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Qualitative analysis and quantitative simulation on Yin-Huang water salinization mechanism in Bei-Da-Gang Reservoir

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Abstract: Yellow River water transfer for Tianjin is important in solving the water shortage in Tianjin, which facilitate economic development and social progress for many years. Fresh water drawn from Yellow River(i.e., Yin-Huang water) becomes saltier and saltier when being stored in the Bei-Da-Gang reservoir. We qualitatively analyze the water salinization mechanism based on mass transfer theory. The main factors are salinity transfer of saline soil, evaporation concentrating, and the agitation of wind. A simulative experimental pond and an evaporation pond were built beside the Bei-Da-Gang reservoir to quantitatively investigate the water salinization based on water and solute balance in the simulative pond. 80% of increased [Cl^-] is due to the salinity transfer of the saline soil and the other 20% is due to evaporation concentrating, so the former is the most important factor. We found that the salinization of Yin-Huang water can be described with a zero-dimension linear model.

Keywords: Yin-Huang-Ji-Jin Project; water salinization; simulative experiment; saline soil; evaporation concentrating; mass transfer; mathematical model

Introduction

Tianjin is located in north China and suffers from serious water shortage. Its water resources, about 180 m^3 per capita, are only about 1/5 of national average and about 1/20 of world average (Tianjin Statistical Bureau, 2001).

The project of Yellow River water transfer for Tianjin(i.e., Yin-Huang-Ji-Jin Project) is an effective measure to solve the problem of water shortage and has played an important role in the economic development and social progress of Tianjin since 1972. Eight times of Yin-Huang-Ji-Jing Project have been finished so far and about 5.0×10^8 m^3 of fresh water has been channeled from Yellow River to Tianjin each time(Zhang, 2002).

Bei-Da-Gang Reservoir is the only regulating reservoir for this project. Each project lasts about 8 months and consists into two phases. The first phase is about 3 months and the second is about 5 months. During the first phase, part of the Yin-Huang water is directly supplied to Tianjin and the other is stored in the reservoir. During the second phase, the water stored in the reservoir is directly supplied to Tianjin.

The Yin-Huang water is fresh before channeled to the Bei-Da-Gang Reservoir but gets saltier and saltier in the reservoir(Table 1). The purposes of this study are (1) to analyze the salinization mechanism qualitatively; (2) to study the salinization factor quantitatively through simulation experiment; and (3) to derive a mathematical model to characterize the water salinization in the Bei-Da-Gang Reservoir.

Alon Rimmer (Alon, 2003) reported the water salinization mechanism in Lake Kinneret. He indicated that the high salinity results from the activity of saline springs located at the bottom of the lake. Based on the main components of the annual water and solute balance, he characterized changes of the solute mass of the lake with time as a differential equation of a linear reservoir on an annual time scale. Zhu Jiang-ping (Zhu, 2002) found that the leakage of sea water mainly leads to the water salinization in the Hu-Chen-Gang Reservoir. The water salinization mechanism in the Bei-Da-Gang Reservoir is different from the above two cases, thus we use a different method for this study.

Table 1 Comparison of Cl^- concentration in Yin-Huang water between entrance to and exit from Bei-Da-Gang Reservoir

Jiu-Xuan South Canal Floodgate (Entrance to Bei-Da-Gang Reservoir)		Tenth Floodgate(exit to Tianjin)	
Date	[Cl^-], mg/L	Date	[Cl^-], mg/L
2003-09-23	47.9	2003-08-17	697.0
2003-10-10	97.2	2003-10-01	598.0
2003-10-21	37.7	2003-10-31	184.0
2003-10-31	43.2	2003-11-11	177.0
2003-11-12	47.6	2003-12-01	155.0
2003-11-21	57.4	2004-02-02	155.0
2003-12-18	71.8	2004-02-25	175.0
2003-12-31	76.2	2004-04-19	237.0
2004-01-05	78.1	2004-05-11	258.0

Notes: The data are taken from Tianjin Environmental Protection Agency inspection station for the eighth Yin-Huang-Ji-Jin Project; the eighth Yin-Huang-Ji-Jin Project began on Sep. 22, 2003 and ended on June 6, 2004

1 Qualitative analysis

1.1 Mass transfer theory

Mass transfer can described with Fick's first law, which assumes that the mass flux of a certain component linearly depends on its concentration gradient:

$$J_A = -D_{AB}\frac{d\rho_A}{dy}, \quad (1)$$

where J_A is mass flux in y-direction, kg/(s·m^2); D_{AB} is the diffusion coefficient of mass A in mass B, m^2/s; $d\rho_A/dy$ is the concentration gradient in the y-direction, kg/(m^3·m) (Cussler, 1984).

