Attenuation of the contribution of groundwater to a wetland caused by groundwater overexploitation

Tianyu Zhou[1], Longcang Shu[1], Chengpeng Lu[1], and Bo Liu[1]

[1]Hohai University College of Hydrology and Water Resources

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Abstract

The continuous exploitation of groundwater has made wetland degradation an ecological and geological environmental problem that cannot be ignored and which has had impacts on the ecological environment and human production and life. In this study, with the help of Visual MODFLOW software, we used numerical simulation technology to simulate the wetland–aquifer interaction during the multiyear pumping process, establish a quasi-ideal model of wetlands based on the actual area of the Baiyangdian Basin, simulate the relationship of water quantity change between wetlands and piedmont plain aquifers during groundwater exploitation and its natural recovery process, and quantify the attenuation of the contribution of groundwater to wetlands caused by groundwater overexploitation. The results show that the impact of groundwater overexploitation on wetland degradation is mainly divided into two parts: one is the reduced base flow from the piedmont plain to the wetland, and the other is the induced infiltration caused by the reverse recharge of groundwater from the wetland due to the pumping effect. At the beginning of pumping, the effect of reduced base flow on wetland degradation is dominant, but with a longer pumping time, the effect of induced infiltration on wetland degradation exceeds the effect of reduced base flow. After stopping pumping, the effect of induced infiltration on wetland degradation responds instantly and decreases rapidly, while the effect of reduced base flow on wetland degradation continues for a long time. The total water reduction of wetlands increases with increasing hydraulic conductivity, and in actual wetland areas, if groundwater overexploitation is not restricted or artificial supply measures are not taken, the amount of wetland water will gradually decrease until it is exhausted.

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Tianyu Zhou [1, 2], Longcang Shu[1, 2, *], Chengpeng Lu[1, 2], Bo Liu[1, 2]

1 College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China;

211301010054@hhu.edu.cn(Z.T.Y.)

2 State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China

* Correspondence:*mailto:lcshu@hhu.edu.cn* ; Tel: +86-138-5194-1641

Abstract : The continuous exploitation of groundwater has made wetland degradation an ecological and geological environmental problem that cannot be ignored and which has had impacts on the ecological environment and human production and life. In this study, with the help of Visual MODFLOW software, we used numerical simulation technology to simulate the wetland–aquifer interaction during the multiyear pumping process, establish a quasi-ideal model of wetlands based on the actual area of the Baiyangdian Basin, simulate the relationship of water quantity change between wetlands and piedmont plain aquifers during groundwater exploitation and its natural recovery process, and quantify the attenuation of the contribution of groundwater to wetlands caused by groundwater overexploitation. The results show that the impact of groundwater overexploitation on wetland degradation is mainly divided into two parts: one is the reduced base flow from the piedmont plain to the wetland, and the other is the induced infiltration caused by the reverse recharge of groundwater from the wetland due to the pumping effect. At the beginning of pumping, the effect of reduced base flow on wetland degradation is dominant, but with a longer pumping time, the effect of induced infiltration on wetland degradation exceeds the effect of reduced base flow. After stopping pumping, the effect of induced infiltration on wetland degradation responds instantly and decreases rapidly, while the effect of reduced base flow on wetland degradation continues for a long time. The total water reduction of wetlands increases with increasing hydraulic conductivity, and in actual wetland areas, if groundwater overexploitation is not restricted or artificial supply measures are not taken, the amount of wetland water will gradually decrease until it is exhausted.

Keywords: Wetland degradation; groundwater overexploitation; numerical simulation; surface water and groundwater; attenuation of contribution.

Introduction

Wetland degradation refers to the unreasonable, weakened or even lost structure and function of wetland ecosystems under the influence of unreasonable human activities or adverse natural factors and leads to the degradation of system stability, resilience, productivity and service functions at multiple levels. Wetland degradation includes three important parts: the degradation of organisms, soil and water[1, 2]. Among them, water is decisive in maintaining the stability and health of wetland ecosystems[3].

