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Study on salt release intensity from sediments and influencing factors in coastal reservoirs: combining small-medium-large experiments

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ABSTRACT

Water salinization is one of the major environmental concerns that endangers water supply security in northern China. To investigate the salt release intensity and influencing factors in reservoirs' daily operation, a series of experiments covered small-medium-large scale were conducted in laboratory, outdoor pool and coastal reservoir, respectively. The findings regarding salt release process in the three experiments were similar: the release fluxes curves follow the power function, $y = ax^b$ (where y is the release fluxes, g m^{-2} d; x is the time, t; a and b are constants). The maximum salt cumulative release intensity in small-scale experiments was 14.83 g m^{-2} when stable, while that in medium-scale was 1,170.11 g m^{-2} (79 times larger), and that in large-scale experiments was 1,875.02 g m^{-2} (126 times larger). Water salinization was found to be more severe under the conditions featured by higher sediment salt content, higher temperature, lower operating water level and more intense disturbance of wind and rainfall, respectively. Furthermore, importing low Cl^- concentration overlying water promoted salt release from sediment, and exchanging water frequently could remove the accumulated salt in water body. These findings could help to better estimate the salt release intensity and thus improve the construction, operation and management process of the coastal reservoirs.

Keywords: Coastal reservoir; Cumulative release intensity; Release flux; Influencing factors; Countermeasures

1. Introduction

Water resources scarcity presents a serious, global problem [1–3]. Particularly China with extremely uneven spatio-temporal distribution of water resources has been one of the most water-scarce countries in the world [4]. The demand of water is, however, increasingly rising due to the rapid blooming urbanization. The contradiction between supply and demand of freshwater resources becomes a critical factor limiting the development of those economic growing regions [5]. Numerous reservoirs are consequently built for storing daily-use freshwater or spare water to relieve the stress of water supply, and in this way civil water quantity can be guaranteed. However, deteriorating water quality such as water eutrophication and salinization frequently plagues reservoirs as a new risk of water resources shortage in recent years [6]. Reservoir eutrophication is widely realized to bring harmful algal blooms and cause water crisis in many areas [7,8], while little attention has been paid

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on water unavailability problems caused by salinization in coastal reservoirs. As a matter of fact in coastal areas with serious sediment salinization and high-salinity groundwater, salinization problem has become another enormous threat to the security of reservoir water supply besides eutrophication [9,10].

Tianjin, an important industrial base and port city in northern China, is located in the southeast of the capital, Beijing, and is short of water resources, accounting for only 1/11 of the national average water resources. In order to solve the problem of serious water shortage in Tianjin, particularly in coastal areas, the South-to-North Water Diversion Project is implementing to ensure sufficient freshwater supply. Beitang Reservoir and Beidagang Reservoir are two regulating reservoirs in coastal areas of Tianjin. There is a high risk of salinization in these reservoirs after water diversion [11], which will affect the safety of water supply. Considering the special geographic position of coastal areas and its urgent demand of water resources, it is necessary to explore the influencing factors of water salinization and relevant mechanisms behind them, which will be of guiding significance to lower the risk of reservoir salinization.

A body of studies has been done concentrating on salt exchange across the water–sediment interface and the mechanisms of water salinization [12–15]. The laboratory column and flume experiments were widely carried out to explore the regularities of salt release and reveal the releasing mechanisms in coastal reservoirs. Generally, reservoir salinization may be influenced by environmental conditions (e.g., saline sediment, shallow underground salt water, salty runoff inflow and sea water intrusion), and some climatic and meteorological factors (e.g., rainfall, wind, temperature and atmospheric sedimentation). Zhao et al. [11] found that mass transfer process of salt from the saline sediment was the main cause of water salinization in Beidagang reservoir, accounting for 80% of total chloride increment. In addition, wind and temperature are regarded as two critical driving factors to control water salinization. Wind forcing strengthens the water disturbance, causing stronger effects of convective diffusion and molecular diffusion, which makes the salt fluxes from the sediment larger than that in the calm condition. Water temperature can enhance the molecular motion and sequentially salt diffusion from the sediment. For example, the flux of salt release from sediment increased by 89% when the temperature increased from 5°C to 15°C [4]. Wind and temperature can also accelerate the evaporation–concentration process of salty water. Such process occupies a relatively large proportion in the total increment of chloride concentration in coastal reservoirs. Besides these experiments, several modeling simulation methods have been used to predict the dynamic flow distribution and variable salinity process under different operation modes, aiming at finding strategies to mitigate the effect of the water salinization problem [16–20]. However, previous studies on reservoir salinization and relevant mechanisms were mainly focused on the stage before the reservoir proposed [21] or at most the initial stage of reservoir operation. Moreover, sediments used in the previous experiments were from dried and sieved sediment or remixed mud, with the original physical properties (e.g., porosity, permeability) changed, and solutes exchange between sediment and overlying water affected, which therefore could not truly represent the regularities of salt release in actual reservoirs.

The overall objective of this paper is to explore the regularities of salt release intensity and the influencing factors in coastal area reservoirs. Long-term laboratory experiments with in situ sediment columns (in small scale) and pool experiments (in medium scale) were integrated to imitate the process of sediment salt release. Contrasted with the results of reservoir operation data (in large scale) in actual operation, the regularities of salt release intensity were verified.

2. Materials and methods

2.1. Field sampling

Beitang Reservoir and Beidagang Reservoir are two typical regulating reservoirs located in coastal area of Tianjin. Beitang Reservoir (117°38′E~117°41′E, 39°06′N~39°08′N) was constructed in 1974 which covers an area of 7.43 km^2 and the storage capacity is 39.77 million m^3. Beidagang Reservoir (117°11′E~117°37′E, 38°36′N~38°50′N) was built in the same year, with a covering area of 164 km^2 and a capacity of 0.50 billion m^3. As the residential scale expanded, the land use patterns around Beitang Reservoir were changed. A lot of domestic sewage and industrial waste inputs resulted in a rising risk of water pollution to Beitang Reservoir. So a new reservoir was proposed to be constructed as an alternative urgently. The new reservoir named Ningchegu Reservoir was planned to locate in a flood detention area at the junction of two rivers (117°34′E~117°37′E, 39°10′N~39°12′N), to the west of Chaobaixin River and to the north of the Yongdingxin River. The area of Ningchegu Reservoir will be 6.2 km^2, with a capacity of 30.2 million m^3. Currently the northern part of Ningchegu Reservoir is shrimp ponds used for *Penaeus orientalis* (a kind of shrimp in China) culture. The locations of the three reservoirs are shown in Fig. 1.

There were 18, 25 and 13 sampling points set for collecting sediment specimens in Beitang Reservoir, Beidagang Reservoir and Ningchegu Reservoir, respectively. The sampling points were evenly distributed in each reservoir. The surficial sediments of 1 m depth were collected in sealed plastic bags using a sediment sampler (04.02.SC, Eijkelkamp, Holland) and carried back to the laboratory. The sediment samples were naturally air dried, ground and shifted in the laboratory, and used for the determination of salt content.