1.2 Water salinization mechanism

Based on mass transfer theory, we qualitatively analyze the Yin-Huang water salinization mechanism. The salinization is related to some conditions of geology, hydrology and aerography in the Bei-Da-Gang Reservoir area. Fig.1 shows a schematic diagram of the salinization mechanism. The main factors are as follows:

(1) Saline soil: The soil in the reservoir is saline. Its

Foundation item: The Science and Technology Development in Tianjin(No. 033112211); * Corresponding author salinity is as high as 0.2%—1.5%. According to the mass transfer theory, salinity will transfer from soil to water through a very thin layer of water membrane that covers the soil.

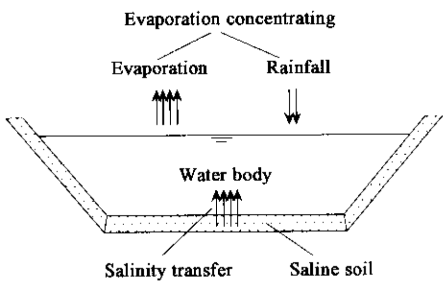

Fig. 1 Yin-Huang water salinization mechanism model sketch about mass transfer and evaporation concentrating in the Bei-Da-Gang Reservoir

(2) Evaporation and rainfall: In the reservoir area, the evaporation is consistently greater than the rainfall by average 1500 mm/a(Fig.2). Thus, the salinity in water will increase as a result of evaporation concentrating.

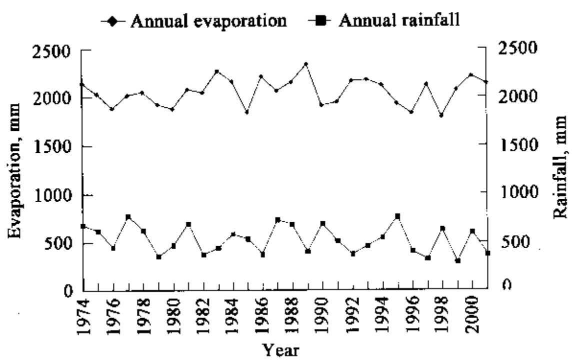

Fig.2 Comparing annual evaporation with annual rainfall from 1974 to 2001 Average value of annual evaporation minus annual rainfall is 1523 mm

(3) Wind: The reservoir area is close to Bohai Sea which is a monsoon area, so it is usually windy. Wang Yun-hong(Wang, 2001) reported that wave and wind current including vertical circumfluence and horizontal circumfluence, will be induced when wind blows the water surface. All these waves and wind currents will intensively agitate the water body and accelerate the mix of salinity, which will in turn directly accelerate water salinization. Furthermore, wind can accelerate the evaporation rate according to the evaporation theory (Charles, 1975) and therefore indirectly accelerates water salinization.

(4) Other factors: There are other factors that can impact water salinization. For example, the atmospheric particulate may contain salinity more or less, which can be brought into water with dry and wet deposition. But this factor is negligible because of the very small quantity of deposition of atmospheric particulate.

2 Quantitative simulation

2.1 Experimental objective

According to the above analysis, the main factors for Yin-Huang water salinization are salinity transfer of saline soil, evaporation concentrating and the agitation of wind. The objectives of the simulation experiment were (1) to quantitatively determine the percentage of increased [Cl^-] caused by salinity transfer of saline soil and evaporation concentrating, respectively; (2) to derive a mathematical model for Yin-Huang water salinization.

Because the speed and direction of wind changes with high frequency, it is very difficult to quantitatively determine how much wind contributes to the water salinization. Therefore, wind is not taken into account in the simulation. We also ignore the unimportant atmospheric particulate precipitation.

2.2 Experimental methods

To make a quantitative analysis on Yin-Huang water salinization mechanism, we built a simulative experimental pond and an evaporation pond beside the Bei-Da-Gang Reservoir. We filled the simulative experimental pond with low saline water and stored the water for specified period of time. During the experiment, we periodically measured the water loss volume of evaporation and leakage and analyze [Cl^-] using titration method recommended by China Environmental Protection Agency(Wei, 2002).

