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ORIGINAL ARTICLE

Zhou Xun
Fang Bin
Chen Mingyou
Zhao Liang
Zhang Hua
Shen Ye

Predictive simulation of three exploitation schemes for the brines in the Bieletan section of the Charham Salt Lake, China

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Z. Xun (✉) · F. Bin · C. Mingyou
Z. Liang · Z. Hua · S. Ye
School of Water Resources and Environment, China University of Geosciences, Xueyuan Road 29, 100083 Beijing, People's Republic of China
E-mail: zhouxun@cugb.edu.cn
Tel.: +86-10-82320674
Fax: +86-10-82321081

Abstract Potassium-rich halite ores and brines occur in the Charham Salt Lake area in the Chaidam Basin in northwest China. The mean 14.3 g/l of potassium in the brines in the near-surface halite aquifer makes the Charham Salt Lake an important base for production of potassium fertilizer in China. About 30×10^4 m^3/day of brines has been pumped from the current ditches in the Bieletan section in the west of the area, creating a cone of depression in the water table near the ditch system. A two-dimensional mathematic model describing the flow of the brines is established to predict the changes in the water table. The flow domain was discretized into 1,185 triangular elements with 641 nodes. Data of brine production through pumping ditches from November 2002 to August 2003 were used to identify the model. The developed model can be employed to predict the exploitation regimes caused by three proposed exploitation schemes A, B and C. A withdrawal rate of 22.67×10^4 m^3/day of brines is pumped through the current ditch system in scheme A and through the current ditch system plus 16 wells in scheme B. The results of the 5 years predictive simulation for schemes A and B indicate that these rates will cause a normal fall in water table in the pumping period of 9 months and a rise in water table in the recovery period of 3 months in each of the 5 years, with one depression cone near the current ditches in scheme A and two depression cones near the current ditches and the proposed wells in scheme B. In scheme C three more ditch systems are proposed to be excavated in the northeast, northwest and southwest of the Bieletan section and brines are pumped through each of the four ditch systems in turn for 1 year in every 4 years. The predictive simulation results of scheme C suggest that normal changes in the water table will also be expected and a continual increasing or decreasing trend in the water table will not be encountered in a 12-year period of prediction. The water table near each of the four ditch systems will recover sufficiently after a 39-month recovery.

Keywords Brines · Crystalline halite aquifer · Salt lake · Numerical modeling · Arid environment · Fertilizer

Introduction

A large-scale halite ore occurs in the Charham Salt Lake area in the middle part of the Chaidam Basin, Qinghai, China (Fig. 1). An estimation of 2.96×10^8 t of solid ore and 2.44×10^8 t of liquid brines coexist in the halite deposits (Yu 2000; Qinghai Geological Survey 2002). Potassium and magnesium are abundant in the ore and the brines. The Charham Salt Lake area has become a main base for producing potassium fertilizer in China. As the raw material for manufacturing potassium fertilizer, brines are exploited through ditches excavated in the halite aquifer. An output of 10^6 t of potassium chloride, which will consume some 7×10^5 m^3/day of brines, is proposed in the Charham Salt Lake area. As brines have intensively been abstracted in the Charham section in the eastern part of the area, another 2×10^5–3×10^5 m^3/day of brines are withdrawn in the Bieletan section in the western part of the area. Ditches of a few kilometers long have been dug in the halite aquifer in the Bieletan section and abstraction of brines began in August 2002. There is a continuous concern about the changes in the water table in the halite aquifer under pumping conditions. If the brines are over-pumped by the current ditches, the lateral flow from the surrounding aquifers will increase, resulting in a decrease in the total dissolved solids (TDS) and the potassium content of the brines. To address the concern of spatial and temporal changes in the water table of the halite aquifer, a two-dimensional numerical modeling of the brine flow system is described and predictive simulations of three proposed exploitation schemes are presented, on the basis of the previous hydrogeologic investigations by several institutes and a current analysis of hydrogeologic conditions of the study area.

Hydrogeology

The Charham Salt Lake area is the lowest part of the Chaidam Basin (Fig. 1). The topography of the area is very flat, with an elevation of 2,680 m or so. Rivers from the southern mountain areas flow to the endorheic basin. Lakes Senie and Dabiele are terminal lakes in the Bieletan section. The study area lies in an arid region in northwest China, with an annual average rainfall of 24.5 mm and a maximum rainfall of less than 60 mm per year.

The Charham Salt Lake area is the depression center of the basin and is underlain by thick Quaternary sediments. Since the late Pleistocene, precipitation of salts (mainly halite) has occurred due to the arid climate and extensive evaporation of the lake (Qinghai Geological Survey 2002). Halite deposits 5–25 m thick cover an area of approximately 1,000 km^2. Interbedded clastic layers and halite can be found in the subsurface. The upper halite, which is referred to as Q_4^{S3} halite, is the thickest and is easily distinguished from the surrounding clastic sediments. Abundant brines are found in the Q_4^{S3} halite. It is the exploitation layer and is also the modeled layer in this study. The Q_4^{S3} layer is composed of halite with small amount of gypsum, carnallite, sylvite, polyhalite, bischfite and epsomite. The idiomorphic crystal of halite in the Q_4^{S3} layer is of middle size. The Q_4^{S3} halite is a phreatic aquifer and depth to the water table ranges from 0.3 to 0.7 m. Statistics of the chemical compositions of 30 brine samples of the halite aquifer collected in July 2002 are presented in Table 1. The density of the brines in the Bieletan section is 1.20–1.36 g/cm^3. Brines of high TDS occur within the halite. Several salt lakes with high salinity, such as Lakes Dabusun, Senie and Dabiele, are also found in the salt lake area (Fig. 1). The brines have TDS in the range 309.0–483.0 g/l, indicating that the brines are saturated with respect to halite, which is precipitated in the lakes. The brines are potassium-rich and of Na–Cl type. Relatively uniform and interconnected pores are encountered between the crystals of the halite. The porosity of the Q_4^{S3} halite can range from 15 to 35%. The halite is extremely porous and permeable. Wells tapping the layer in the middle of the Bieletan section produce as high as 1,270–4,396 m^3/day of brines with drawdown of about 1 m (Qinghai Geological Survey 2002). Hydraulic conductivity in the middle of the section is 114–368 m/day. Approaching the margin of the Q_4^{S3} halite, hydraulic conductivity and well yields gradually decrease.

Brines in the Q_4^{S3} halite aquifer receive recharge from precipitation, lateral inflow from the surrounding clastic sediments, leakage from the lower aquifers and infiltration from Lakes Senie and Dabiele. Due to the shallow water table and easy dissolution of the halite, the rainfall can recharge the halite aquifer if the depth to the water table is less than 0.8 m. The Q_4^{S3} layer is in the lowest part of the basin and is a convergent area of groundwater and surface water in the Chaidam Basin. Lateral inflow from the clastic sediments to the west and south of the halite and leakage from the aquifers below are appreciable. In the rainy season (in July and August in particular) the water levels in Lakes Senie and Dabiele rise by 0.5 m or more as a result of receiving water from rivers from the southern mountain area, leading to infiltration to the halite aquifer. Evaporation is the major discharge of the brines in the aquifer. The study area is in an extremely arid region with an evaporation of 3,495.8 mm. Evaporation is significant when the depth to the water table is shallow. Infiltration from precipitation and evaporation from the aquifer can be ignored if the depth to the water table is greater than 1.2 m (Table 2). In the dry season the water stages in Lakes Senie and Dabiele are lower than the water table of the aquifer, resulting in discharge of the brines in the aquifer into the lakes. In recent years pumping through ditches has become an important discharge for the brines.