The contour maps of Cl^- content in surficial sediment of Beitang Reservoir, Beidagang Reservoir and Ningchegu Reservoir are presented in Fig. 2, showing the different horizontal distribution features of salty sediments in the three reservoirs. In Beitang Reservoir, the range of Cl^- content in the surficial sediment was 0.009%–0.141% with the lowest Cl^- content in the middle part of the reservoir. Beidagang Reservoir had the higher level of Cl^- content in surficial sediment than Beitang Reservoir. The Cl^- content in the surficial sediment of Beidagang Reservoir ranged from 0.050% to 0.600% with the highest Cl^- content in the middle, which was contrary to the distribution characteristics of Beitang Reservoir. The Cl^- content of surficial sediments in Ningchegu Reservoir was the highest among the three reservoirs, varying from 0.340% to 0.900% and presenting a trend of increase from south to north.

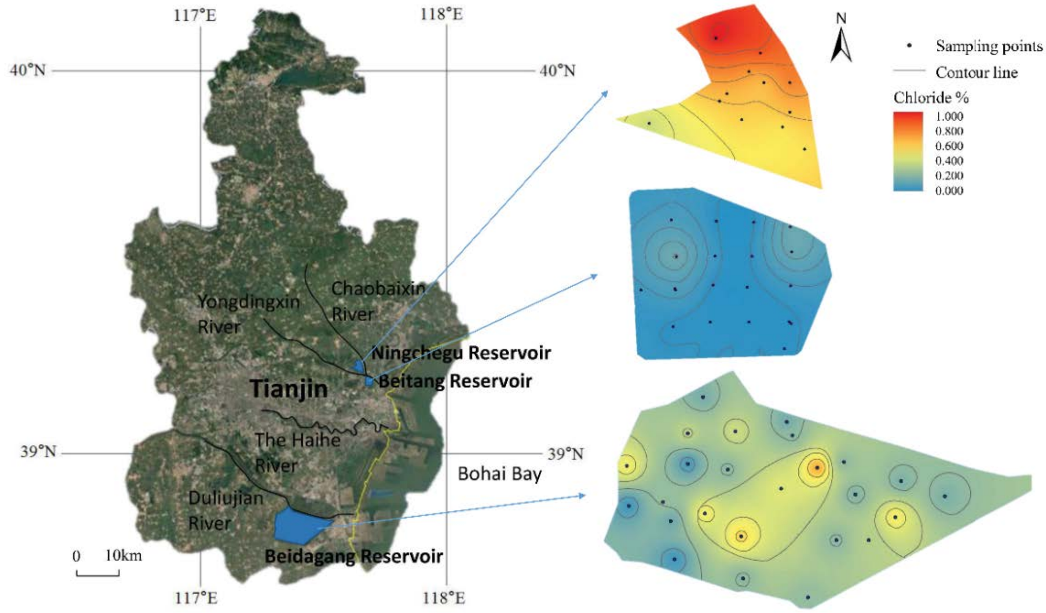

Fig. 1. Locations and salt distribution features of surficial sediments in Beitang Reservoir, Beidagang Reservoir and Ningchegu Reservoir.

2.2. Experimental setup

The experiments were performed in different scales to explore the influencing factors of salt release regularities from sediments. Relative works have been lasted for a long period of time from 2005 till now.

2.2.1. Laboratory experiment (small scale)

Laboratory experiments were performed using the sediments from the three reservoirs and here we take the experiments using samples from Beitang Reservoir as an example for expatiation. The sediment cores were sampled from different points with a depth of 0–0.6 m using a drill. The cores were filled into PVC tubes with a diameter of 75 mm and taken back to the laboratory under constant temperature. The custom-made Perspex tubes were then connected on the top of PVC tubes and the joints were sealed. Three water holes were placed at the bottom of the sediment, the sediment–water interface and the middle of the overlying water for periodical monitoring of salt changes in overlying water (Fig. 2a). After assembly, the overlying water was slowly injected above the sediments using a siphon pipe. The device was made and deployed for further incubation under different controlling conditions as shown below:

Salt content of sediments: three columns labeled 1#, 2# and 3# were set using sediments of different salt contents (0.012%, 0.021% and 0.043%, representing a low, medium and high level of sediment salinization, respectively). The deionized water was filled into the columns with a depth of 1 m.

Cl^- concentration of overlying water: two columns labeled 4# and 4#′ were set with overlying water of different salt concentrations (C_{Cl^-} = 325.9 mg L^{-1} water from Beitang Reservoir and the deionized water, respectively). The depth of overlying water was 1 m and the sediments used in the two columns were from the same sampling site (C_{Cl^-} = 0.040%).

Water depth: two columns labeled 5# and 5#′ were set with different water depths of 1 and 1.5 m, respectively. The sediments were from the same sampling site (C_{Cl^-} = 0.066%), and the deionized water was used in both columns.

Disturbance: Two columns labeled 6# and 6#′ were set as a contrast to evaluate the effect of disturbance on sediment salt release. The column 6#′ was disturbed with a blade in the overlying water at a rate of 30 rpm for 3 min each 3 h, with no disturbance in column 6#. The sediments used in the two columns were collected from the same sampling site (C_{Cl^-} = 0.011%) and the overlying water (1 m, C_{Cl^-} = 4.0 mg L^{-1}) was sampled from the middle route of the South-to-North Water Diversion Project.

Temperature: three columns labeled 7#, 7#′ and 7#′′ were set in the thermostat with different temperatures of 5°C , 10°C and 30°C, respectively. The sediments in the columns were from the same sampling site (C_{Cl^-} = 0.014%) and the depth of deionized water was 1 m.

Water exchange: after the temperature experiment was finished, the salty overlying water was exchanged for fresh deionized water in all the columns for continuous observation.

2.2.2. Pool experiments (medium scale)

Pool experiments were performed in a tested pool under the natural state. The tested pool was dug on the south east of Ningchegu Reservoir, with the shape of an inverted trapezoidal platform. The side length in the top of the tested pool is 22 m × 22 m and that in the bottom is 18 m × 17 m, with a north–south slope ratio of 1:1.2 and an east–west slope ratio of 1:1.5 (Fig. 2b). The initial water level and capacity of

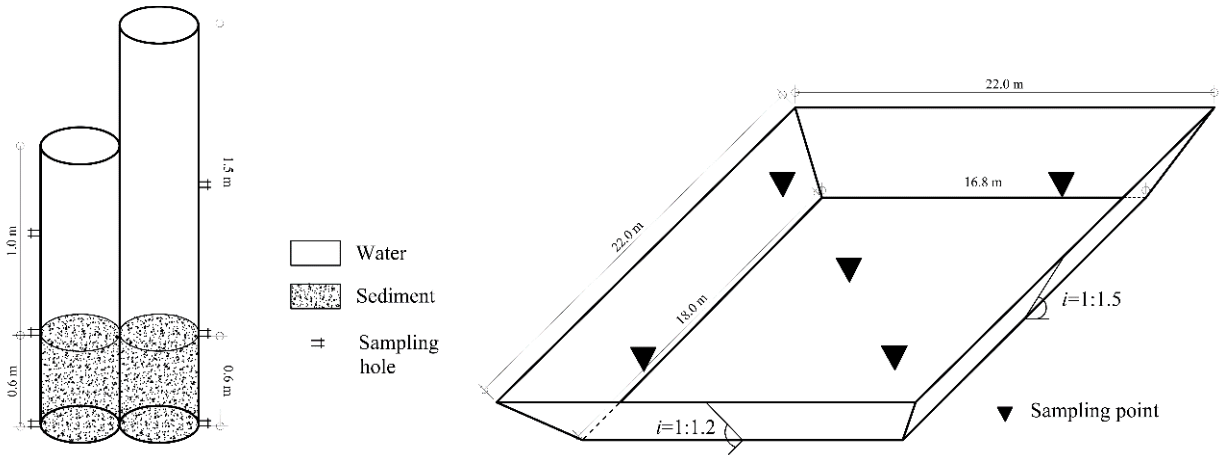

Fig. 2. Schematic diagram of laboratory experiments and pool experiments. (a) The column 5# (left) and 5#′ (right). The settings of other columns were similar to 5#; (b) The depth of the tested pool was 1.67 m.

the pool were 1.21 m and 434 m^3, respectively, after impounding water from Yongdingxin River (C_{Cl^-} = 556.0 mg L^{-1}). As the bottom elevation of reservoir was higher than the highest groundwater level in the history, the influences of groundwater supply can be ignored.

