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RESEARCH ARTICLE

# The influence of slope collapse on water exchange between a pit lake and a heterogeneous aquifer

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## HIGHLIGHTS

- Slope collapse will reduce the water exchange.
- Slope collapse will affect the spatial distribution of the water exchange.
- Precipitation have the most impact on the dynamics of the water exchange.

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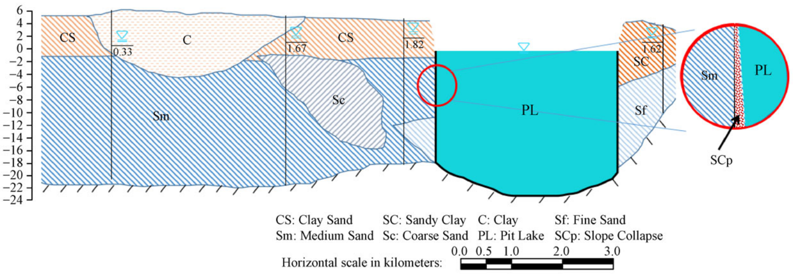
## GRAPHIC ABSTRACT



## ABSTRACT

Due to the increase in open pit mining, pit lakes have become common surface water features, posing a potential risk to subsurface aquifer. In this study, a pit lake–groundwater interaction model is built based on the general program MODFLOW with the LAK3 package. For the first time, the effects of lake-slope collapse and aquifer heterogeneity on pit lake–groundwater interactions are analyzed by dividing the lake into six water exchange zones based on the aquifer lithology and groundwater level. Our investigation and simulations reveal a total water exchange from groundwater to the lake of 349000 $m^3/a$ without collapse of the pit lake slope, while the total net water exchange under slope collapse conditions is 248000 $m^3/a$ (i.e., a reduction of 1.40-fold). The monthly net water exchange per unit width from groundwater to the lake reaches the largest in April, shifting to negative values in zone IV from June to August and in zone V in June and July. Moreover, the monthly net water exchange per unit width decreases from north to south, and the direction and magnitude of water exchange are found to depend on the hydraulic gradients between the lake and groundwater and the hydraulic conductivity of the slope collapse.

## 1 Introduction

Groundwater is exploited as a valuable resource for socioeconomic development in modern societies (Hou et al., 2018) and has a close exchange relationship with surface water. At present, large amounts of gravel and sand are mined to ensure the development of construction and production. The data from the United States Geological Survey show that about 165 million tons of sand and gravel are extracted per year (Mollema and Antonellini, 2016). Pit lakes are common water bodies resulting from open pit mining that cover about 3% of the Earth's land surface, an area much greater than previously believed, and that have become a common source of surface water (McDonald et al., 2012; Verpoorter et al., 2014; Mollema et al., 2015).

In contrast to natural lakes, pit lakes are a relatively new environmental phenomenon (Muellegger et al., 2013). The natural recharge ability of the aquifer is altered because pit lakes provide direct contact between the aquifer and the crust surface. Pit lakes also disturb the original hydrologic budget and flow paths of groundwater by altering the

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hydraulic gradients (Drew et al., 2002; Peckenham et al., 2009). In addition, under the impact of a pit lake, the water quality may gradually improve. For example, when groundwater flows through a pit lake, the nitrate and phosphate species in the groundwater are depleted by various biochemistry actions (Weilhartner et al., 2012). While, the water quality may also gradually deteriorate under the influence of a pit lake, such as by making the soil-bound compounds more accessible to groundwater (Downing et al., 2001; Herzsprung et al., 2010). Some of these effects may be more prominent if the pit lake was formed a long time ago. Therefore, in order to scientifically manage water resources in regions with pit lakes, the unification of the management of pit lakes and groundwater must be addressed (Ala-aho et al., 2015). The implementation of such a management method requires excellent understanding of the water exchange between groundwater and pit lakes and a reliable method to accurately simulate these interactions (El-Zehairy et al., 2018).

All the current models used to simulate the exchange of water between pit lakes and groundwater ignore the effects of thin layers such as the lake bed sediments formed by lake-slope collapse (Davis et al., 2006; McJannet et al., 2017). However, studies on the exchange of natural lakes with groundwater have shown that the thin layers formed by lake bed sediments can significantly reduce the exchange rate between lakes and groundwater (Genereux and Bandopadhyay, 2001; Hunt, 2003; Schneider et al., 2005). Therefore, the main objectives of this study were as follows: 1) to study the complexity of the influence of slope collapse on lake–groundwater interactions, and 2) to analyze the spatio-temporal characteristics of said lake–groundwater interactions. A pit lake in Qingdao City (Shandong Province, China) was selected to evaluate the above characteristics, mostly as a representative pit lake with slope collapse, but also because of the extensive available data on it, including long time-series records of groundwater levels, water level, river discharge, lake bed measurements, and pumping tests. The main novelties of this study are: 1) for the first time, a pit lake was modeled to study the impact of slope collapse on pit lake–groundwater interactions, and 2) the assessment of the spatio-temporal variation in the water exchange pattern of a pit lake with slope collapse.