The flat topography of the Bieletan section of the salt lake area leads to a flat water table in the halite aquifer. The hydraulic gradient of the water table is less than 0.0001 and the brines flow extremely slowly. There is a groundwater divide in the eastern part of the study area, which separates the Bieletan section from the Dabusun section. As greater exploitation of the brines

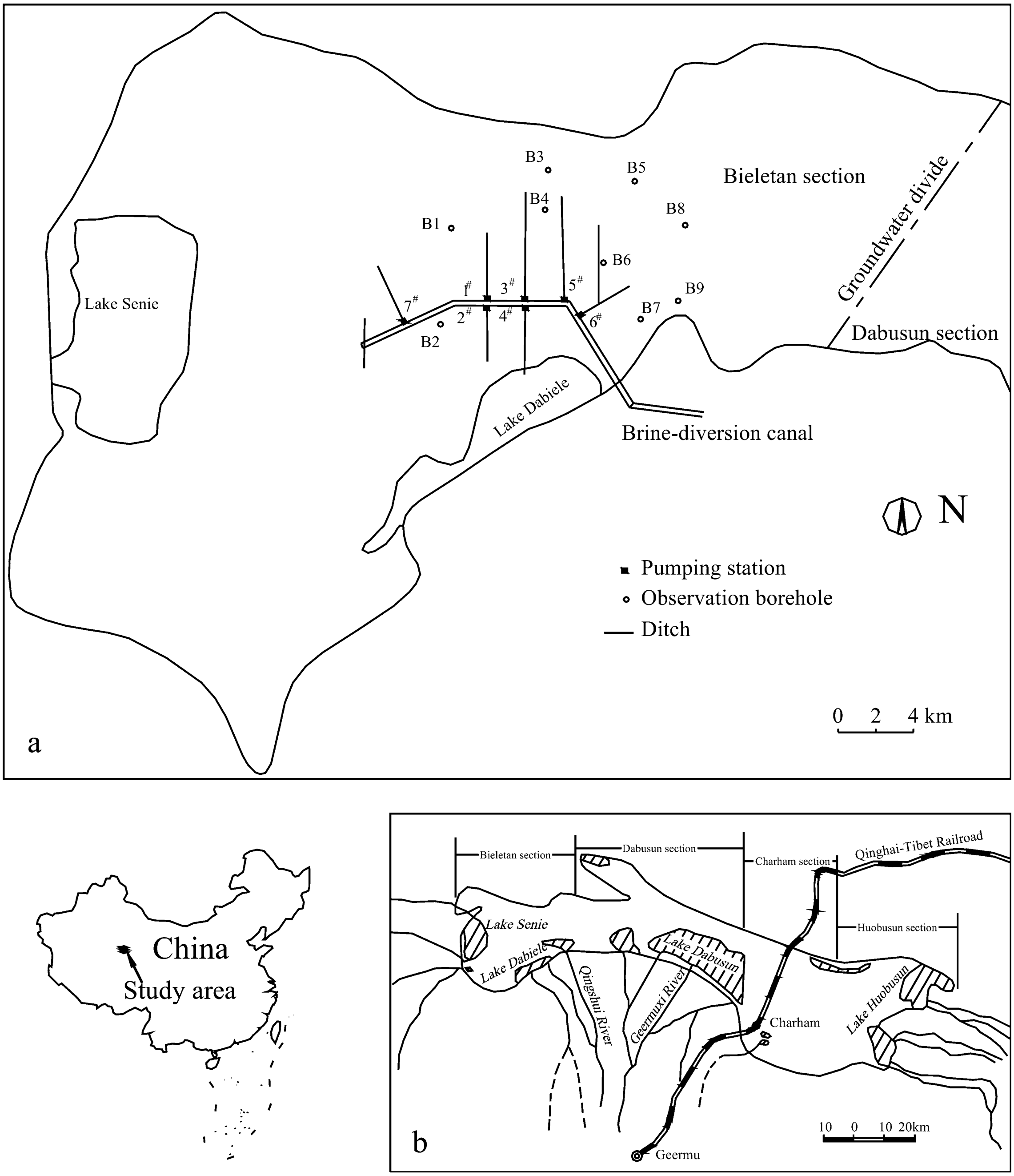

Fig. 1 A simplified hydrogeologic map of the study area (**a**) and the Charham Salt Lake area (**b**)

Table 1 Chemical compositions (g/l) of the brines in the Q_4^{S3} halite aquifer

	Na	K	Mg	Ca	Li	Cl	SO_4	HCO_3	B_2O_3	TDS	KCl (%)	pH	Density (g/cm^3)
Maximum	99.5	23.3	90.7	5.6	0.6	355.6	32.2	–	1.76	482.3	3.56	8.77	1.352
Minimum	1.9	0.9	7.9	0.1	0	192.0	0.1	–	0.08	309.4	0.13	7.26	1.206
Mean	27.0	14.3	58.1	0.9	0.3	246.1	8.8	–	0.67	366.3	2.71	8.37	1.256

began in 2002, the flow of the brines has been altered greatly and the brines flow towards the ditches. A cone of depression in the water table of some 300 km^2 occurs near the ditches in the Bieletan section, with a maximum drawdown of about 5 m. The shape of the cone of depression is controlled by the orientation of the ditches.

Simplification and mathematic model

The model area includes the Bieletan section of the salt lake area, with an area of 938 km^2 (Fig. 1). The model layer is the Q_4^{S3} halite, which constitutes a horizontally extending unconfined aquifer. The hydraulic conductivity of the salt aquifer varies laterally but not vertically. The Q_4^{S3} halite aquifer can be generalized as heterogeneous, isotropic porous media of crystalline rocks. As the thickness of the unconfined aquifer is small compared to its lateral extent, the flow of the brines in the Q_4^{S3} aquifer is assumed to be two-dimensional and follows the Darcy's law. In the numerical modeling only the flow of brines is considered; the dissolution and precipitation of halite are not examined.

No-flow boundary was assigned to the northern border. Boundaries of prescribed flux were assigned to the western and southern border. The groundwater divide in the eastern part serves as a no-flow boundary. The following governing equation (Bear 1979; Chen and Tang 1990; Anderson and Woessner 1992) can be used to describe the flow of brines in the Q_4^{S3} halite aquifer in the Bieletan section of the Charham Salt Lake.