The simulative experimental pond is 50 m long, 50 m wide, and 2.5 m deep. The length and width of the bottom are both 40 m with a side slope of 1:2. To better simulate the Bei-Da-Gang Reservoir, we applied saline soils, which are dug from on the spot, to the bottom and 4 sides of the simulative pond. We did a sample at five different sample locations in the horizontal and at three vertical locations, with a total number of 15 sample points(Fig.3).

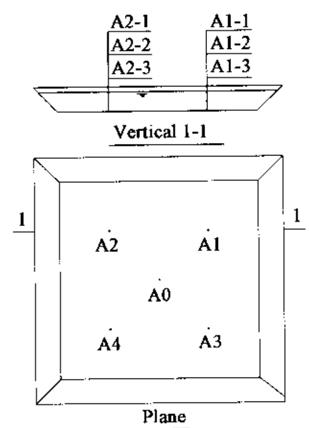

Fig.3 Sketch of sampling point in simulative experimental pond

The length, width, and depth of the evaporation pond are 2 m, 1 m and 1 m, respectively. The bottom and 4 walls of the pond are waterproofed to avoid salinity transfer of saline soil.

The experiment began on April 19, 2004 and ended on June 2, 2004. During the preliminary three days low salinity water is pumped into the simulative pond with an initial water depth of 1.85 m. Then, the low salinity water was stored in the pond without outflow during the rest of the experiment. During the experiment, we periodically monitored the falling water level in both ponds and simultaneously measure the [Cl^-] concentration at each sampling location.

2.3 Results and discussion

2.3.1 Water balance

The water loss in the simulative pond is due to evaporation and leakage. The water balance in the simulative pond can be described as:

$$\frac{dV_{TL,t}(t)}{dt} = \frac{dV_{Et}(t)}{dt} + \frac{dV_{Lt}(t)}{dt}, \quad (2)$$

where $V_{TL,t}$ is the volume of the total water loss(m^3), which can be determined from the water level fall in the simulative pond; t is time(d); V_{Et} is the volume of the evaporation water loss(m^3) which can be calculated from the water level fall in the evaporation pond; V_{Lt} is the volume of the leakage water loss (m^3), which can be derived using Eq. (2). Original data and calculations are presented in Table 2.

Table 2 Water loss due to evaporation, leakage and their sum

Date	Evaporation pond			Simulative pond		
	Water level fall, mm	Evaporation, mm	V_{Et}, m^3	Water level fall, mm	V_{TLt}, m^3	V_{Lt}, m^3
2004-4-19	0	0	0	0	0	0
2004-4-28	90	90	171	280	528	357
2004-5-11	150	150	282	610	1132	850
2004-5-19	160	160	300	740	1365	1065
2004-5-26	190	190	354	850	1560	1206
2004-6-2	225	225	415	935	1710	1295

2.3.2 Cl^- concentration data analysis and process

Based on measured [Cl^-] of all the samples, we find that the [Cl^-] is nearly the same at different sampling locations in the same plane but slightly varies with depth. The average [Cl^-] of surface, middle, and bottom samples, and all the samples are shown in Table 3. We can see slightly different values at different depth. But the differences are relatively insignificant compared to the change of [Cl^-] with time, therefore the average of all samples can be used in the solute balance. Furthermore, the temporal variation of [Cl^-] can be described with zero-dimension model.

Table 3 Average [Cl^-] of all the samples in the simulation pond (mg/L)

Date	2004-4-19	2004-4-28	2004-5-11	2004-5-19	2004-5-26	2004-6-2
Time, d	0	9	22	30	37	44
Surface	275.27	304.8	370.32	414.62	451.66	482.56
Middle	274.23	303.07	370.87	415.4	450.6	490.6
Bottom	273.76	307.32	369.27	416.04	459.56	498.09
All	274.42	305.06	370.15	415.35	453.94	490.42