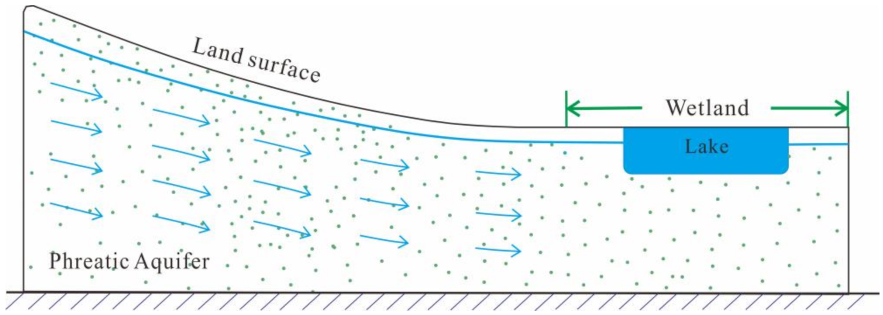
The decrease in water resources leads to the shortage of wetland water replenishment, which is a direct natural factor[4]. Human activities are the main driving factor of wetland water reduction, and they are also one of the main causes of wetland degradation[5, 6]. In China, the main groundwater overexploitation areas are concentrated in North China and Northeast China. The North China Plain is one of the water-scarce areas as well as an area of fast socioeconomic development in China[7]. Groundwater exploitation has supported quick economic growth, which has also caused wetland degradation, land subsidence, sea water intrusion, and other adverse effects[8]. Groundwater exploitation in the North China Plain has changed the groundwater flow pattern from natural horizontal flow to vertical flow under exploitation conditions, and many large groundwater cones of depression have been formed[9]. By using the backpropagation (BP) neural network analysis method, Wei, L et al. determined the control factors affecting the change in shallow groundwater in overexploitation areas. The results show that the groundwater depth in most areas of the North China Plain is increasing continuously except for a few areas, and artificial exploitation is the controlling factor affecting the shallow groundwater in the North China Plain[10].

Baiyangdian Lake is the largest freshwater lake in North China[11, 12], and it is also the largest wetland ecosystem in the North China Plain. In recent years, the ecological environment has been severely damaged, and the ecological function of the Baiyangdian wetland has gradually weakened since 1989[13]. Insufficient water intake is an important reason for the deterioration of the Baiyangdian wetland ecology and its environment, as well as the shrinking of Baiyangdian Lake[14]. During the 1990–2017 period, natural wetlands in Baiyangdian shrank as a whole. Precipitation was the main influencing factor of the changes in natural wetlands, and remedial water replenishment measures could only temporarily alleviate the water crisis in Baiyangdian[15]. The South-North Water Transfer Project plays a positive role in alleviating the short supply of groundwater in the North China Plain as well as in the maintenance and protection of groundwater[16]. It will relieve the groundwater shortage problem, but it cannot eradicate the water shortage problem, and groundwater will still be the main source of industrial, agricultural and domestic water consumption[17]. At present, research on the main factors influencing Baiyangdian wetland degradation is mainly divided into two aspects: climate change and human activities[18]. The impact of climate change is mainly due to the decrease in atmospheric precipitation, which leads to a decrease in water inflow into the lake. The impact of human activities includes the construction of upstream water conservancy projects and the exploitation of groundwater[19]. The reason for the decrease in wetland water volume caused by groundwater exploitation is the interaction between wetland surface water and groundwater.

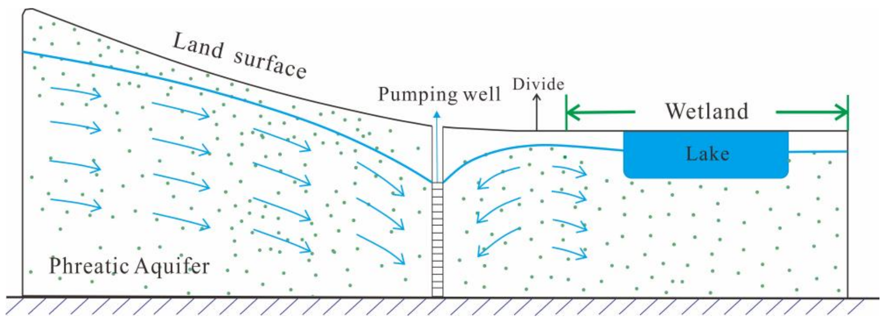
Rivers, lakes and wetlands interact with groundwater in many ways[20, 21]. Zektser, S et al. described the environmental impact of large-scale groundwater exploitation and its overexploitation. A case study in the southwestern United States shows that large amounts of groundwater exploitation can reduce lake levels[22]. Yang, Z et al. used multiple field measurements in the semiarid Bulang subcatchment, part of the Hailiutu River basin in Northwest China, to identify and quantify groundwater and surface water interactions, which showed that groundwater and stream water are essentially one resource and need to be managed together[23]. Wang, W. K et al. discovered that the hydrodynamic processes and ecological effects of groundwater and river water are controlled by stream–groundwater transformation[24]. Zhang Haojia et al. used the GSFLOW pair to build a coupling model of surface water and groundwater and studied the conversion relationship between surface water and groundwater[25]. Shu Longcang et al. quantitatively studied the exchange capacity of surface water and groundwater in the New Bianhe River in Suzhou City[26]. Chen Xunhong used numerical simulation techniques to simulate the interaction between rivers and aquifers in the process of seasonal groundwater pumping, quantitatively analyzed the process of total river water depletion in pumping and later pumping periods, and described the interaction between surface water and groundwater in this process[27].