Five points at the center and four corners were set for monitoring water level and Cl^- concentrations. Water levels were measured at the center point and water samples were collected from all the five points at the same time. Daily rainfall data were provided by the local hydrologic station. The concentration of Cl^- in rainfall was measured twice at random during the whole observation period.

2.2.3. Beitang Reservoir experiments (large scale)

Beitang Reservoir is a closed plain reservoir without any tributary rivers inflow. Considering the relatively simple hydrological and terrain conditions, Beitang Reservoir was chosen as an ideal area for the large-scale experiments. The experiments were carried out in the natural condition, totally exposed to the original geographic environment and climate environment. Inflow water was pumped from Chaobaixin River during the flood period. Water was impounded for three times and the total amount was 11 million m^3. After impounding, the water level in Beitang Reservoir reached 6.98 m. The inflow data and Cl^- concentrations of inflow water were obtained at the inlet sluice. The Cl^- concentrations of the reservoir water were obtained from nine sampling points set uniformly in the reservoir.

2.3. Sampling and chemical analysis

In laboratory experiments, samples were collected from the upper two sampling holes after 1, 2, 5, 10 d and then every 5 d until the systems become stable. In addition, to avoid the errors caused by changing water depths, the tubes were replenished with the same amount of water after samples being taken each time and the Cl^- quantity taken away would be recorded. In pool experiments, water in the tested pool were sampled on day 1, day 3, day 5, day 10, day 15, day 20, and then every 10 d until day 80 and day 100, respectively. In Beitang Reservoir experiments, the water samples were obtained from each sampling point on day 1 and every 5 d till day 141. The Cl^- concentrations of all the samples were analyzed by ion chromatograph (ICS-2000, Dionex, USA).

2.4. Calculation and statistical analysis

The calculation formulas of the cumulative salt release intensity and fluxes are as follows [22]:

$$J = \frac{\sum_0^t M_t}{A_t} \tag{1}$$

$$F = \frac{\sum_0^t M_t}{tA_t} \tag{2}$$

where J is the cumulative salt release intensity, F is the salt release flux, M_t (mg) is the increment of salt releasing from the sediment from t to t-Δt, A_t (km^2) is the sectional area of the tubes or the water surface area at t.

In laboratory experiments, pool experiments and Beitang Reservoir experiments, M_t were calculated using different formulas.

In laboratory experiments, the calculation formula is as follows:

$$M_t = V\left(C_t - C_{t-\Delta t}\right) + V_0 C_{t-\Delta t} \tag{3}$$

where V (L) is the volume of overlying water, C_t (mg L^{-1}) is the Cl^- concentration in the overlying water at t, $C_{t-\Delta t}$ (mg L^{-1}) is the Cl^- concentration in the overlying water at t-Δt, V_0 (L) is the volume which is taken from the overlying water used for testing.

In pool experiments and Beitang Reservoir experiments, M_t was calculated by mass balance model.

The water balance equation is as follows:

$$W_{t+\Delta t} = W_t + W_{\text{in}} + h_r \times A_t - W_{\text{out}} - W_l - h_e \times A_t \tag{4}$$

where $W_{t+\Delta t}$ (10^4 m^3) is the capacity of reservoir at $t+\Delta t$, W_t (10^4 m^3) is the capacity of reservoir at t, W_{in} (10^4 m^3) is the water diversion quantity in Δt, h_r (cm) is the rainfall in Δt, A_t (km^2) is the water surface area at t, W_{out} (10^4 m^3) is the water discharge in Δt, W_l (10^4 m^3) is the leakage in Δt, h_e (cm) is the evaporation in Δt.

The water quality equilibrium equation is as follows:

$$W_{t+\Delta t}C_{t+\Delta t} = W_tC_t + W_{in}C_{in} + h_rA_tC_r + M_t - W_lC_t - W_{out}C_t \quad (5)$$

where $C_{t+\Delta t}$ (mg L^{-1}) is the Cl^- concentration of reservoir at $t+\Delta t$, C_t (mg L^{-1}) is the Cl^- concentration of reservoir at t, C_{in} (mg L^{-1}) is the average Cl^- concentration of the transferred water in Δt, C_r (mg L^{-1}) is the average Cl^- concentration of the rainfall in Δt (5.42 mg L^{-1}), M_t (mg) is the amount of salt releasing from the sediment at t.

The maps were drawn by Arcmap 10.1. All the graphs were plotted by OriginPro 2016, and statistical analysis was accomplished by SPSS 24.0.

3. Results

3.1. Laboratory experiments

Salt release intensity in 1#, 2# and 3# columns increased continuously from the beginning of experiment and reached stable on the 50th d as shown in Fig. 3a. The cumulative release intensity of Cl^- in 1#, 2# and 3# was 5.56, 6.19 and 7.09 g m^{-2}, respectively, when it was stable. Meanwhile, the release intensity of 3# was larger than that of 2#, and 2# had greater intensity than 1#, which was consistent with the salt contents in sediment (3# > 2# > 1#). The release fluxes of salt decreased sharply in the first 5 d of experiment and gradually slowed down till the experiment finished (Fig. 4a). Similarly, larger salt contents of sediments resulted in larger release fluxes in overlying water (3# > 2# > 1#). The salt release fluxes were nearly the same after 50 d, with values of 0.09, 0.10 and 0.11 g m^{-2} d^{-1} in 1#, 2# and 3# respectively.