If the increased [Cl^-] by salinity mass of saline soil is not considered, the [Cl^-] by evaporation concentrating at time t (C_{Et}) is:

$$C_{Et} = M_0/(V_t + V_{Lt}), \quad (3)$$

where V_t is the volume in the pond at time t. Then the increased [Cl^-] by evaporation concentrating at time t (C_{IEt}) can be obtained by:

$$C_{IEt} = C_0 - C_{Et}. \quad (4)$$

The increased [Cl^-] by salinity transfer of saline soil (C_{ISt}) can be similarly calculated by:

$$C_{ISt} = C_0 - C_t - C_{Et}, \quad (5)$$

where C_t is the Cl^- concentration in simulative pond at time t. Therefore, the percentages of the increased [Cl^-] by salinity transfer of saline soil (P_{ISt}) and by evaporation concentrating(P_{IEt}) are:

$$P_{ISt} = \frac{C_t - C_0 - C_{Et}}{C_t - C_0} \times 100\%, \quad (6)$$

$$P_{IEt} = 1 - P_{ISt}. \quad (7)$$

All the above intermediate calculations are shown in Table 4. P_{ISt} and P_{IEt} are compared in Fig.4. We can clearly see that salinity transfer of saline soil is the most important factor to affect the water salinization in the simulative pond.

Table 4 [Cl^-] data processing results

Date	2004-4-19	2004-4-28	2004-5-11	2004-5-19	2004-5-26	2004-6-2
Time, d	0	9	22	30	37	44
C_t, mg/L	274.42	305.06	370.15	415.35	453.94	490.42
C_{Et}, mg/L	274.42	289.67	300.57	302.41	308	314.72
C_{IEt}, mg/L	0	15.25	26.15	27.99	33.58	40.3
C_{ISt}, mg/L	0	15.39	69.58	112.94	147.47	181.92
P_{ISt}, %	0	50.2	72.7	80.1	81.5	81.9
P_{IEt}, %	0	49.8	27.3	19.9	18.5	18.1

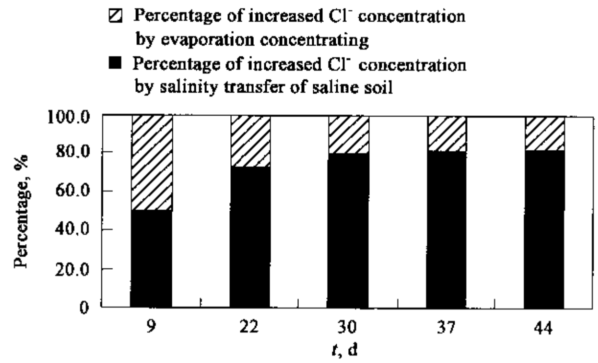

Fig.4 Comparison of increase in [Cl^-] due to salinity transfer of saline soil and evaporation concentration

2.3.3 Water salinization mathematical model

Because water salinization mathematical model can be described with zero-dimension model, the change of [Cl^-] with time can be written as:

$$\frac{dC_t(t)}{dt} = \frac{dC_{St}(t)}{dt} + \frac{dC_{Et}(t)}{dt}. \quad (8)$$

According to the data in Table 4, $dC_{St}(t)/dt$ and $dC_{Et}(t)/dt$ can be obtained by linear regression methods as 3.8823 and 0.9576(mg/(L·d)), respectively(Fig.5). So the water salinization is described as:

$$\frac{dC_t(t)}{dt} = 4.8399. \quad (9)$$

The integral of Eq. (9) gives

$$C_t = 4.8399t + C_0, \quad (10)$$

where C_0 is 274.42(mg/L). The final water salinization can be modeled as:

$$C_t = 4.8399t + 274.42. \quad (11)$$

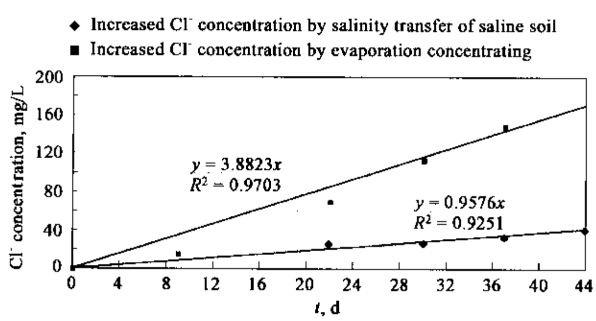

Fig.5 Calculation of $dC_{St}(t)/dt$ and $dC_{Et}(t)/dt$ by linear regression methods