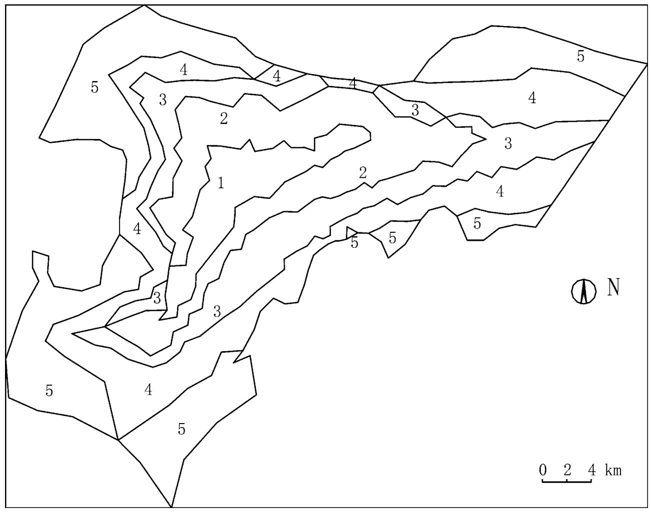

Fig. 3 Subdivisions for hydraulic conductivity of the modeled layer

$$
\begin{aligned}
S\frac{\partial H}{\partial t} = {} & \frac{\partial}{\partial x}\left(MK_{11}\frac{\partial H}{\partial x} + MK_{12}\frac{\partial H}{\partial y}\right) \\
& + \frac{\partial}{\partial y}\left(MK_{21}\frac{\partial H}{\partial x} + MK_{22}\frac{\partial H}{\partial y}\right) + K_z(H_z - H) + Q \\
& + W_1 + W_2
\end{aligned}
$$

$$(x, y) \in \Omega, \quad t > 0$$

$$MK_n\frac{\partial H}{\partial n}\bigg|_{\Gamma_2} = \beta, \quad t > 0$$

$$H|_{t=0} = H_0, \quad (x, y) \in \Omega$$

where S is the storage coefficient, H is the elevation of the water table, M is the thickness of the halite aquifer, $\begin{pmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{pmatrix}$ is the matrix of hydraulic conductivity, K_z

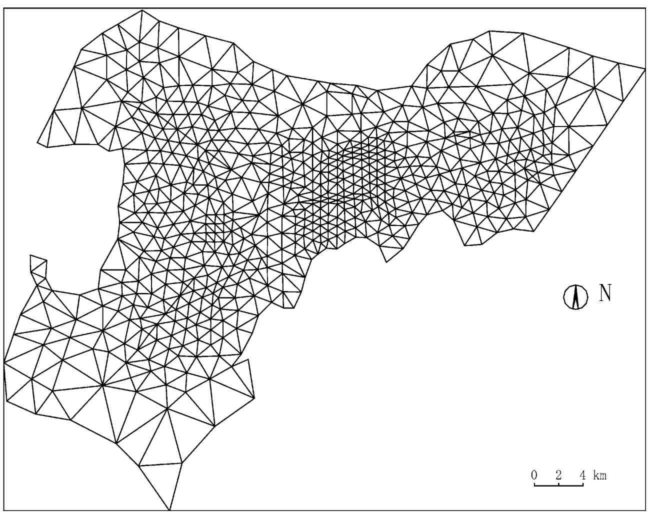

Fig. 2 Discretization map of the flow domain

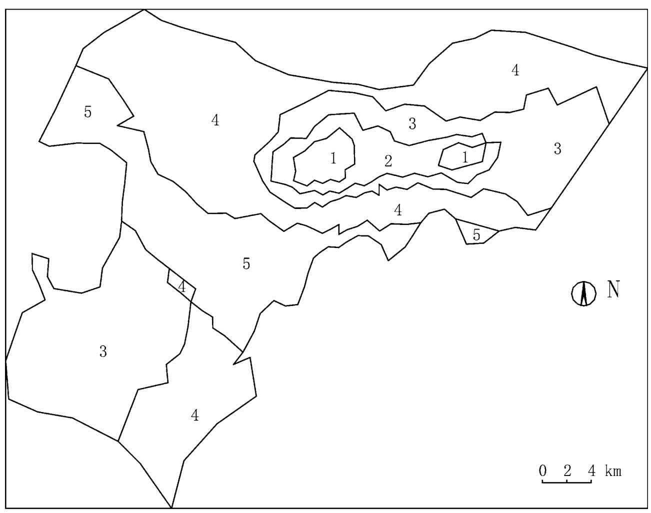

Fig. 4 Subdivisions for storage coefficient of the modeled layer

Table 2 Infiltration rate of precipitation and evaporation of brines at different depths of the water table

Depth to water table (m)	< 0.4	0.4–0.8	> 0.8–1.2	> 1.2
Infiltration rate of precipitation (%)	65	28	7	0
Evaporation per unit area (mm/day)	0.097	0.044	0.012	0

is the leakance of the aquitard underlying the halite aquifer, H_z is the water level of the aquifer underlying the aquitard, Q is the pumping rate (negative), W_1 is the recharge rate from precipitation, W_2 is the evaporation rate, Ω is the flow domain, Γ_2 is the boundary of prescribed flux (including no-flow boundary), K_n is the hydraulic conductivity in the direction of the outward normal to the boundary surface of the flow domain, $\partial H/\partial n$ is the derivate in the direction of the outward normal to the boundary surface of the flow domain, H_1 is the initial water level of the halite aquifer, and β is flux through the boundary of prescribed flux (zero for no-flow boundary).

Model calibration

The flow domain of the Q_4^{S3} halite aquifer was discretized with irregular triangles. The grid of the model area was composed of 641 nodes and 1,185 elements (Fig. 2). Locations of observation boreholes and ditches were set on the nodes as much as possible. A finer grid discretization was made near the ditches and the observation boreholes. As the exploitation record of the brines before October 2002 are incomplete, the monthly averaged values of water level of October 2002 were used as initial values of water levels for all the nodes. The modeling period began in November 2002 and ended in August 2003 with a 30-day time step. The inflow rate through the western and southern boundaries ranges from 0.06 to 0.11 m^3/day/m. Aquifer parameters identified with the model are hydraulic conductivity and storage coefficient. The Q_4^{S3} halite aquifer was further divided into five zones for hydraulic conductivity (Fig. 3) and another five subdivisions for storage coefficient (Fig. 4) on the basis of analyses of hydrogeologic features and well yields of the aquifer. Recharge from precipitation and evaporation of the brines varies in the horizontal direction, depending on the depth to the water table (Table 2). The leakance of the underlying aquitard also needed to be identified. Based on the lithologic features, the underlying aquitard was divided into three zones for studying leakance.

The ditches are straight-extending. A pump is located on one end of each of the ditches and the pumps are set in the vicinity of a brine-diversion canal. Each ditch can