The Cl^- contents in sediments and the corresponding cumulative release intensity when stable of the three reservoirs

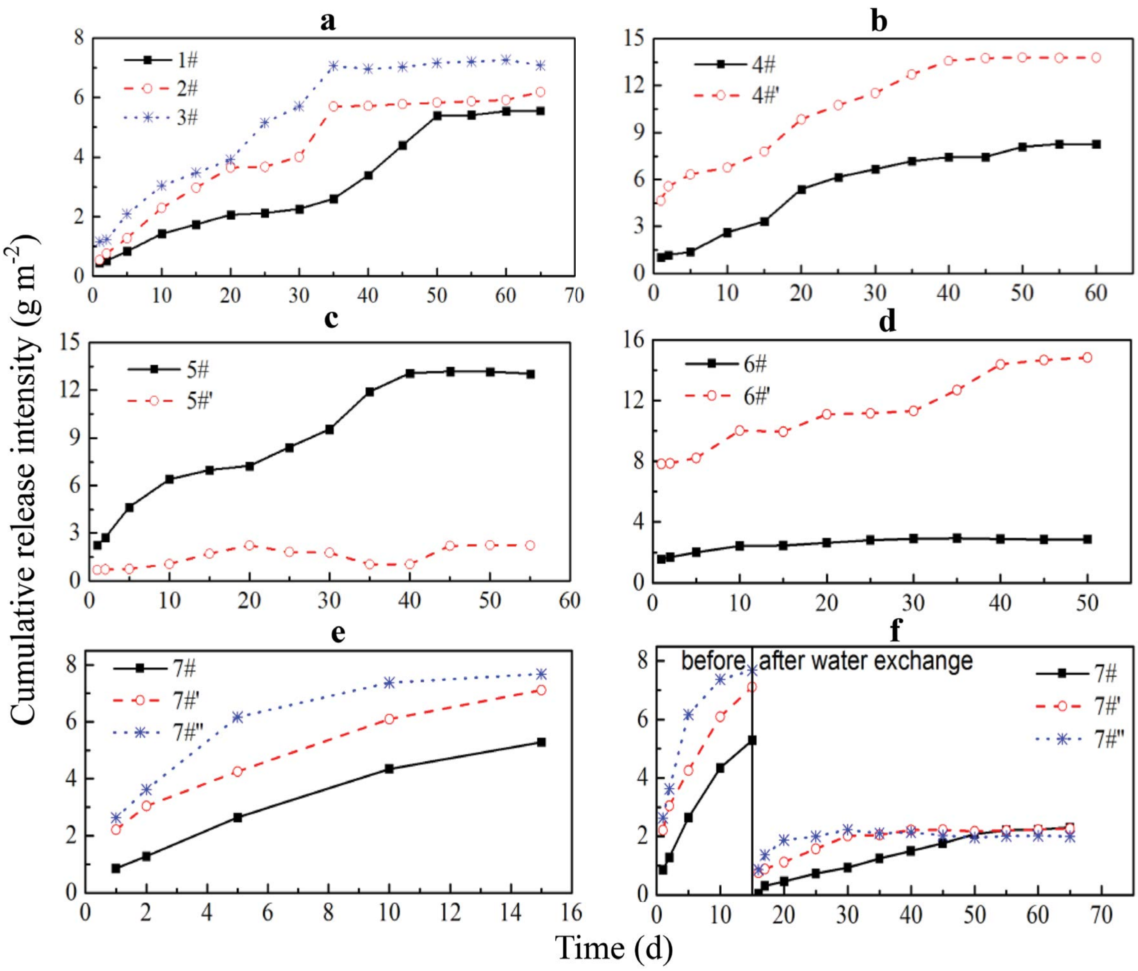

Fig. 3. Cumulative sediment release intensity in different conditions. (a) under the influence of sediment salt content, column 1#–0.012% Cl^- content of sediment; column 2#–0.021% Cl^- content of sediment; column 3#–0.043% Cl^- content of sediment; (b) under the influence of Cl^- concentration of overlying water, column 4#-Beitang Reservoir water (C_{Cl^-} = 325.9 mg L^{-1}); column 4#'–deionized water; (c) under the influence of water depth, column 5#–1.0 m water depth; column 5#'–1.5 m water depth; (d) under the influence of disturbance, column 6#–no disturbance; column 6#'–disturbance; (e) under the influence of temperature, column 7#–5°C; column 7#'–10°C; column 7#''–30°C; (f) under the influence of water exchange, overlying water was exchanged for fresh deionized water.

were shown together in Table 1. It turned out that the cumulative release intensity was increased with a higher Cl^- content in sediment. Moreover, significantly positive correlation was found between the cumulative release intensity and the Cl^- content in sediment when stable (R^2 = 0.98**, p-value < 0.001), using the Pearson's correlation coefficients.

The salt release regularities of 4# and 4#′ columns with different Cl^- concentrations of overlying water (column 4#′ < 4#) were compared (Figs. 3b and 4b). The cumulative salt release intensity in column 4#′ was larger than that in column 4# significantly (T-test, p-value < 0.001). The average value of the cumulative release intensity in the first 50 d in the column 4#′ was 2.01 times larger than that in the column 4#. After the 50th d, the cumulative release intensity of the two columns tended to be stable, the value of which in column 4#′ was 13.80 g m^{-2}, reaching 167% of column 4# (8.27 g m^{-2}). The release fluxes of salt in column 4#′ was also larger than column 4#, particularly during the first 15 d (Fig. 4b). The average salt release flux before day 15 in the column 4#′ was 3.25 times larger than that in the column 4#. The stable value of release fluxes in column 4#′ and 4# was 0.28 and 0.15 g m^{-2} d^{-1}, respectively.

The process of salt release in 5# and 5#′ columns under different water depths (column 5#′ > 5#) is shown in Figs. 3c

Table 1
Relationship of Cl^- content in sediment and cumulative release intensity when stable. Beitang Reservoir had three sets of data, Beitang Reservoir had three sets of data and Ningchegu Reservoir had two sets of data

	Beitang Reservoir			Beidagang Reservoir			Ningchegu Reservoir	
Cl^- content in Sediment (%)	0.011	0.021	0.043	0.300	0.390	0.580	0.300	0.350
Cumulative release intensity(g m^{-2})	5.56	6.19	7.09	112.00	162.36	198.20	120.0	140.60