2.3.4 Solute balance

Among the main factors mentioned in section 1.2, only salinity transfer of saline soil increases the mass of Cl^- in the simulative pond. The leakage of water reduces the mass of Cl^- from the simulative pond. Therefore, the solute balance of the pond can be written as:

$$M_t = M_0 + M_{St} - M_{Lt}, \quad (12)$$

where $M_t = C_t V_t$ is the mass of Cl^- in the simulative pond at time t; $M_0 = C_0 V_0$ is the initial mass of Cl^- in the simulative pond; M_{St} is the added mass of Cl^- at time t by salinity transfer of saline soil; M_{Lt} is the reduced mass of Cl^- at time t due to leakage of water.

The mass flux of Cl^- from saline soil at time t. J_t can be calculated by:

$$J_t = M_{St}/(A_t \cdot t), \quad (13)$$

where A_t is the conterminous area between water and saline soil. All calculations are presented in Table 5.

Table 5 Mass of Cl^- calculation result

Date Time, d	2004-4-19 0	2004-4-28 9	2004-5-11 22	2004-5-19 30	2004-5-26 37	2004-6-2 44
M_t, g	889741	828050	780858	779368	765803	760853
M_{Lt}, g	0	102664	269257	353747	415427	457176
M_{St}, g	0	40974	160374	243374	291489	328288
J_t, kg/(m^2·s)	0	3.95E-8	4.45E-8	4.36E-8	4.16E-8	4.24E-8

3 Water salinization mathematical model in Bei-Da-Gang Reservoir

Because the simulative pond is built beside the Bei-Da-Gang Reservoir, the natural conditions between them are similar. Some of the conclusions based on the simulative experiment can be applied to the Bei-Da-Gang Reservoir.

For example, a zero-dimension linear model can be used to describe the water salinization in the Bei-Da-Gang Reservoir. The model derived from water and solute balance theory and actual data is as follows:

$$C_t = 1.0792t + C_0, \quad (14)$$

where C_0 is 108.35(mg/L) on Jan. 6, 2004. So the final water salinization is characterized as:

$$C_t = 1.0792t + 108.35. \quad (15)$$

We forcasted the [Cl^-] in the Bei-Da-Gang Reservoir using Equation (15) between Jan.6, 2004 and May 22, 2004. The predicted data matches very well with the actual measured data (Fig. 6), so the derived model well characterizes the actual water salinization in the Bei-Da-Gang Reservoir.

4 Conclusions

We performed a qualitative analysis on the salinization mechanism of Yin-Huang water based on mass transfer theory and found that the main factors for water salinization are salinity transfer of saline soil, evaporation concentrating, and the agitation of wind.

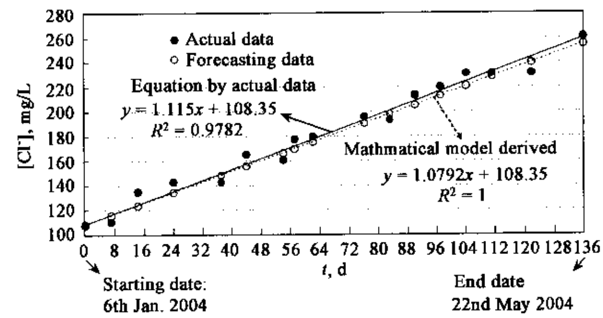

Fig.6 Comparisons of forecasted and actually measured [Cl^-]

The important conclusions were made through quantitative simulative experiment which is based on water and solute balance:

(1) Salinity transfer of saline soil is the most important factor for water salinization in the simulative pond because 80% of increased [Cl^-] is due to salinity transfer of saline soil and the other 20% increase in [Cl^-] is due to evaporation concentrating.

(2) A zero-dimension linear model could be used to describe the water salinization in simulative pond because the wind agitates the water body in the simulative pond and leads to complete mixing in the pond. The model is:

$$C_t = 4.8399t + 274.42 . \quad (11)$$

(3) The mass flux of Cl^- (J_t) from saline soil in the simulative pond is about 4.24E-8 kg/(m^2·s).

A zero-dimension linear model can also be used to describe water salinization in the Bei-Da-Gang Reservior. The water salinization is modeled as:

$$C_t = 1.0792t + 108.35 . \quad (15)$$

The agreement between the prediction and the actual data verifies this model.

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