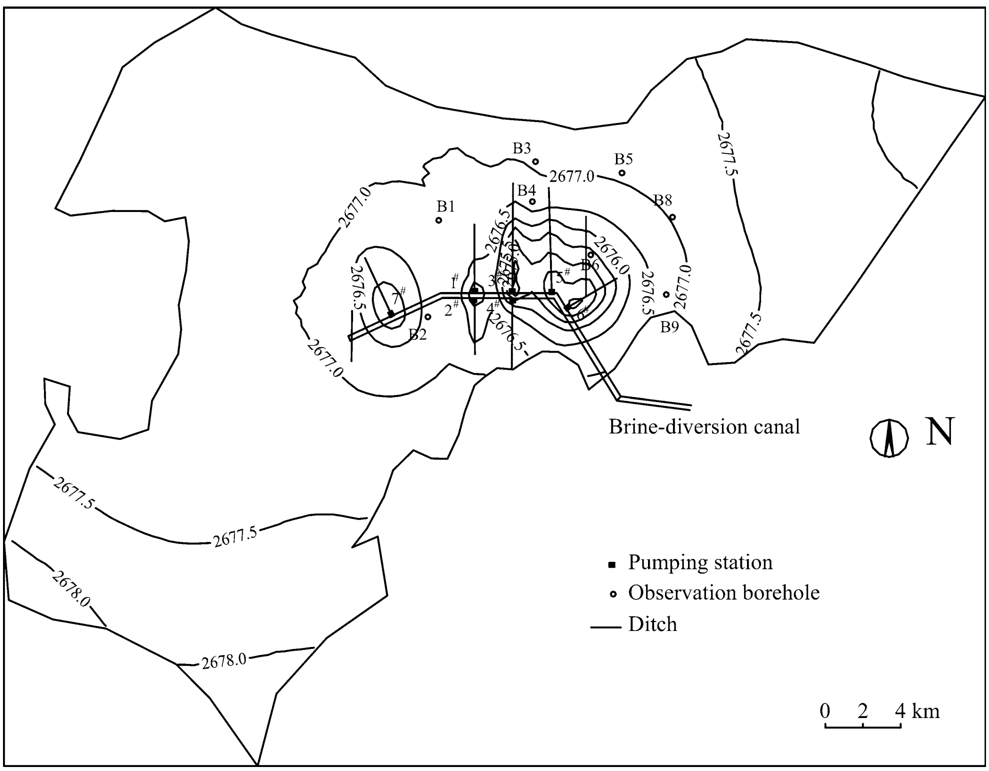

Fig. 5 Contour map of the water table at the end of the modeling period

Table 3 Aquifer parameters for different zones used in the model

Layer	Parameter	1	2	3	4	5
Q_4^{S3} halite aquifer	Hydraulic conductivity (m/day)	335	295	265	225	173
	Storage coefficient	0.118	0.094	0.088	0.079	0.068
Underlying aquitard	Leakage coefficient (1/day)	0.00097	0.014	0.0002		

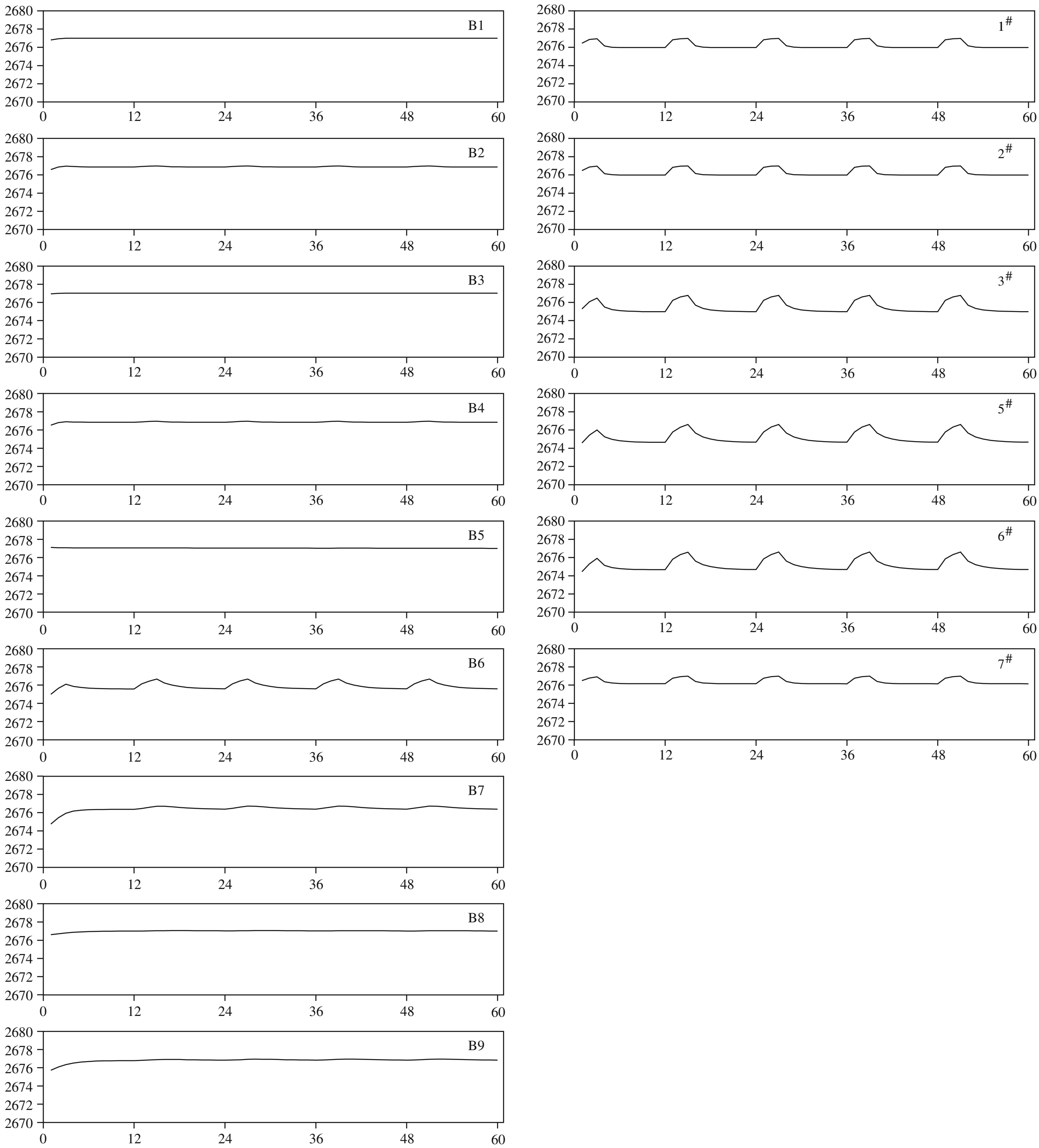

Fig. 6 Changes in water table at the observation boreholes and pumping stations for the predictive exploitation scheme A (*Y* coordinate refers to elevation of the water table in meters and *X* coordinate refers to time in months)

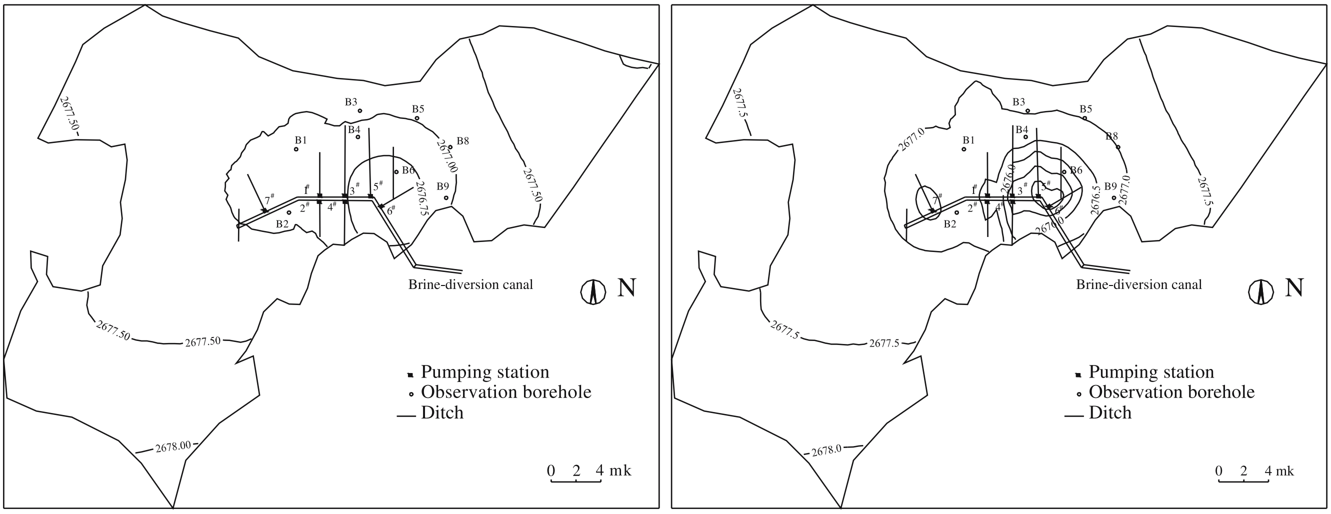

Fig. 7 Contour maps of the water table at the end of the recovery period (**a**) and at the end of the pumping period in the fifth year for the predictive exploitation scheme A (**b**)