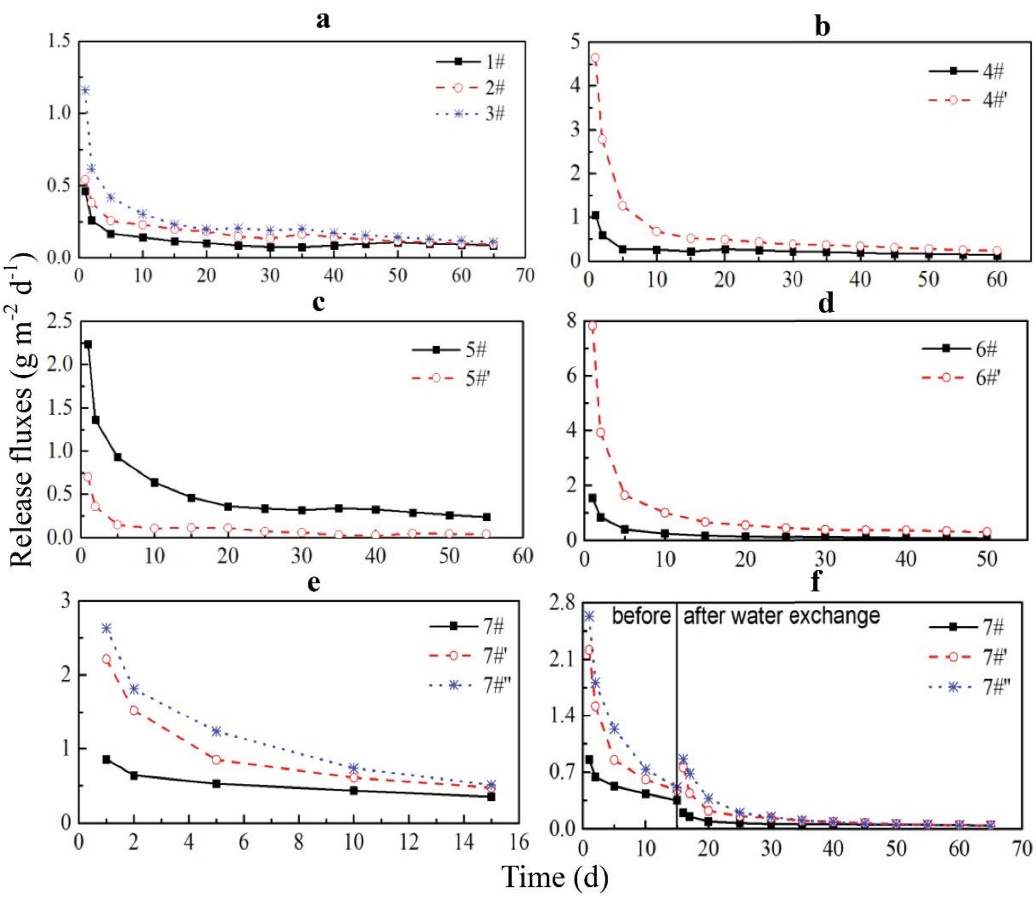

Fig. 4. Sediment release fluxes in different conditions. (a) under the influence of sediment salt content, column 1#-0.012% Cl^- content of sediment; column 2#-0.021% Cl^- content of sediment; column 3#-0.043% Cl^- content of sediment; (b) under the influence of Cl^- concentration of overlying water, column 4#-Beitang Reservoir water (CCl^- = 325.9 mg L^{-1}); column 4#′-deionized water; (c) under the influence of water depth, column 5#-1.0m water depth; column 5#′-1.5m water depth; (d) under the influence of disturbance, column 6#-no disturbance; column 6#′-disturbance; (e) under the influence of temperature, column 7#-5°C; column 7#′-10°C; column 7#′′-30°C; (f) under the influence of water exchange, overlying water was exchanged for fresh deionized water.

and 4c. The cumulative release intensity and release fluxes in column 5#′ were far lower than column 5#. The water depth was 1.0 m in column 5#, and the cumulative salt release intensity continuously increased since the beginning, and reached stable on the 40th d with the value of 13.04 g m^{-2}. While, in the column 5#′ when water depth was increased to 1.5 m, the cumulative release intensity of salt slightly fluctuated in the vicinity of 2.0 g m^{-2}, and the stable value was 2.23 g m^{-2}, only reaching 17.1% of that in the column 5#. Similar regularities on salt release fluxes were also found between the column 5#′ and 5#. The stable value of salt release fluxes in the column 5#′ was 0.04 g m^{-2} d^{-1}, which was only 16.7% of that in column 5#.

The regularities of salt release between 6# and 6#′ columns with and without disturbances were compared, showing that disturbance greatly increased the cumulative release intensity and release fluxes (Figs. 3d and 4d). The cumulative release intensity of Cl^- in column 6#′ with disturbance was much greater than that in column 6# without any disturbance, with an average value of 11.17 g m^{-2} in 6#′, reaching 4.47 times of that in 6# (2.50 g m^{-2}). The stable value of the cumulative release intensity in column 6#′ reached 14.83 g m^{-2} on the 50th day, and was 5.18 times of that in column 6# (2.86 g m^{-2}). The average value of salt release fluxes in column 6#′ (1.48 g m^{-2} d^{-1}) was 4.67 times larger comparing with that in column 6# (0.32 g m^{-2} d^{-1}). The release fluxes in column 6# and 6#′ reached 0.06 and 0.30 g m^{-2} d^{-1}, respectively, when they were stable.

The influences on salt release with different temperatures (7#-5°C, 7#′-10°C and 7#′′-30°C) were studied, showing that the cumulative release intensity and release fluxes of Cl^- increased with the increase of temperature (Figs. 3e and 4e). The average of the cumulative Cl^- release intensity in 7#, 7#′ and 7#′′ in 15 d was 2.88, 4.54 and 5.49 g m^{-2}, respectively. The cumulative release intensity was increased by 57.7% and 20.9% when the temperature rising from 5°C to 10°C and 10°C to 30°C, respectively. Meanwhile, the average release fluxes of Cl^- were 0.56, 1.13 and 1.39 g m^{-2} d^{-1} in 7#, 7#′ and 7#′′, respectively. The release fluxes were increased by 101.6% and 22.2% when the temperature rising from 5°C to 10°C and 10°C to 30°C, respectively.

The cumulative release intensity and release fluxes of the periods before and after water exchange were presented in Figs. 3f and 4f, showing a great decrease after water exchange. The cumulative release intensity before the water exchange was 5.28, 7.11 and 7.68 g m^{-2} in column 7#, 7#′ and 7#′′, respectively, while the values were sharply decreased after water exchange, then increased slowly and was stable at 2.31, 2.27 and 2.00 g m^{-2} in 7#, 7#′ and 7#′′, respectively (Fig. 3f). The maximum decrement reached up to 74.0% between before and after water exchange in these three columns. Meanwhile, salt release fluxes were declined after water exchange, except the instantaneous bounce at the beginning period after water exchange, and tended to be almost the same and low since the 30th day. The stable value of salt release fluxes was 0.05, 0.05 and 0.04 g m^{-2} d^{-1} in 7#, 7#′ and 7#′′, respectively.

Whether the experiments were in different controlling conditions or not, a common phenomenon was found that the cumulative release intensity would always increase over time while the release fluxes would decrease, and finally tended to be stable at last. Furthermore, the changes of release fluxes against time in all the columns were in accordance with the power function equation. The corresponding equations and coefficients of determination were shown in Table 2. The power function equation was summarized to describe the power exponential relationship between salt release fluxes and time as follows:

$$y = ax^b \tag{6}$$

where y is the release fluxes (g·m^{-2}·d), x is the time (t), a and b are constants.

3.2. Pool experiments

The general trend of sediment salt release in the tested pool after impounding was similar to the trends of laboratory experiments performed in different conditions (Fig. 5). The cumulative salt release intensity was significantly increased from 115.39 to 1,170.11 g m^{-2}, with the increment of 914.0% during the 100-d experiment. Moreover, the increment of cumulative salt release intensity in the first 30 d accounted for 75.1% of the total process (Fig. 5a). Meanwhile, the release fluxes were gradually going down from 115.39 to 11.70 g m^{-2} d^{-1} with time. Especially in the first 15 d, the release flux was decreased by 78.6% of the total decline (Fig. 5b). In contrast to laboratory experiments, although the variation tendency was alike in the test pool, the cumulative release intensity was far greater. The largest value of cumulative release intensity in laboratory experiment was found in column 7#′ under the condition of disturbance, with the value of 14.83 g m^{-2} when stable. Nevertheless, cumulative release intensity in tested pool when stable was 1,170.11 g m^{-2}, reaching 79 times of the maximum value in the laboratory experiments.