## 2 Background of the study area

### 2.1 Position

The study area is located in the south of Qingdao, China, downstream of the Dagu River Basin, with an area of about 25 km$^2$ (Fig. 1).

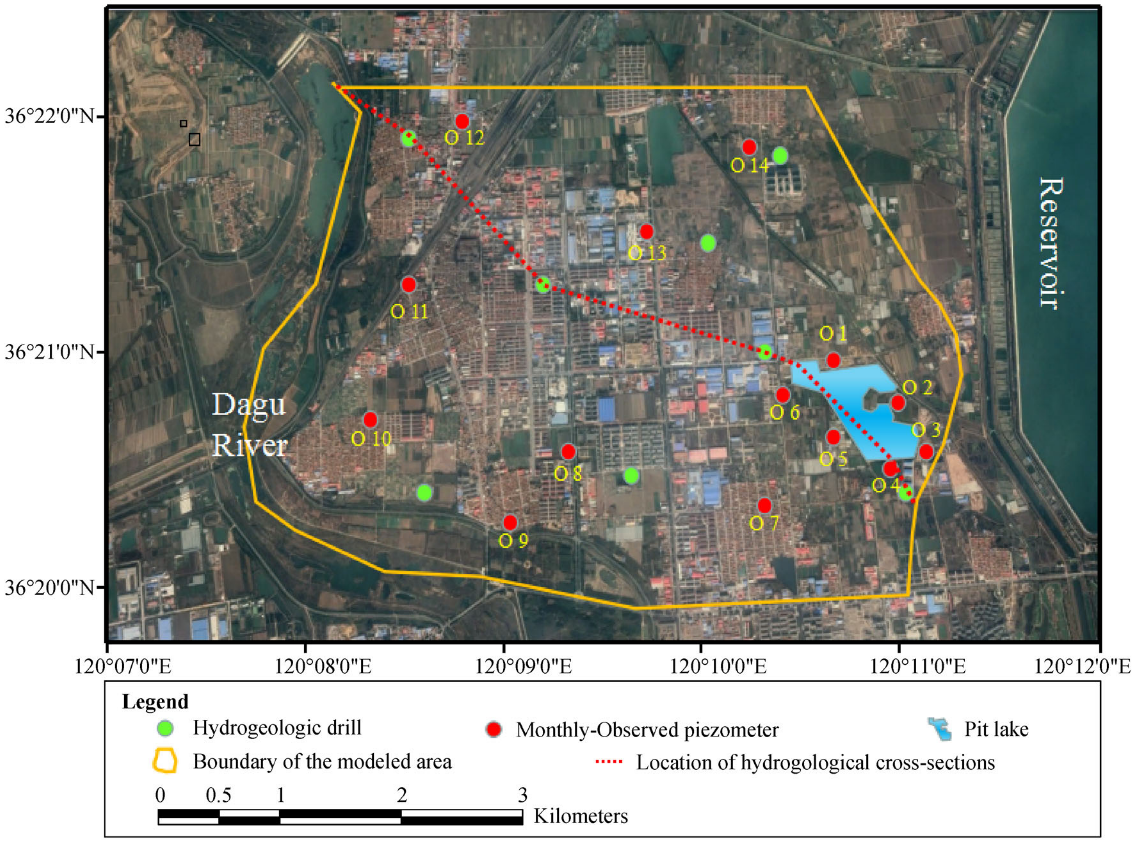

**Fig. 1** Location of the study area.

### 2.2 Climate

The study area presents monsoon continental climate influenced by marine climate. The multi-year meteorological data of the study area show an average annual temperature, precipitation, and evaporation of 12.5°C, 677.95 mm, and 1044.4 mm, respectively (Fig. 2).

### 2.3 Hydrology

The Dagu River is a major river that originates in Fushan (Zhaoyuan City) and finally flows into Jiaozhou Bay. Its length in the study area is around 11 km and the river in this region is controlled by the Jiatuan Rubber Dam.

The pit lake formed by surface mining activities is located in the south-east part of the study area. The area of the pit lake is about 1.00 km$^2$ without obvious surface inflow and outflow. The pit lake is recharged by groundwater and precipitation and is discharged by evaporation. The water level of the pit lake varied from 0.23 to 2.16 m during the period from January to December 2013, with smaller values in April and larger values in July.