be simplified as several pumping wells, which are arranged in a straight line and on the nodes of the grid. The pumping rate of a pump is assigned to the wells from the end with the pump to the other end according to a linearly decreasing trend. Ten wells were assigned for the longest ditch.

To identify the values of the aquifer parameters and the boundary conditions for the model, a calibration process was made using a trial-and-error procedure (Anderson and Woessner 1992; Zhou et al. 2000, 2003), and satisfactory fitting between observed and computed heads at the observation wells and pumping stations were obtained. Figure 5 shows the water table of the halite aquifer at the end of the modeling period. The aquifer parameters verified with the model are listed in Table 3.

Predictive simulation of three proposed exploitation schemes

It has been estimated that 22.67×10^4–28×10^4 m^3/day of brines is needed from the Bieletan section for production of potassium chloride in the fertilizer factory in Charham (Qinghai Geological Survey 2002). Three exploitation schemes are proposed to satisfy the requirement of brine production. The model developed previously can be used to predict the spatial and temporal evolution of the water table of the halite aquifer under the exploitation of each of the three proposed exploitation schemes.

Exploitation scheme A

The current ditches are proposed to pump brines at a total rate of 22.67×10^4 m^3/day under the exploitation scheme A. The total withdrawal rate is assigned to the seven ditches, each of which is treated as several pumping wells in a straight line. The initial and boundary conditions are kept the same. The time step is 1 month and the predictive period lasts 5 years. In each year production of brines through the ditches begins in April and ends in December, and the recovery lasts for another 3 months from January to March. Shown in Fig. 6 are the changes in water table at some of the observation boreholes and pumping stations. Contour maps of the water table at the end of the recovery and pumping periods of the fifth year are presented in Fig. 7. Water table at the observation boreholes and the pump stations rises during the recovery period and falls slowly during the pumping period. A depression cone is caused by the pumping ditches. At the end of the pumping period of the fifth year, the lowest water table is 2,674.63 m at the center of the depression cone, whereas at the end of the recovery period of the fifth year the elevation of the water table reaches 2,676.59 m at the center of the depression cone. The drawdown in the water table caused by pumpage in the pumping period will normally recover in each year.

Exploitation scheme B

In exploitation scheme B 16 pumping wells are to the west of the current ditches. The total withdrawal rate of the wells and the ditches is also 22.67×10^4 m^3/day. Withdrawal rate of 0.69×10^4 m^3/day is assigned to each of the wells and 1.66×10^4 m^3/day is assigned to each of the ditches. Other conditions used for predictive simulation in exploitation scheme B are the same as those in exploitation scheme A. The results of predictive

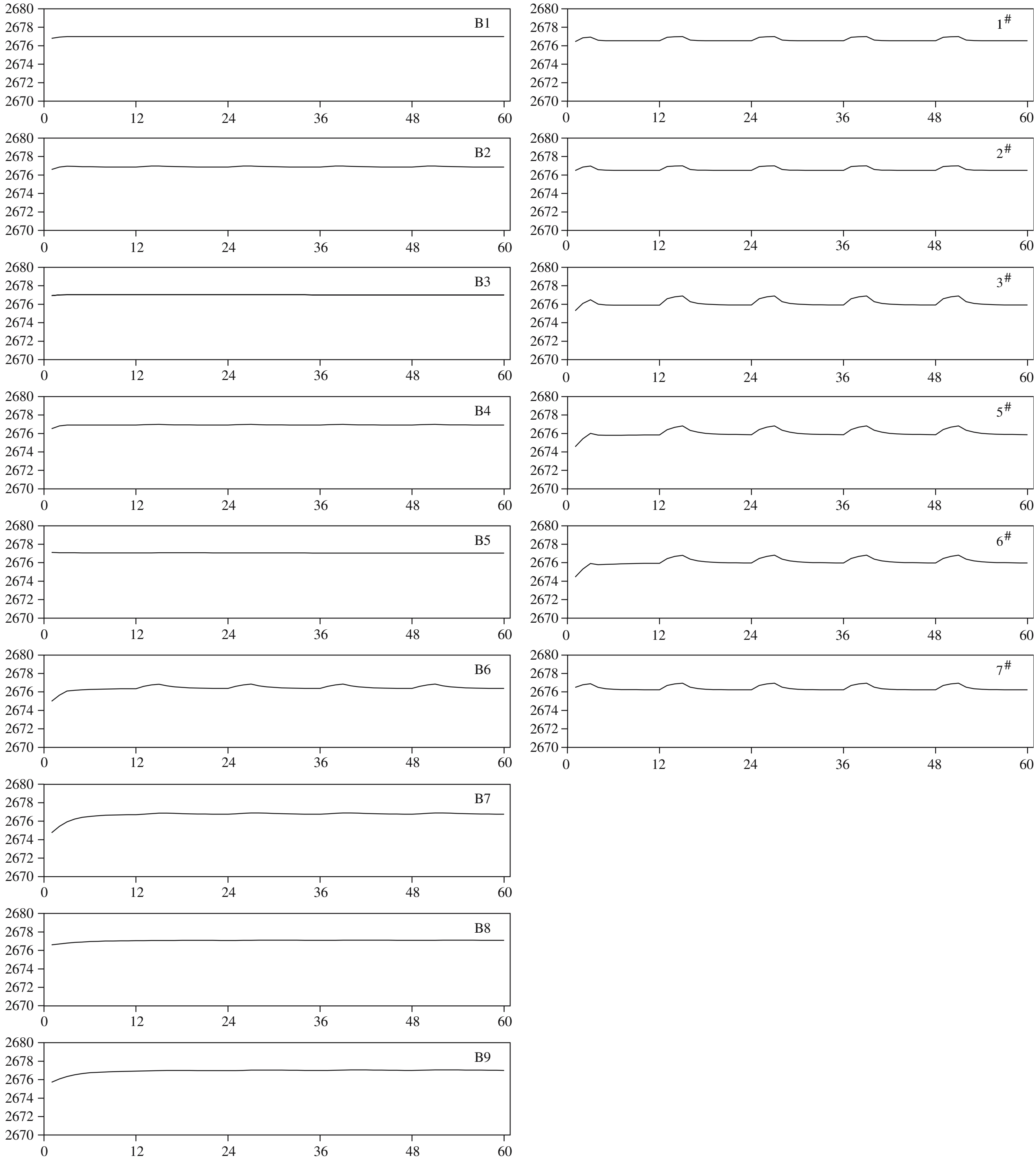

Fig. 8 Changes in water table at the observation boreholes and pumping stations for the predictive exploitation scheme B (*Y* coordinate refers to elevation of the water table in meters and *X* coordinate refers to time in months)

simulation are illustrated in Figs. 8 and 9. Water table at the observation boreholes and the pump stations rises during the recovery period and falls slowly during the pumping period. However, fall in water table at the pumping stations in exploitation scheme B is less than that in exploitation scheme A because the with-