Table 2
Relationship curves of release fluxes under different influencing factors

Influencing factors	Samples	Relation curves	R^2
Salt content of the sediments	1#	$y = 0.3447x^{-0.365}$	0.8593
	2#	$y = 0.5274x^{-0.383}$	0.9677
	3#	$y = 0.9876x^{-0.500}$	0.9756
Cl^- concentration of overlying water	4#	$y = 0.7987x^{-0.585}$	0.9052
	4#′	$y = 4.2047x^{-0.707}$	0.9897
Water depth	5#	$y = 2.1011x^{-0.537}$	0.9858
	5#′	$y = 0.6222x^{-0.715}$	0.9101
Disturbance	6#	$y = 1.5468x^{-0.827}$	0.9988
	6#′	$y = 6.9445x^{-0.830}$	0.9935
Temperature	7#	$y = 0.8370x^{-0.304}$	0.9826
	7#′	$y = 2.2169x^{-0.570}$	0.9985
	7#′′	$y = 2.7618x^{-0.585}$	0.9819
Water exchange	7#	$y = 0.1804x^{-0.344}$	0.9624
	7#′	$y = 0.7544x^{-0.694}$	0.9914
	7#′′	$y = 1.1483x^{-0.824}$	0.9807

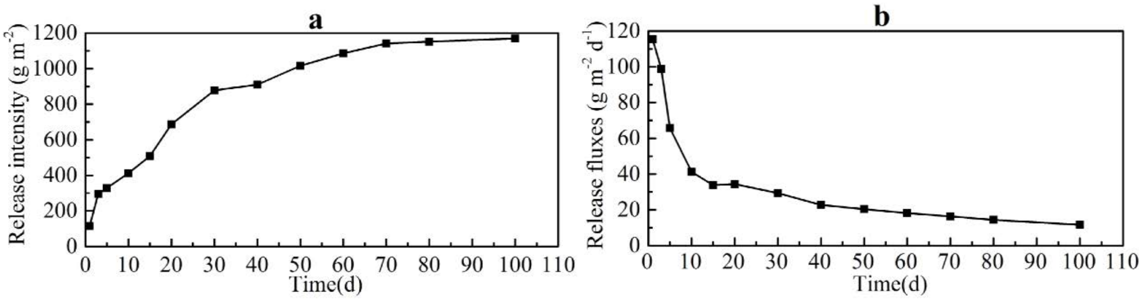

Fig. 5. Cumulative sediment release intensity and fluxes in the tested pool. (a) cumulative sediment release intensity; (b) sediment release fluxes.

3.3. Salt release in Beitang Reservoir

The cumulative release intensity and release fluxes in natural state after water impounding process were presented in Fig. 6, showing a tendency of increasing constantly and decreasing gradually, respectively. Cumulative release intensity was increased from 370.06 to 1,875.02 g m^{-2}, with the increment of 406.7% during the 140-d experiment (Fig. 6a). The release fluxes were decreased from 370.06 to 13.30 g m^{-2} d, which decreased by 93.6% in the first 20 d (Fig. 6b). Cumulative release intensity in Beitang Reservoir experiment was two orders of magnitude larger than that in laboratory experiments, compared with the largest cumulative release intensity in laboratory experiments (14.83 g m^{-2}, under the condition of disturbance when stable). And compared with pool experiment, in which the value of the release intensity when stable (1,170.11 g m^{-2}) was about 62.4% of that in Beitang Reservoir experiment (1,875.02 g m^{-2}). The release fluxes were 13.30 and 11.70 g m^{-2} d^{-1} in Beitang Reservoir experiment and pool experiment, respectively when the releasing process got stable, showing no giant differences.

4. Discussion

4.1. Influencing factors

Several environmental and hydrological conditions including salt content of the sediments, Cl^- concentration in the overlying water, water depth, temperature, disturbance (e.g., wind) and water exchange have been recognized as main influencing factors in controlling salt release from the sediment in coastal reservoirs [4,13].

In this study, the salt release intensity and fluxes from the sediments increased with the higher salt content of the sediments, but decreased with the higher Cl^- concentration in overlying water. According to the Fick's first law, a higher salt content in sediments or lower Cl^- concentration in overlying water can enlarge the concentration gradient of Cl^- from the sediments to the above water, promoting the sediment salt release to the overlying water, and thus resulting in the increase of salt release intensity and fluxes. Moreover, the cumulative release intensity when stable was found with a linear and proportional relation with the initial Cl^- content of sediments, and the fitted curve was calculated, with high correlation coefficient. Therefore, high salt content of sediments and impounding water with low Cl^- concentration are two driving factors to promote salt release from sediments. Additionally, the cumulative release intensity when stable can be estimated through the linear relationship between initial Cl^- content of sediments and the cumulative release intensity in laboratory scale.

The water depth is another factor influencing salt release from the sediment. The salt release intensity and fluxes were decreased under higher water depth. This is due to a higher water depth implying larger pressure of water column on the sediment, the interspace of which will be compressed, lowering the porosity and thus lengthening the diffusion distance, consequently inhibiting the salt release from the sediments. This is the process commonly called salinization

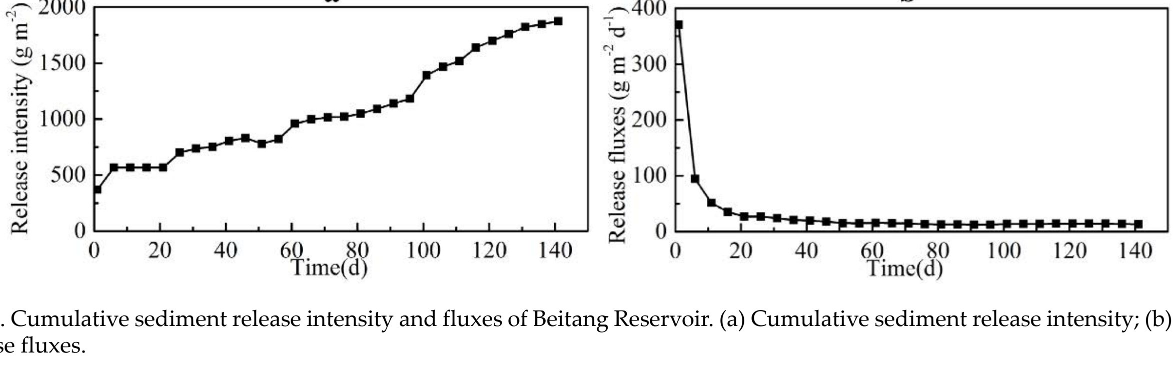

Fig. 6. Cumulative sediment release intensity and fluxes of Beitang Reservoir. (a) Cumulative sediment release intensity; (b) sediment release fluxes.

suppressing, so that maintaining proper water level plays a vital role in the actual operation of coastal reservoirs [23,24].

For disturbance, the results showed that the sediment salt release is faster under the disturbance of wind, which confirmed the results of an experiment carried in Veluwe Lake [25], that release flux of solutes exchanging from sedimentwater interface is greater under the influence of the wind than that in static state [26]. In fact, disturbance makes the upper and lower water fully mixed, which promote the convective diffusion so that the salt release from the sediment is more and faster than the static condition which merely depending on molecular diffusion [27].

In general, the solubility of chemicals in water and their adsorption and desorption on solid surfaces are related to temperature [28]. The influence of temperature essentially manifested in changing the rate of molecular motion. As the temperature increased, the molecular motion becomes active and the release rates will be accelerated, which indicates that higher temperature favors salt release. Moreover, climate change has a long-term effect on salinity, considering the increasing temperature and severe evaporation [29–31].