Precipitation and infiltration from the Dagu River are the main sources of recharge of the study area, while groundwater extraction and evaporation are the main methods of discharge.

### 2.4 Hydrogeological conditions

The aquifer of the study area is unconfined and it has a two-layer structure. The upper layer is between 0.5 and 12 m thick and composed of clay and sandy clay. The lower layer is medium sand or coarse sand, with a thickness between 4.0 and 16.6 m. The aquifer is underlain by impermeable clay rock and/or glutenite (Fig. 3).

The groundwater in the study area flows from NE to SW. To prevent seawater intrusion, a 4.2 km cut-off wall was built at the southern boundary of this area. Its top elevation is 0 m, and the lower end is directly embedded in the lower confining bed. Therefore, only when the groundwater level is higher than 0 m in the vicinity of the southern boundary, does the study area present a hydraulic connection with the downstream section.

The pit lake edge is almost vertical, and its bottom is located on the lower confining bed. In addition, because the slope of the pit lake is high and steep, obvious collapse of the edge occurs. During slope collapse, clay sand and sandy clay slid down and form a low hydraulic-conductive layer between the pit lake and the aquifer (Fig. 3).

## 3 Numerical model setup

### 3.1 Hydrogeologic conceptual model

The hydrogeologic model of the study area can be conceptualized as an unconfined aquifer system with two layers. To represent the pit lake, an extra inactive layer is placed at the top.

The two layers are parameterized in terms of hydraulic-conductivity zones and, in order to investigate the effect of slope collapse, the pit lake was divided into six water