Research on wetlands mainly focuses on the current status of wetland degradation and the influence of the reduction in surface water and atmospheric precipitation on wetland degradation. There are few studies that quantitatively analyze the relationship between wetland surface water and groundwater. Therefore, we used the quasi-ideal model of wetland–aquifer, with the help of the Baiyangdian wetland, to explore the relationship between wetland surface water and groundwater overexploitation, reveal the mechanism of water exchange between groundwater and wetland surface water, and provide a reference for solving the problem of wetland degradation.

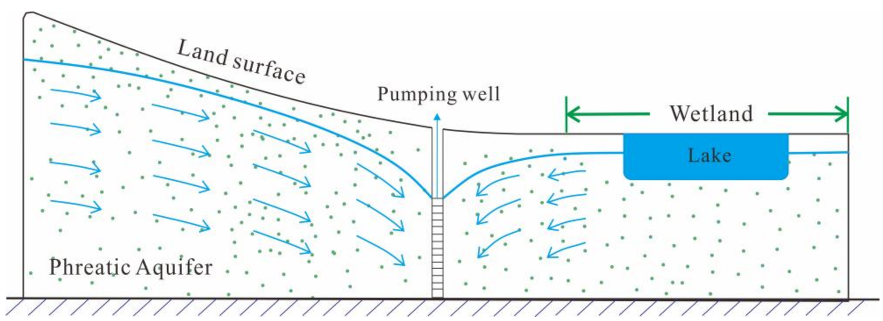
Wetland–aquifer interaction : In the wetland–aquifer system, when the head of the piedmont plain aquifer is higher than the head of the wetland, the wetland receives groundwater recharge from the piedmont plain aquifer, and when there is a head difference and hydraulic connection between the piedmont plain and the wetland, the groundwater recharges the wetland. Under natural conditions, the base flow does not change significantly due to natural variability and is basically stable. However, when pumping is performed at a location where the head is higher than the wetland, the groundwater flow field in the area will be changed. Initially, when the pumping volume is small and the pumping time is short, the cone of depression is small, which will not change the recharge relationship between the piedmont plain aquifer and the wetland. However, the base flow from the piedmont plain aquifer to the wetland decreases, the amount of water obtained by the wetland gradually decreases, and a groundwater divide forms between the wetland and the pumping wells; as the pumping time and the pumping rate increase, the cone of depression expands, and the divide gradually shifts to the wetland, and the base flow recharge to the wetland decreases until the divide expands to the wetland boundary. At the same time, the hydraulic gradient between the pumping wells and the wetland is reversed, the wetland's supply from groundwater disappears, and the piedmont plain aquifer will no longer recharge the wetland, while the wetland will continuously recharge the piedmont plain aquifer. The process of recharging the piedmont plain aquifer from the wetland is called induced infiltration. Therefore, the reduced base flow and induced infiltration are the reason for the depletion of the total water flow in the wetland, which leads to wetland degradation. The three processes of wetland–aquifer interaction are shown in Figure 1(a), (b), and (c).



Process 1: No pumping well



(b) Process 2: The existence of a groundwater divide



(c) Process 3: Wetland recharge to groundwater

Figure 1.Schematic diagram of wetland-aquifer interaction at different pumping stages

Methods

In this study, the models were built using Visual MODFLOW software, which is the most popular and internationally recognized professional standard visualization software system for 3D groundwater flow and solute transport simulation and evaluation. The system was developed by Waterloo Hydrogeology Canada based on the original MODFLOW software and has a powerful graphic visual interface function. The model area and the calculation unit can be circled directly on the computer, and the values for each unit and boundary condition can be assigned directly on the computer.

In this study, a quasi-ideal model is used to add the hydrogeological parameters of the actual area to the ideal model. The study area of the ideal model is a 10 km × 20 km rectangular area, with 10 km × 12 km of groundwater recharge area on the left side of the piedmont plain, 10 km × 8 km of wetland on the right side, and 4 km × 4 km of lake in the middle of the wetland.