Water exchange can greatly reduce the average level of Cl^- concentration in overlying water by taking away the accumulated salt in the overlying water releasing from the sediment. And it is the most commonly used method for reducing salt content of coastal reservoirs [32,33]. In addition, the bounce at the point of water exchange was caused by unavoidable initial disturbance temporarily, which will not affect the overall trend.

In addition, the cumulative release intensity and release fluxes show some common regularities in spite of its variation in various situations. The cumulative release intensity was constantly increased at the beginning, reached a stable value in the end, and the release fluxes were largest initially, gradually decreased and tended to be stable ultimately. The salt release is owing to the concentration gradient between sediments and overlying water, and the diffusion flux is proportional to the concentration gradient, which is corresponding to the first Fick's law. The concentration gradient of Cl^- between sediments and overlying water was maximum in the beginning, the salt released rapidly. With the overlying water Cl^- concentration rising, the concentration disparity become smaller, the releasing rate slowed.

4.2. Release regularities in three-scale experiments

The general trend of salt release intensity and fluxes in pool experiment and the actual operation experiment are similar to the laboratory experiments. What different is that there are some fluctuating sites not in line with the curve trend during the experiment period, which was attributed to the disturbance of heavy rainstorms (such as the 19th d of the pool experiment, the rainfall was 42.8 mm). In contrast to the laboratory experiments, the value of salt cumulative release intensity in outdoor experiments was far greater. In laboratory experiments, the maximum of the salt cumulative release intensity and fluxes appeared in 7#′ (under the influence of disturbance), which the values were 14.83 g m^{-2} and 0.30 g m^{-2} d^{-1} when stable. While in pool experiment, the cumulative release intensity and fluxes were 1,170.11 g m^{-2} and 11.70 g m^{-2} d^{-1} (79 times and 39 times than that in laboratory experiments) and in Beitang Reservoir experiment, they were 1,875.02 g m^{-2} and 13.30 g m^{-2} d^{-1} (126 times and 44 times than that in laboratory experiments), respectively. For pool experiment which was dug for a depth of 1.67 m, with shallow water in the tested pool, the effect of the new interface salt releasing will be relatively large considering the disturbance of impounding, rainfall and wind forcing. For Beitang Reservoir experiment, the salt release process will be affected by more strong dynamic conditions in the complex natural state. Moreover, the disturbance of wind and rainfall was magnified with the area becoming larger. In combination with the results in the laboratory, the sizable gap of the cumulative release intensity and fluxes between indoor and outdoor experiment was mainly owing to the following two reasons: one is the huge disparity of contact area (the area is 44.18 cm^2 in columns, 448.30 m^2 in tested pool, about 10^5 times larger than the former) and the other is that the complex and changeable field conditions such as the mixed disturbance of rainfall and wind forcing, which will make the molecular diffusion and the convective diffusion more faster. As for the pool experiment and Beitang Reservoir experiment which were both performed under the influences of natural conditions, the results showed no order of magnitude differences, probably because that the influence of area size is less prominent comparing with the other factors.

These release regularities concluded from the experiments are of great significance to propose control countermeasures on reservoir management [34]. The sediment salt content increases with the bottom elevation of Beitang Reservoir, Beidagang Reservoir and Ningchegu Reservoir raising owing to the influence of high salinity groundwater, which is consistent with the results in Li et al.'s study [35]. Therefore, it is suggested to heighten the dam rather than excavate if the reservoir is newly-built or the capacity need to be expanded before impounding. As for the influence of water depth, it is suggested that the reservoir should maintain at a high water level during actual operation, which can reduce the release intensity of Cl^- and the risk of groundwater recharge [36,37]. The overall salt concentration level will be increased under the influence of wind or rainfall disturbance, and sometimes lead to the sudden salt salinization phenomenon [38]. It is important to maintain routine real-time monitoring and propose pre-solutions plan. Seasonal variation will lead to the change of the water temperature of the whole reservoir, thus affecting the release of salt in the sediment. Therefore, it is suggested that the reservoir should not impound water in summer. Water exchange can lower the total Cl^- concentration level of the reservoir. Therefore, it is suggested to maintain certain frequency of water exchange, which can effectively reduce the salinization of reservoirs in coastal areas.

5. Conclusions

Salt release intensity and fluxes were influenced by salt content of sediments, Cl^- concentration of overlying water, water depth, temperature, disturbance and water exchange. The Cl^- concentration will increase in conditions of the high sediment salt content, high temperature, low operating water level and the intense disturbance of wind and rainfall, respectively. Meanwhile, importing low Cl^- concentration overlying water can promote salt release from sediment, and the accumulated salt in water body can be removed through exchanging water frequently. The cumulative salt release intensity will increase gradually and tend to be stable at last, while the release fluxes will decline by degrees and approach invariable ultimately as the system becomes stable, wherever in small-, medium- or large-scale experiments. Moreover, the fitted curves of the release fluxes with time follow the power function, $y = ax^b$. However, the release intensity in natural state is far more than that in laboratory experiments. The maximum of the salt cumulative intensity in small-scale experiments were found under the influence of disturbance, with the values of 14.83 g m^{-2} when stable. The results are two orders of magnitude far less than that in medium-scale and large-scale experiments (1,170.11 and 1,875.02 g m^{-2}, respectively). The continuous small-medium-large-scale experimental research laid a good foundation for the salt release theory in coastal reservoirs, and provided scientific and reliable countermeasures for the operation and management of the reservoirs. Based on the fundamental release regularities, keeping the higher operating water level of the reservoir and changing water more frequently in the operation period will contribute to controlling the water salinization problems in coastal reservoirs.