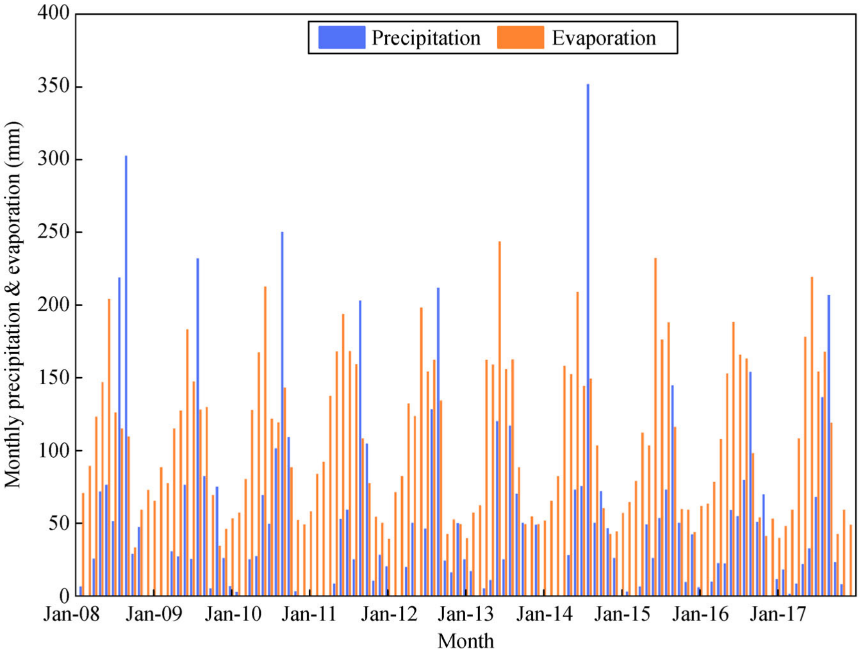

**Fig. 2** Monthly precipitation and evaporation in the study area from Jan. 2008 to Dec. 2017.

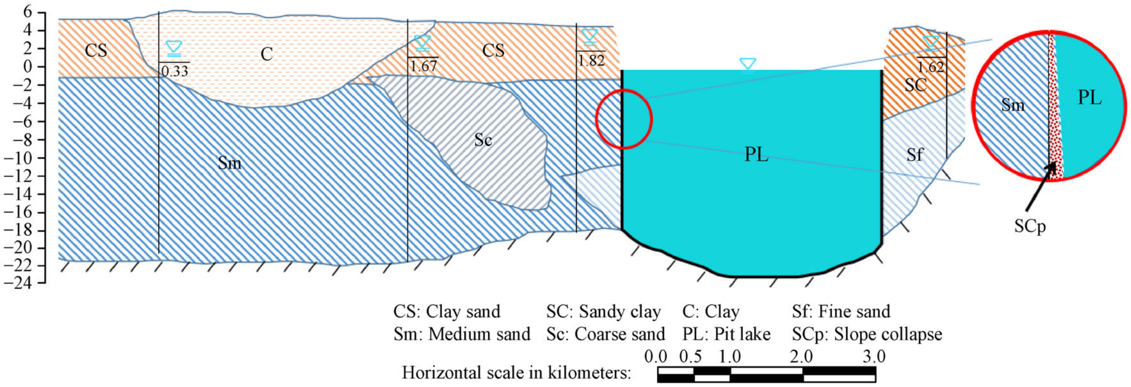

**Fig. 3** Hydrogeological cross-section of the study area (Section 1–1′).

exchange zones based on the aquifer lithology and groundwater level (Fig. 4).

## 3.2 Numerical model

### 3.2.1 The groundwater flow equation

The governing equation used in our study is a standard transient three-dimensional groundwater flow equation (Eq. (1)):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial H}{\partial z}\right)+W = S_s\frac{\partial H}{\partial t}, \quad (1)$$

where, $K_{xx}$, $K_{yy}$ and $K_{zz}$ represent the values of hydraulic conductivity (m/d) along the $x$, $y$ and $z$ coordinate axes respectively, $H$ is the groundwater head (m), $W$ represents the amount of water flowing in or out of a unit volume of aquifer per unit time, $S_s$is the specific storage of the aquifer and $t$ is time (d).

### 3.2.2 Lake water budget

In our research, the LAK3 package was used to construct the pit lake (Været et al., 2009). And In LAK3, the net water exchange rate between the pit lake and groundwater is represented by calculating the pit lake water budget at the end of each time step. The lake water budget in LAK3 is calculated with Eq. (2):

$$h_l^n = h_l^{n-1} + \Delta t\frac{p-e+rnf-w-sp+Q_{si}-Q_{so}}{A_s}, \quad (2)$$

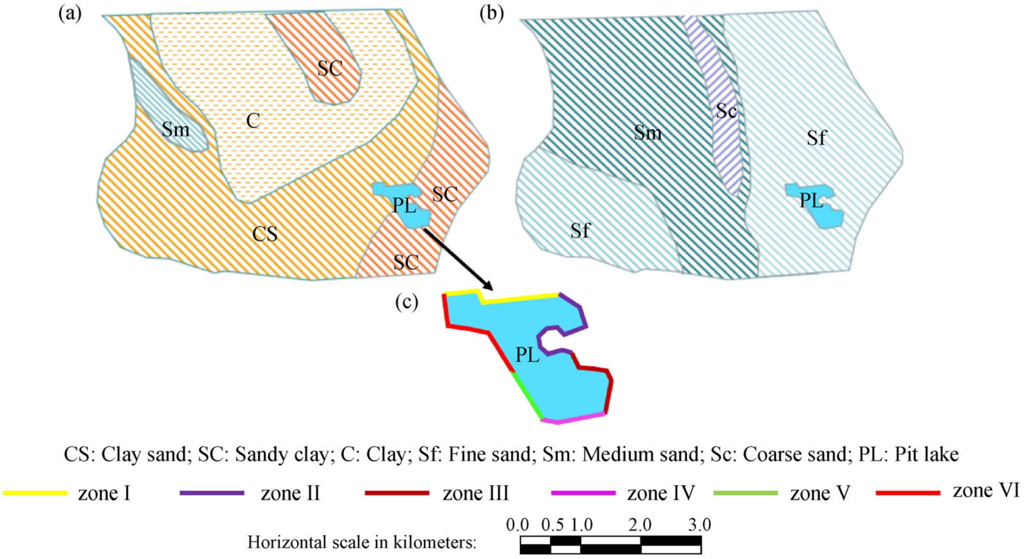

**Fig. 4** Distribution of double-layer aquifer: upper layer (a), lower layer (b) and 6 slope zones (c) around pit lake.

where $h_l^n$ and $h_l^{n\text{-}1}$ are lake water level (m) of the present and previous time steps respectively, $\Delta t$ is the length of time step (d), $p$ is the precipitation rate (mm/d), $e$ is the evaporation rate (mm/d), *rnf* represents the rate of surface runoff to the lake (m$^3$/d), $w$ is the pumping rate from the lake (m$^3$/d), $Q_{si}$and $Q_{so}$ represent the inflow rate from streams and the outflow rate to streams (m$^3$/d), $A_s$ is the lake surface area at the beginning of the time step (m$^2$) and *sp* is the net water exchange rate (m$^3$/d).