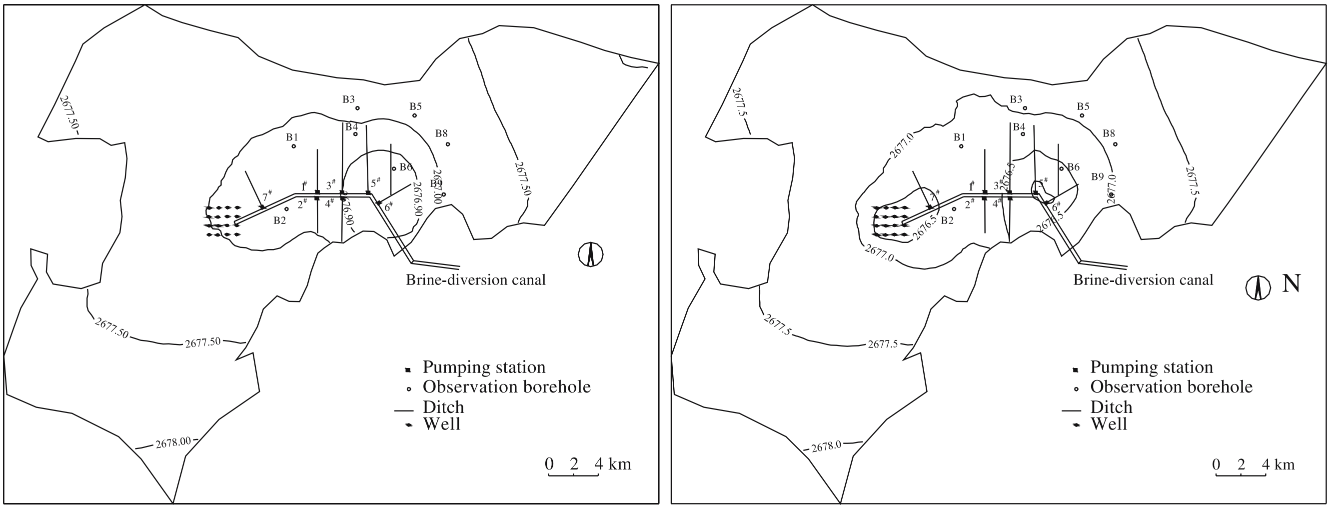

Fig. 9 Contour maps of the water table at the end of the recovery period (**a**) and at the end of the pumping period in the fifth year for the predictive exploitation scheme B (**b**)

drawal rate of the ditches in B is less than A, even though pumping rates remain the same. Two depression cones of the water table exist near the wells and the pumping stations at the end of the pumping period of the fifth years, with the lowest elevation being 2,675.85 m near the ditches. The water table recovers significantly during the recovery period in each year and reaches 2,676.81 m at the end of the recovery period of the fifth year. As brines are produced from both the wells and the ditches, drawdown in the water table in exploitation scheme B is less than that in scheme A.

Exploitation scheme C

In exploitation scheme C, three more ditches system are proposed to be dug in the northeast (Ditch system 1), northwest (Ditch system 3) and southwest (Ditch system 4) of the study area and in the current ditches system (Ditch system 2) only one or two of the ditches are lengthened. The four ditch systems are proposed to pump brines from the halite aquifer in turn for 1 year (3 months recovery followed by 9 months pumping), that is, brines are produced in each ditch system for 1 year in every 4 years. The total withdrawal rate of Ditch systems 2, 3 and 4 is 22.67×10^4 m^3/day. A total withdrawal rate of 28×10^4 m^3/day is assigned to Ditch system 1 because of the relatively low concentration of potassium in the brines in the northeastern part of the area. Other conditions used for predictive simulation in exploitation scheme C are the same as those in exploitation scheme A. The predictive water table at the observation wells and the pumping stations for 12 years is shown in Fig. 10 and contour maps of the water table for predictive simulation at the end of recovery and pumping periods of each ditch system are presented in Figs. 11, 12, 13 and 14. The water table falls during the pumping period in each of the ditch system and recovers during the recovery period in each of the ditch system and the non-pumping years. It can also be seen that water table at some of the observation wells and pumping stations in the Ditch system 2 falls during the non-pumping years as a result of the production of brines by the nearby ditch systems. A depression cone exists at the end of the pumping period in each of the ditch systems. The shape of the depression cone coincides with the orientation of each of the ditch systems. Drawdown in water table caused by Ditch system 1 is greater than those caused by the other three ditch systems due to the greater withdrawal rate. In exploitation scheme C any two ditch systems are relatively far from each other and a longer recovery period (39 months) follows a pumping period. Therefore, exploitation scheme C is helpful in recovering the brines and in turn producing brines.

Summary

Abundant potassium-rich brines occur in the crystalline halite deposits of Quaternary age in the Bieletan section of the western part of the Charham Salt Lake area in the middle of the Chadam Basin, Qinghai, China. The thickness of the near-surface Q_4^{S3} halite aquifer is in the range 5–25 m. TDS of the brines in this phreatic aquifer range from 309.0 to 483.0 g/l. The aquifer recharge includes lateral inflow from outside the halite deposits, leakage from the lower layers and infiltration from precipitation and lakes. Discharge occurs as evaporation