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References

[1] M. Dolatyar, T.S. Gray, Water Scarcity: A Global Problem?, In: Water Politics in the Middle East, M. Palgrave Macmillan, London, 2000, pp. 60–84.
[2] B.C. Moore, A.M. Coleman, M.S. Wigmosta, R.L. Skaggs, E.R. Venteris, A High Spatiotemporal Assessment of Consumptive Water Use and Water Scarcity in the Conterminous United States, Water Resour. Manage., 29 (2015) 5185–5200.
[3] Q.W. Zhou, S.T. Yang, C.S. Zhao, M.Y. Cai, H.Z. Lou, Y. Luo, L.P. Hou, Development and implementation of a spatial unit non-overlapping water stress index for water scarcity evaluation with a moderate spatial resolution, Ecol. Indic., 69 (2016) 422–433.
[4] L.P. Zhang, J. Xia, Z.F. Hu, Situation and problem analysis of water resources security in China, Resour Environ. Yangtze Basin, 18 (2009) 116–120.
[5] X.M. Wang, J.Z. Zhou, S. Ouyang, C.L Li, Research on joint impoundment dispatching model for cascade reservoir, Water Resour. Manage., 28 (2014) 5527–5542.
[6] G. Wen, X. Li, X.P. Qiu, X.Y. Cheng, Y.K. Sun, T.L. Huang, Characteristics of Water Pollution in Typical Reservoirs// Water Pollution and Water Quality Control of Selected Chinese Reservoir Basins, Springer International Publishing, 2016, pp. 25–94.
[7] D.J. Conley, H.W. Paerl, R.W. Howart, D.F. Boesch, S.P. Seitzinger, K.E. Havens, C. Lancelot, G.E. Likens, Ecology. controlling eutrophication: nitrogen and phosphorus, Science, 323 (2009) 1014.
[8] H.W. Paerl, H. Xu, M.J. Mccarthy, G.W. Zhu, B.Q. Qin, Y.P. Li, W.S. Garner, Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): the need for a dual nutrient (N & P) management strategy, Water Res., 45 (2011) 1973–1983.
[9] G.V. Dijk, A.J.P. Smolders, R. Loeb, A. Bout, J.G.M. Roelofs, L.P.M. Lamers, Salinization of coastal freshwater wetlands; effects of constant versus fluctuating salinity on sediment biogeochemistry, Biogeochemistry, 126 (2015) 71–84.
[10] M.R.R. Talukder, S. Rutherford, D. Phung, M. Zahirul islam, C. Chu, The effect of drinking water salinity on blood pressure in young adults of coastal Bangladesh, Environ. Pollut., 214 (2016) 248–254.
[11] W.Y. Zhao, Q.S. Wang, L.B. Wu, B. Zhang, X.Q. Wang, Qualitative analysis and quantitative simulation on Yin-Huang water salinization mechanism in Bei-Da-Gang Reservoir, J. Environ. Sci., 17 (2005) 853–856.
[12] A. Rimmer, The mechanism of Lake Kinneret salinization as a linear reservoir, J. Hydrol., 281 (2003) 173–186.
[13] C.L. Jiang, H.F. Pei, Reasons of water salinization and its prevention measures in Beitang Reservoir, Tianjin City, J. Lake Sci., 19 (2007) 42–433.
[14] X.L. Zhang, M.H. Zhu, X.L. Zheng, Test investigation for salt release from sediments in a polder reservoir under effects of environmental factors, Marine Sci. Bull., 29 (2010) 135–142.
[15] B. Zhang, X.L. Liu L, Z.L. Wang, J.Y. Han, X.F. Song, Isotopic and hydrochemical characteristics of salinization water in Beidagang Reservoir, Tianjin, J. China Hydrol., 37 (2017) 44–50.
[16] V.A. Post, H. Kooi, Rates of salinization by free convection in high-permeability sediments: insights from numerical modeling and application to the Dutch coastal area, Hydrogeol. J., 11 (2003) 549–559.
[17] A.N. Popov, G.A. Oboldina, Prediction of water salinity in the Yumaguzinskoe Reservoir under construction, Water Resour., 32 (2005) 192–199.
[18] C. Zhang, X.P. Gao, H.F. Zhu, S.X. Zhao, Water quality Control Technology of Beidagang Reservoir taking chlorine Ion as an example, J. Tianjin Univ. 45 (2012) 6–12.
[19] J. Gu, J.Z. Yang, W. Chen, X. Qin, Numerical analysis of the influence of saltwater intrusion on Qingcaosha Reservoir, Appl. Mech. Mater., 212–213 (2012) 216–220.
[20] Q.H. Ye, Y. Li, W. Wang, Y. Yang, Numerical simulation of water salinity change process in coastal reservoir influenced by sediment salt release, J. Hohai Univ., 43 (2015) 513–528.
[21] L.Q. Zhu, C.L. Jiang, Y.H. Wang, Y.M. Peng, P Zhang, A risk assessment of water salinization during the initial impounding period of a proposed reservoir in Tianjin, China, Environ. Sci. Process. Impacts, 15 (2013) 1743–1751.
[22] J. Liu, X.L. Zheng, L. Chen, C.C. Wu, Study on nitrogen and phosphorus release flux and release rule of reservoir sediment, J. Lake Sci., 39 (2012) 339–343.
[23] Q. An, Y.Q. Wu, S. Taylor, B. Zhao, Influence of the Three Gorges Project on saltwater intrusion in the Yangtze River Estuary, J. Environ. Geo., 56 (2008) 1679–1686.
[24] G.E. Pan, L.C. Huang, L.J. Jin, X.A. Zhu, Study on technology of fresh water storage of reservoirs on coastal areas, Water Conservancy Plann. Des., 2 (2004) 51–55.
[25] R. Portielje, L. Lijklema, Estimation of sediment-water exchange of solutes in lake Veluwe, The Netherlands, Water Res., 33 (1999) 279–285.
[26] J. Ahlgren, K. Reitzel, H.D. Brabandere, A. Gogoll, E. Rydin, Release of organic P forms from lake sediments, Water Res., 45 (2011) 565–572.
[27] J.S.D. Santos, E.D. Oliveira, R.E. Bruns, R.F. Gennari, Evaluation of the salt accumulation process during inundation in water resource of Contas river basin (Bahia–Brazil) applying principal component analysis, Water Res., 38 (2004) 1579–1585.
[28] C.A. Atkinson, D.F. Jolley, S.L. Simpson, Effect of overlying water pH, dissolved oxygen, salinity and sediment disturbances on metal release and sequestration from metal contaminated marine sediments, Chemosphere, 69 (2007) 1428–1437.
[29] T.D. Phan, J.C.R. Smart, O. Sahin, S.J. Capon, W.L. Hadwen, Assessment of the vulnerability of a coastal freshwater system to climatic and non-climatic changes: a system dynamics approach, J. Cleaner Prod., 183 (2018) 940–955.

[30] J. Susnik, L.S. Vamvakeridou-Lyroudia, D.A. Savic, Z. Kapelan, Integrated system dynamics modelling for water scarcity assessment: case study of the Kairouan region, Sci. Total Environ., 440 (2012) 290–306.
[31] S.M.S. Shokri-Kuehni, T. Vetter, C. Webb, N. Shokri, New insights into saline water evaporation from porous media: complex interaction between evaporation rates, precipitation, and surface temperature, Geophys. Res. Lett., 44 (2017) 5504–5510.
[32] X.Z. Mao, X.A. Zhu, F.Y. Chen, Q.W. Yu, B.Z. Weng, Study on accelerating water desalinization in a polder reservoir for storage of fresh water along the coast, Adv. Water Sci., 16 (2005) 773–776.
[33] G.Q. Jin, Y.M. Mo, M.D. Li, H.W. Tang, Y.Z. Qi, L. Li, D.A. Barry, Desalinization and salinization: a review of major challenges for coastal reservoirs, J. Coast. Res., 35 (2019) 664–672.
[34] X.J. Wang, H.T. Mao, H.X. He, D.G. Shao, Study on seepage control measures of plain reservoirs based on soil salinization after dam, Appl. Mech. Mater., 511–512 (2014) 805–810.
[35] Q.F. Li, M. Xi, Q.G. Wang, F.L. Kong, Y. Li, Characterization of soil salinization in typical estuarine area of the Jiaozhou Bay, China, Phys. Chem. Earth, S1 (2017) 51–61.
[36] H. Scarborough, O. Sahin, M. Porter, R. Stewart, Long-term water supply planning in an Australian coastal city: dams or desalination?, Desalination, 358 (2015) 61–68.
[37] V.P. Hai, S.I. Lee, Assessment of seawater intrusion potential from sea-level rise and groundwater extraction in a coastal aquifer, Desal. Wat. Treat., 53 (2015) 2324–2338.
[38] Z.W. Gao, Y.H. Li, Q.S. Zhao, L. Jie, S.Y. Ye, Time scale of the influence of Bay Reservoir sediment on water body salinization, Adv. Water Sci., 26 (2015) 221–226.