Within this work, the net water exchange rate (*sp*) is calculated as the sum of individual water exchange terms for all lake/aquifer cell interfaces ($M$) (Eq. (3)):

$$sp = \sum_{m}^{M} c_m (h_l - h_{am}), \tag{3}$$

where $h_{am}$ is the head in the aquifer cell across the $m$ interface (m) and $c_m$ is the hydraulic conductivity across the $m$ interface (m/d).

### 3.3 Model discretization and input

The numerical model of the problem in this study is built using MODFLOW, and the model layers are divided in grid blocks 50 m long per side.

Two different types of lakes are simulated: 1) a lake with collapsed slopes, where a low hydraulic conductivity layer exists between the pit lake and the aquifer; and 2) a lake without slope collapse, in which the aquifer is directly in contact with the pit lake. The other initial parameters of the two models were the same.

Three types of model boundary conditions are set: 1) an impermeable boundary on the east side, assigned based on gradual taper of the aquifer on the east side and contact with bed rock, which is impermeable; 2) to the north, the boundary was either similar to that in point 1 or a given head boundary, assigned based on the often stable groundwater head on the north side (the same boundaries are also assigned on the west to simulate the Dagu River); and 3) a drain boundary is located on the south, to simulate the cut-off wall (Fig. 5).

The two layers are assumed to be isotropic and the assigned horizontal hydraulic conductivities ($K_h$) for the upper and lower layers of the aquifer are varied from 0.46 to 88.21 m/d and from 25.2 to 106.7 m/d, respectively. The specific yield ($S_y$) is varied from 0.03 to 0.18.

The precipitation recharge rate is calculated by the model based on the rate of precipitation and infiltration parameters ($a$). The infiltration rate of the Dagu River is estimated according to seasonal river stages. The evapotranspiration (*ET*) zone of the study area includes two components. The Penman open-water equation is used to compute the *ET* of the pit lake. For the land surface, the *ET* is calculated using an empirical formula that considers the surface, elevation, maximum *ET* rate, and extinction depth (El-Zehairy et al., 2018). The groundwater pumping rate was estimated using statistics from the local Water Department Bureau.

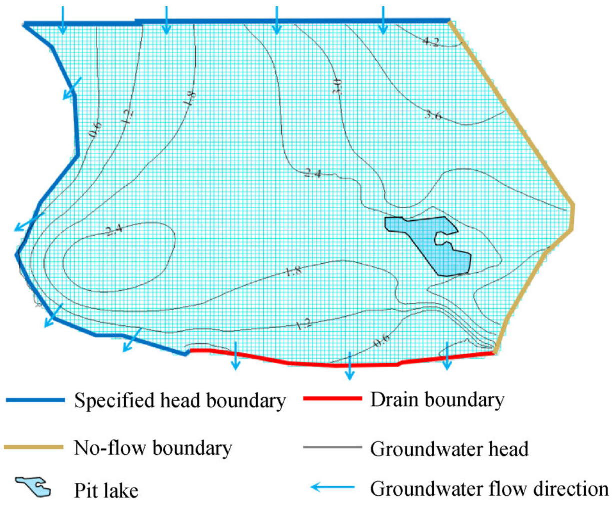

**Fig. 5** Model grid, boundary conditions and groundwater flow direction.

The hydraulic conductivity of the thin layer for each water exchange zone of the slope-collapsed lake is determined by on-site sampling and laboratory measurements (Table 1).

**Table 1** Hydraulic conductivity of the thin layer

| Zone | $K_h$ (m/d) |
|---|---|
| Ⅰ | 0.322 |
| Ⅱ | 0.063 |
| Ⅲ | 0.088 |
| Ⅳ | 0.072 |
| Ⅴ | 0.081 |
| Ⅵ | 0.382 |

### 3.4 Model calibration

The two models are calibrated using the same method and standards. The model for the lake with the collapsed slopes is described as an example. First, the data from 4 January 2013 is applied to develop and correct a steady-state model. After this, a transient model is developed by applying the results of the steady-state model, and runs throughout the months of the hydrological year (i.e., from 6 February 2013 to 30 December 2013). The stress period is set as one month and the time step of each stress period as one day.

Figure 6 shows the partial results of the transient model calibration. Figures 5(a) and 5(b) shows that the correlation coefficient between the simulated and measured groundwater levels is 0.99, with a mean absolute error of 0.27 m and root-mean-square error (RMSE) of 0.36 m. In addition, Fig. 5(c) shows that the simulated and observed water levels of the pit lake are also in good agreement. The calibrated model parameters are listed in Table 2.