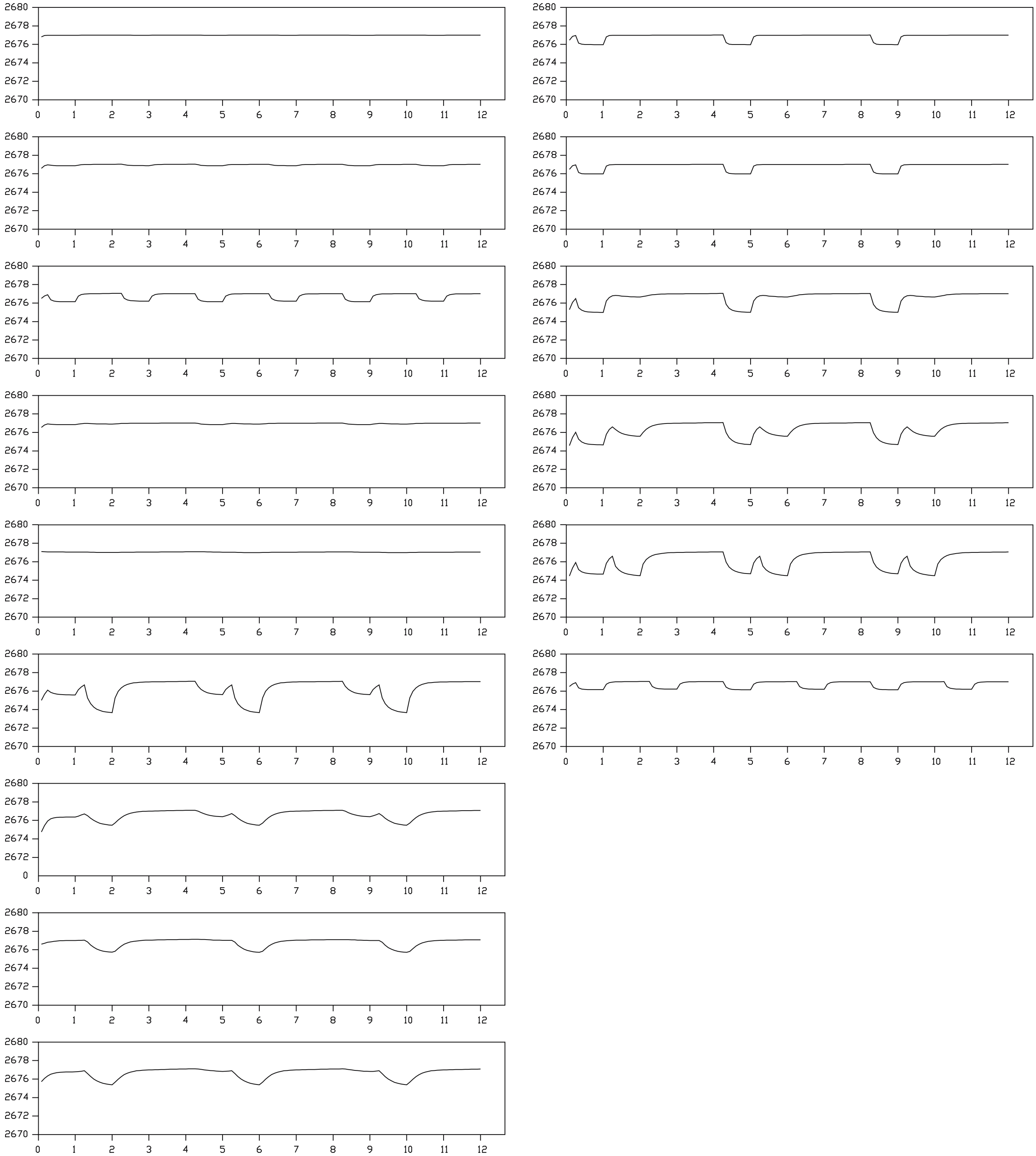

Fig. 10 Changes in water table at the observation boreholes and pumping stations for the predictive exploitation scheme C (*Y* coordinate refers to elevation of the water table in meters and *X* coordinate refers to time in months)

and towards the lakes. The shallow water table makes it easy to pump the brines through the ditches for production of potassium fertilizer in the local factories. About 30×10^4 m^3/day of brines has been pumped from the current ditches, creating a depression cone in the water table near the ditch system.

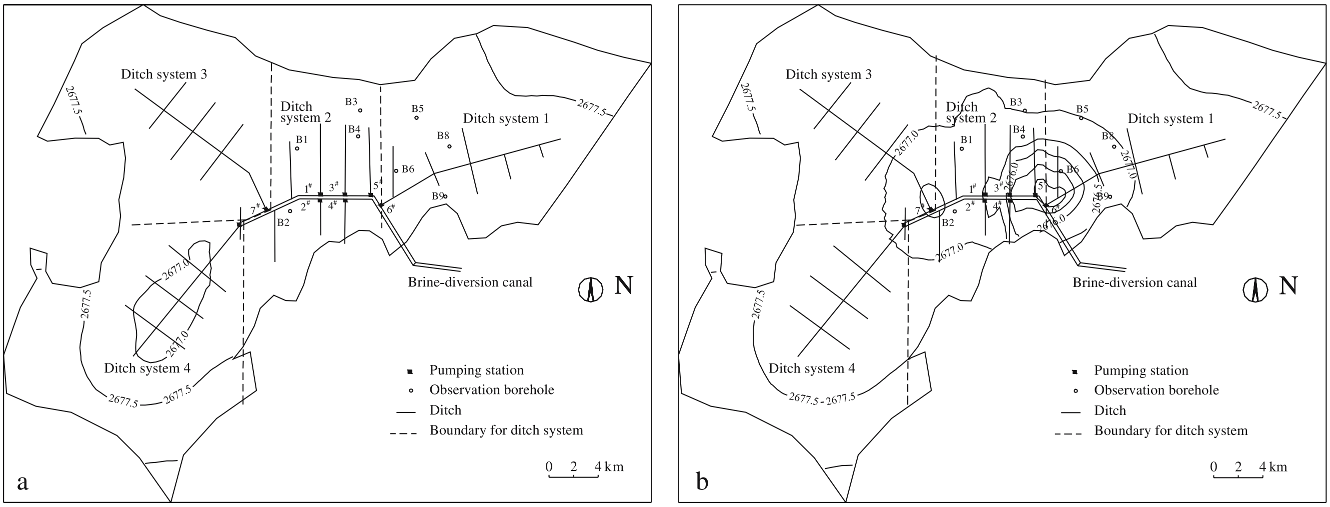

Fig. 11 Contour maps of the water table at the end of the recovery period (99th month) (**a**) and at the end of the pumping period (108th month) (**b**) of the third turn by the Ditch system 2 for the predictive exploitation scheme C

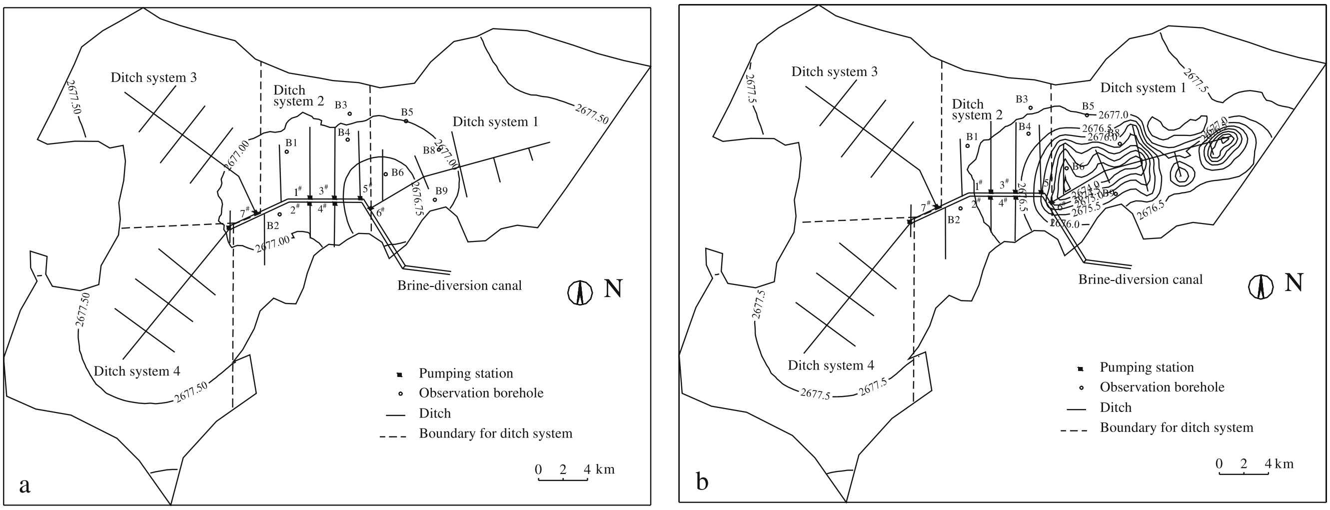

Fig. 12 Contour maps of the water table at the end of the recovery period, 111th month, (**a**) and at the end of the pumping period, 120th month, (**b**) of the third turn by the Ditch system 1 for the predictive exploitation scheme C

As the spatial and temporal changes in water table of the Q_4^{S3} halite aquifer in the Bieletan section is a concern to the local government, a numerical model is constructed to predict the change in the water table. The flow of the brines in the halite aquifer can be described using a two-dimensional mathematic model. The flow domain was discretized into 1,185 triangular elements with 641 nodes. Each of the ditches is treated as several pumping wells in a straight line. The exploitation regime caused by the pumping ditches from November 2002 to August 2003 was used to identify the model and satisfactory fit was obtained. The developed model is employed to predict the exploitation regimes caused by three proposed exploitation schemes.

