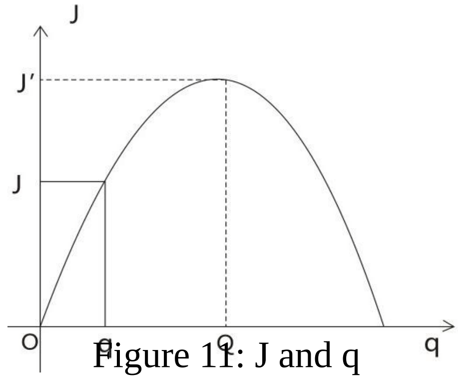

Figure 11: J and q

Then the increased economic benefits with the water allocation of Δq are:

$\Delta J = (q + \Delta q)^2 + b(q + \Delta q) - (aq^2 + bq)$

$= a\Delta q^2 + (2aq + b)\Delta q$ (21)

Assume that there are i units (families) within the zone, then the increased total benefits after introducing water Q are:

$$H = \sum_i \Delta J = \sum_i [a\Delta q_i^{\ 2} + (2aq + b)\Delta q_i] \quad (22)$$

$$Q = \sum_i \Delta q_i \quad (23)$$

The maximum economic benefits, namely the largest $H$.

So this question can be converted into another, namely, when $Q = \sum_i \Delta q_i$, seek the maximum value $H_{max}$ on the basis of $H =$

$\sum[a\Delta q_i^2 + (2aq + b)\Delta q_i]$

This problem can be solved by using the Lagrange multiplier method to obtain its extreme value：

Make $K = \sum[a\Delta q_i^2 + (2aq + b)\Delta q_i] + \gamma \sum_i \Delta q_i$ (24)

$K' = 0$ , then $\Delta q_i$ is optimum solution

In actual situation, water consumption units, which refer to families, are often not able to grasp the optimal water consumption $Q$. Then it is necessary to add up the past water usage situations to determine the best range of water consumption.

## 6.The non-technical position paper

Among the seven zones ,only zone A,D,E would have enough water supply in 2025,their redundant water quantity is respectively 63.52，401.65，108× $10^8 m^3$.while zone B,C,F,G would be in water shortage in 2025, their water shortage is respectively 352.83，316.42，229.65，281.85 × $10^8 m^3$.

**The solutions are**：

For C zone， it is necessary to build CD、 CE two routes， and transfer water from D zone 208.42 in 2025，from E zone 108，with the total costs 72.78 billion yuan.

For F zone， it is necessary to build route FD， and transfer water from D zone 193.23 in 2025 with the costs 444.4. And it is necessary to build at least 100 desalinators in Shandong、 Tianjin before 2025, with the costs 5.43 billion yuan.

For B zone，it is necessary to build route AB， and transfer water from A zone 63.52 in 2025 with the costs 146.1.And it is necessary to build at least 990 desalinators before 2025, with the costs 14.75 billion yuan.

For G zone, it is necessary to build at least 50 desalinators in Liaoning before 2025, and 903 sewage treatment plants before 2025, with the respective costs 2.72 billion yuan、13.44 billion yuan.

For the whole country, it is necessary to replenish water resources of the underground reservoirs. In order to protect the underground storage space, apart from land subsidence, good storage work must be done.

For the regional freshwater allocation, a lot of statistical work needs to be done. And it is necessary to determine the optimum water consumption to achieve maximum production efficiency.

**Feasibility analysis:**

From reality, the routes of the water diversion schemes determined by models in this article are some routes of the South-to-north project. And the solutions of C、F zone are cost-effective and practical.

It is impractical to build 990 desalinators in B and 903 sewage treatment plants in G. Because of the low price of treated water, sewage treatment plants can only gain profits after forming a certain scale. Nowadays, most of the domestic sewage treatment plants operate under the state support and grants. So according to the current sewage treatment level, it is unwise to build more than 900 sewage treatment plants.

So the water shortage problem in zone B、 F D is very serious, and it is very difficult to solve the water shortage problem in accordance with the current level of technology.

Therefore， for B、F zone， the problems can't be solved by the above measures. The government should increase investment in desalination and sewage treatment, and reduce operating costs, improve production efficiency.

In addition to increasing the available freshwater, the government also should try to reduce the demand for fresh water、 increase water prices、 popularize agricultural irrigation drip technology and develop new energy to reduce dependence on water resources and so on. On the other hand, the government should improve the national water-saving awareness.

**The reasons for the best water strategy**：

1.Replenishment measures taken by the article is the mainstream replenishment strategy nowadays, which has passed through the experts' research.

2. In the water mobilization model, the water diversion route was determined using Lingo program, for solving the optimal solution to minimize the cost.

3.The other replenishment strategies were obtained by reference to the actual production data, which is true and reliable.

4. In all the permutations and combinations of the various replenishment measures, the priority of various strategies is determined by the analytic hierarchy process models. To take optimal measures first, and then take the second-best measures supplement, to ensure that the combined effect of the best. Taking the best measures firstly, taking suboptimal measures added to ensure that the combined effect is the best.

5. The establishment of the regional freshwater allocation model provided possibility for the optimization of water resources allocation

within the zone, which ensured that the region could maximize the economic benefits.

# 7.Examination

By the first prediction model, it can be found that the determined water-poor zones and wet zones in China meets the current distribution of regional water resources, with more Water in southern, less water in northern.

Mobilization model determined the best water transfer lines, based on linear programming, and some lines such as AB, DF, ED + DF are part of the south-to-north water diversion project routes in China.

In the process of sensitivity analysis of the mobilization model, it can be found that the more the water demand proportion of the C zone (Beijing, Tianjin, Shandong), in the case of constant water demand of all zones, the less the total costs, which is in line with the actual situation, in which the costs of the south-to-north water diversion project center line are respectively low.

# 8.Evaluation

## 8.1Strengths

The study of water resources in China took the pattern of partition first and then studying within each region, which determined the significant water-scarce regions and seized the key points of the problem.

Replenishment measures are not only qualitative but also quantitative, along with the quantitative modeling and costs calculation.

Integrated to determine the water strategy in 2025, after the permutations and combinations of various replenishment measures, the priority of each measure is assessed to determine a complete and feasible water strategy.

Various replenishment measures have followed principles of the lowest cost and the best combined effect, to ensure the best strategy.

## 8.2Weaknesses

When build the prediction models, only eight years of data are collected. Because the data is respectively little, the fitting results existed certain errors.

Partition number is not enough, 2 more can be added to increase the accuracy of the model.

Optimal allocation of regional freshwater lacked for experimental data, without quantitative calculations.

## 9.Improvement

Because the water data collected is less, in order to improve the accuracy of prediction model, related data of the 2014,2015,2016,2017 can be predicted firstly, then setting these data as the known data to re-establish the prediction model. Then the new function of water amount and time can be obtained. And what' more, water demand in 2015 can be calculated by the new function - iterative method.

The cost of water diversion has taken the average value of the south-to-north water diversion project center line、western line and eastern line, with big errors. In fact, the average value should be calculated by some more collected water diversion project data. Or it is also feasible to collect the cost sources, establish a function of its distance and water transfer volume respectively, and finally get a function about the total costs .

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