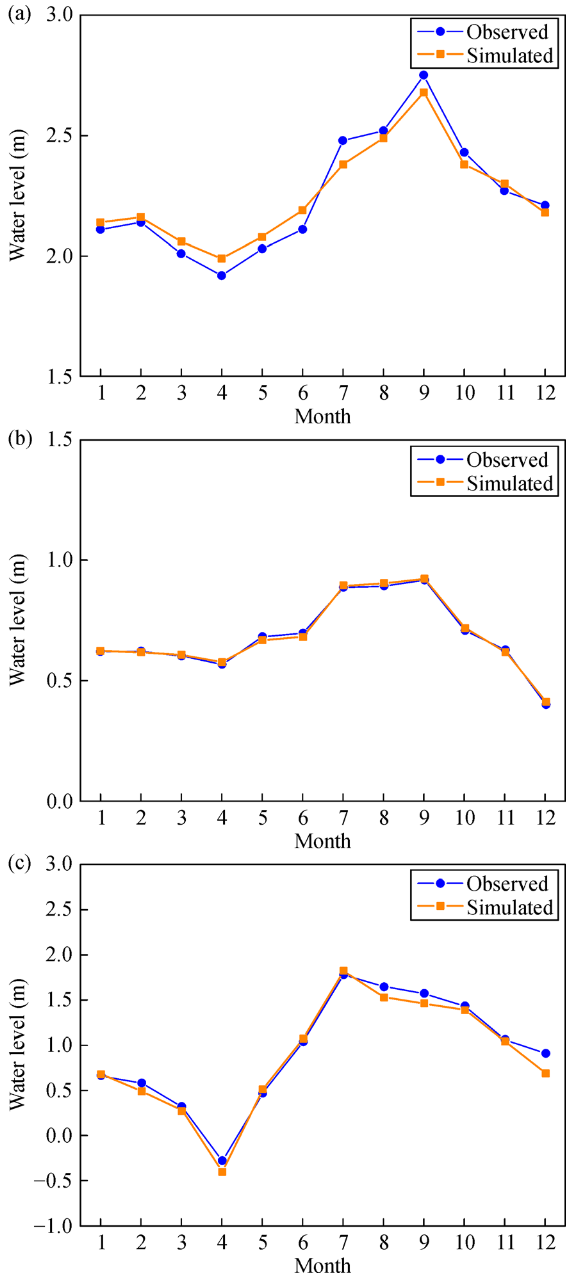

**Fig. 6** Simulated and observed water tables for groundwater (a) and (b); and the lake (c).

## 4 Results and discussion

### 4.1 Effect of slope collapse on water exchange into the lake

Figure 7 shows the net water exchange of the two types of lake during the simulation period, where positive values indicate groundwater recharging the pit lake. For the slope-collapsed lake, zone I exhibits the maximum net water exchange (74100 $m^3/a$) while zone IV presents the lowest net water exchange (17800 $m^3/a$). In addition, the total net water exchange is 248000 $m^3/a$. Similar exchange patterns can be observed in the other type of lake, with the difference that the net water exchange increased obviously in each water exchange zone. For example, in zone I, the water exchange increased by 35% (from 74100 to 103000 $m^3/a$), and the total water exchange of the pit lake rose by 40% (from 248000 to 349000 $m^3/a$).

Considering the thin layer between the pit lake bottom and the aquifer formed after slope collapse, it is not surprising that such a large difference in water exchange is observed. As previously mentioned, a thin layer is formed upon slope collapse affording a hydraulic conductivity between 0.35 and 0.88 m/d, much smaller than that of the aquifer. Therefore, compared to the pit lake without slope collapse, the water exchange in the lake with the collapsed slopes substantially decreases.

To the best of our knowledge, this is the first time that the effect of slope collapse on the water exchange between a pit lake and groundwater has been analyzed. However, many scholars have studied the effect of thin layers formed by lake sediments on the water exchange between natural lakes and groundwater. Genereux and Bandopadhyay applied a steady-state numerical model to investigate the impact of sediments on lake-bed water exchange patterns. They found that the addition of a sediment layer with conductivity of 0.01 m/d (1% of the aquifer conductivity) would reduce the annual water exchange. Moreover, reducing the sediment layer conductivity from 0.01 to 0.001 m/d decreased the water exchange value by 25%, similar to the change in water exchange in this pit lake

**Table 2** Model parameters after calibration

| Aquifer lithology | $K_h$ (m/d) | $K_h/K_v$ | $S_y$ | $a$ |
|---|---|---|---|---|
| Clay | 0.18 | 1 | 0.03 | 0.15 |
| Sandy clay | 0.46 | 1 | 0.05 | 0.23 |
| Clay sand | 1.29 | 1 | 0.07 | 0.25 |
| Fine sand | 12.34 | 1 | 0.10 | 0.28 |
| Medium sand | 82.32 | 1 | 0.12 | 0.30 |
| Coarse sand | 110.70 | 1 | 0.18 | 0.35 |