Brines of 22.67×10^4 m^3/day are pumped through the current ditch system in exploitation scheme A and through the current ditch system and 16 wells in exploitation scheme B. Three months of recovery follow 9 months of pumping in each of the 5 years of predictive simulation. The results of the predictive simulation indicate that normal fluctuations in water table (i.e., fall due to pumping and rise due to recovery) occur at the observation wells and the pumping stations and no systematic decline in water table can be noticed. Pumpage of the brines will cause one depression cone in the water table near the current ditches in exploitation scheme A and two depression cones near the current ditches and the proposed wells in exploitation scheme B, respectively.

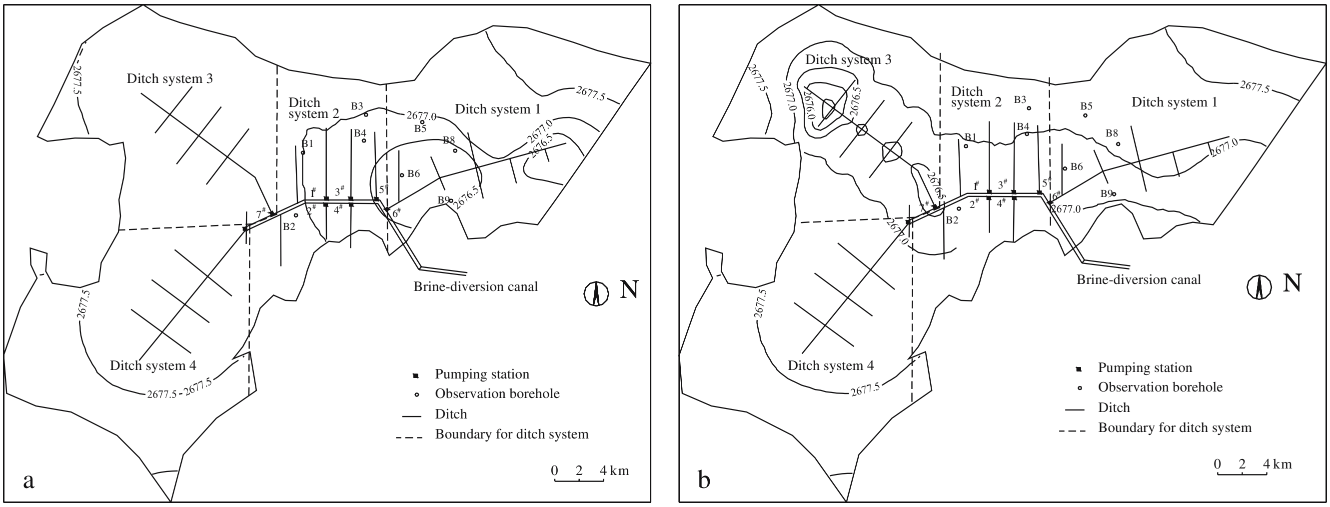

Fig. 13 Contour maps of the water table at the end of the recovery period (123rd month) (**a**) and at the end of the pumping period (132nd month) (**b**) of the third turn by the Ditch system 3 for the predictive exploitation scheme C

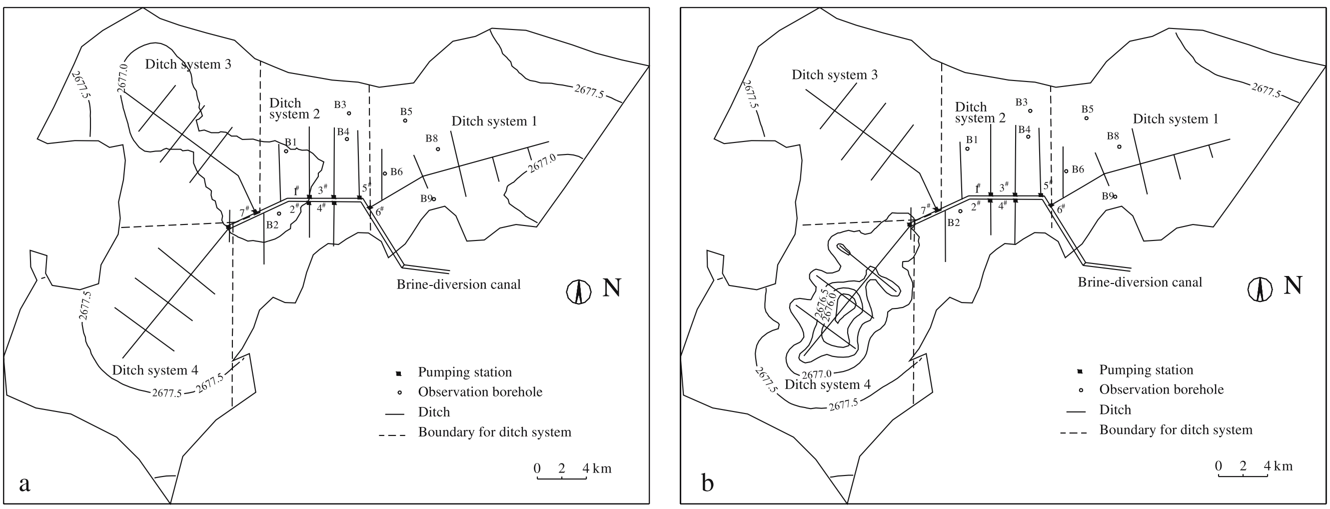

Fig. 14 Contour maps of the water table at the end of the recovery period (135th month) (**a**) and at the end of the pumping period (144th month) (**b**) of the third turn by the Ditch system 4 for the predictive exploitation scheme C

The drawdown of the depression cone near the current ditches caused by exploitation scheme A is greater than that of the exploitation scheme B, owing to the lesser withdrawal rate of the ditches in B.

In exploitation scheme C three more ditch systems are proposed to be excavated in the northeast, northwest and southwest of the Bieletan section. Brines are pumped through each of the four ditch systems in turn for 1 year. Each of the ditch systems pump brines for 9 months and recovers for 3 months in 1 year of every 4 years. A withdrawal rate 28×10^4 m^3/day is assigned for the northeastern ditch system and 22.67×10^4 m^3/day for the other three ditch systems. The results of the predictive simulation of the exploitation scheme C suggest that normal changes in the water table will be expected and an increasing or decreasing trends in the water table will not be encountered in a 12-year period of prediction. A depression cone in the water table will occur at the end of the pumping period near each of the ditch system when brines are produced by this ditch system. The water table near each of the four ditch systems will recover sufficiently after 39 months of recovery in exploitation scheme C.

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