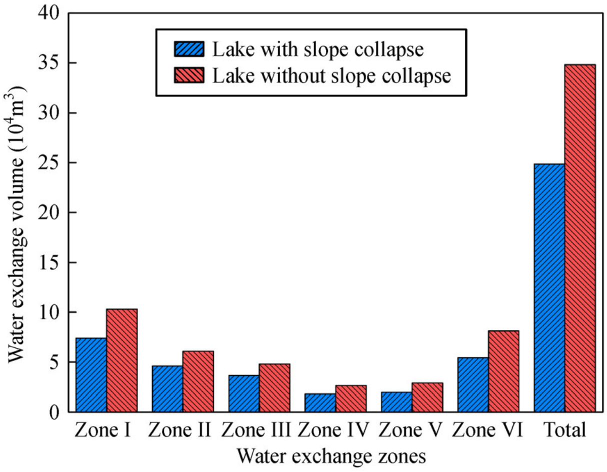

**Fig. 7** Net water exchange with and without collapse between groundwater and the pit lake in 2013.

study. They concluded that lake-bed-sediment layers are a major factor affecting the lake bed water exchange (Genereux and Bandopadhyay, 2001).

### 4.2 Spatio-temporal variation of water exchange

For the slope-collapsed pit lake, the different water exchange zones have corresponding water exchange areas. To compare the water exchange rates in different zones, the monthly net water exchange is normalized using the monthly net water exchange per unit width. The monthly net water exchange per unit width, together with the pit lake level and adjacent groundwater level, are presented in Fig. 8. This involves two water exchange components, a positive value indicates that the pit lake is recharged by groundwater, while a negative value indicates that groundwater is recharged by the pit lake.

In Fig. 8(a), it is obvious that, during the 1-year simulation period, the groundwater level adjacent to water exchange zones I and II is higher than the pit lake water level, affording an always positive monthly net water exchange per unit width. In addition, the groundwater level adjacent to zone I is lower than in zone II, but the monthly net water exchange per unit width is higher than that in zone II. Moreover, the monthly net water exchange per unit width of these two zones shows a similar change. For example, in zone I during the period from January to April, the monthly net water exchange per unit width increases from 14.7 to 23.6 m$^3$ and gradually decreases to its lowest value from May to July. The lowest value is 3.8 m$^3$ (16.1% of the maximum value). After July, it increases again, from 5.3 to 12.3 m$^3$.

From Fig. 8(b), a similar monthly net water exchange per unit width pattern can be observed for zones III and IV with the following differences: 1) the monthly net water exchange per unit width clearly decreases, and 2) from June to August, the monthly net water exchange per unit width of zone IV is negative. From Fig. 8(c), zones V and VI also have a similar monthly net water exchange per unit width pattern, with the difference that the monthly net water exchange per unit width of zone V is negative in June and July.

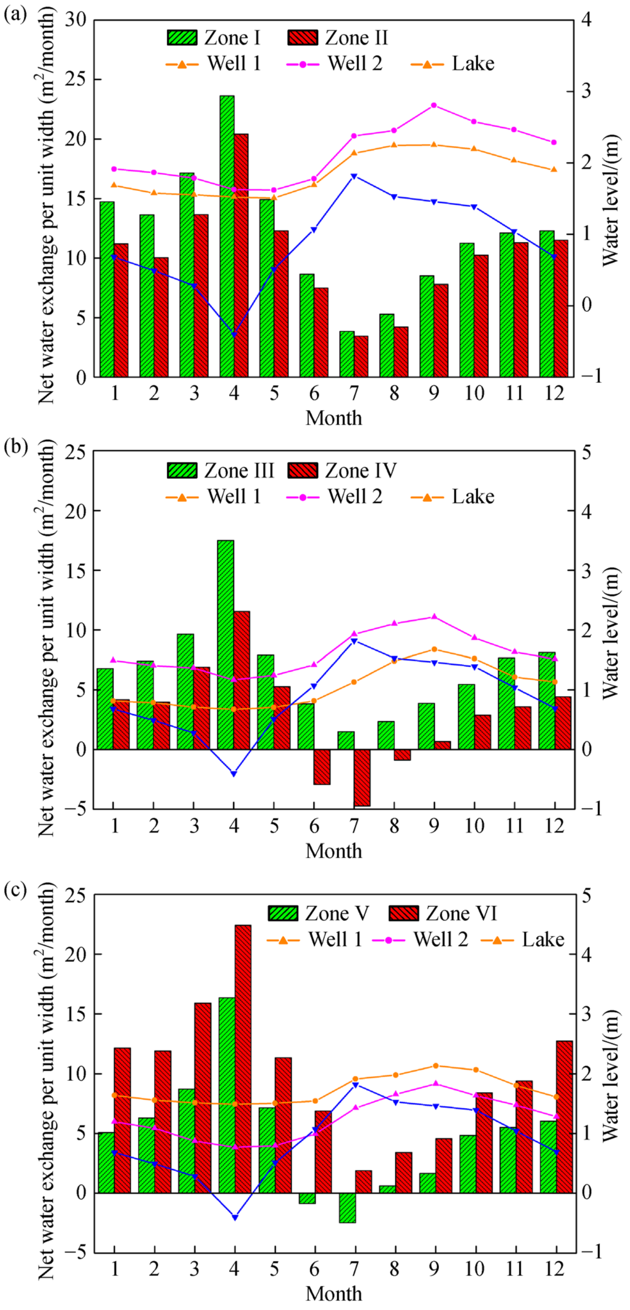

**Fig. 8** Monthly unit width flow-in or flow-out of water exchange zones and water tables of lake and monitoring wells in 2013: (a) zones I and II, (b) zones III and IV, and (c) zones V and VI.

In addition, according to Figs. 4 and 8, it can be seen that, for the pit lake, the largest monthly net water exchange per unit width is observed in the northern peripheral zones (zone I) throughout the simulation period. Outwards from zone I, the monthly net water exchange per unit width decreases in the southern direction toward zone IV.

As mentioned earlier, the positive and negative changes in the monthly net water exchange per unit width indicate the recharge relationship between the pit lake and groundwater. From Figs. 8(b) and 8(c), the change in the monthly net water exchange per unit width is clear, when we notice the relationship between the pit lake level and the groundwater level adjacent to each water exchange zone. This indicates direct dependence of the monthly net water exchange per unit width on the hydraulic gradient (Virdi et al., 2013; Taviani and Henriksen, 2015). However, from Fig. 8(a), analysis by the hydraulic gradient alone can not explain the reason that the monthly net water exchange per unit width in zone II is smaller than that in zone I. This is led by the difference in hydraulic conductivity of the thin layer formed by the collapsed pit lake slope.

Genereux and Bandopadhyay (2001) found that the amount of water exchange decreases when introducing a lower hydraulic conductivity aquifer below the lake bed, which is similar to the water exchange pattern in zones I and II in this study. In addition, for the previously mentioned artificial Lake Turawa (TL), El-Zehairy found that compared to a natural lake, the hydraulic gradient between TL and groundwater is larger, but the water exchange peaks of TL are smaller than in the natural lake (El-Zehairy et al., 2018). This is believed to occur most likely because the natural lake leakage (0.059–0.077 $d^{-1}$) is much larger than the leakage of TL (0.0007–0.0015 $d^{-1}$).

Also, it is worth noticing that the seasonal amplitude of the water level of natural lakes is small ($<0.5$ m) compared to that of pit lakes (~2 m) (Smerdon et al., 2007; Taviani and Henriksen, 2015). The water level of the pit lake varies by ~1.5 m within 12 days. Owing to such large and fast water level changes, the amount of water exchange between the pit lake and groundwater also changes dramatically. This is also the reason behind the largest net exchange (45300 $m^3$) in April being 57 times the smallest net exchange (790 $m^3$) in July.

## 5 Conclusions

In this study, the influence of slope collapse on water exchange between the pit-lake and groundwater and the space-time changes of the water exchange were deeply analyzed by constructing a pit lake–groundwater interaction numerical model. And the following conclusions can be drawn:

1) In the absence of pit lake slope collapse, the water exchange between the pit lake and groundwater is 349000 $m^3/a$, which is 1.40 times the water exchange observed under slope collapse conditions. Therefore, the collapse of the pit lake slope reduces the water exchange between the pit lake and groundwater.

2) During the simulation period, for all the water exchange zones, the monthly net unit-width exchange showed the same trend: increasing first, then decreasing, and finally increasing again. It is mainly because that the heavy rainfall changes the hydraulic gradient between the pit-lake and groundwater.

3) During the same water exchange period, in the northwestern part of the pit lake, the monthly net unit-width exchange is the largest, showing a downward trend in the southern direction. The direction and magnitude of water exchange between the pit lake and groundwater depends on the hydraulic gradient between the pit lake and the aquifer around the lake bed and the hydraulic conductivity of the thin layer formed upon slope collapse.

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