In the ideal model, the western boundary is set as the flux boundary, the eastern boundary is the constant head boundary, the western boundary of the wetland completely cuts the phreatic aquifer, the direction of groundwater flow in the study area is from west to east, and the contour of the groundwater level is perpendicular to the north and south boundaries, which is set as the no-flux boundary. The generalized schematic diagram of the simulation area is shown in Figure 2.

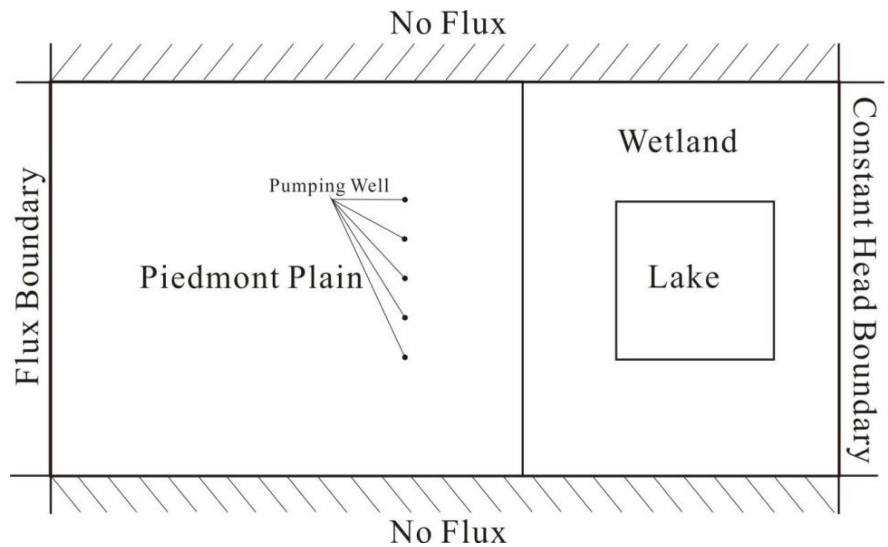


Figure 2. Generalized schematic diagram of the simulation area

The actual area on which this quasi-ideal model relies is the plain area of the Baiyangdian Basin in the North China Plain, wetland degradation refers to the degradation of the Baiyangdian wetland, and the lake set up is Baiyangdian Lake. The aquifer in this study area is a phreatic aquifer, which is divided into one layer in the vertical direction with a thickness of 60 m. In this model, precipitation infiltration recharge is the main source of groundwater recharge in the North China Plain. The coefficient of precipitation infiltration recharge α is approximately 0.17–0.35, which is taken as 0.2; the lateral recharge in the study area is 25% of the rainfall infiltration recharge. The average depth of Baiyangdian Lake is 3.5 m, the elevation of the lake surface is 10.5 m, and the elevation of the lake bottom is 7 m. The water-bearing medium is a sand layer, the hydraulic conductivity is set as 25 m/d, the specific yield μ=0.20, and the bottom of the phreatic aquifer is a clay layer, taken as the confining bed.

According to the above hydrogeological conceptual model, the groundwater flow in the study area is generalized to a homogeneous isotropic submerged two-dimensional transient flow model, and the corresponding mathematical model is as follows:

$$\frac{\partial}{\partial x}\left(K\left(H-B\right)\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\left(H-B\right)\frac{\partial H}{\partial y}\right)+W=\mu\frac{\partial H}{\partial t},(x,y)\in D \quad (1)$$

$$H\left(x,y,t\right)|\tau_1 \ = H_1\left(x,y,t\right),(x,y)\in\tau_1, t\geq 0 \quad (2)$$

$$K\left(H-B\right)\frac{\partial H(x,y)}{\partial n}|\tau_2 \ = q\left(x,y,t\right),(x,y)\in\tau_2 \quad (3)$$

$$H\left(x,y,t\right)|t=0 \ = H_0\left(x,y\right),(x,y)\in D \quad (4)$$

where K is the hydraulic conductivity; W represents the source-sink term; D represents the extent of the simulation area; H represents the groundwater level; B is the elevation of the phreatic aquifer bottom; H_1

is the initial groundwater level; q is the flow rate; μ is the specific yield; t is the time; τ_1 is the Dirichlet condition; and τ_2 is the Neumann condition.

The model is split into 50 rows and 100 columns, and according to the Zone Budget module in Visual MODFLOW, the wetland and piedmont plain aquifers are divided into two zones, zone 1 and zone 2, as shown in Figure 3. This is done to quantitatively calculate the changes in reduced base flow, induced infiltration and total water reduction due to pumping during the wetland–aquifer interaction.

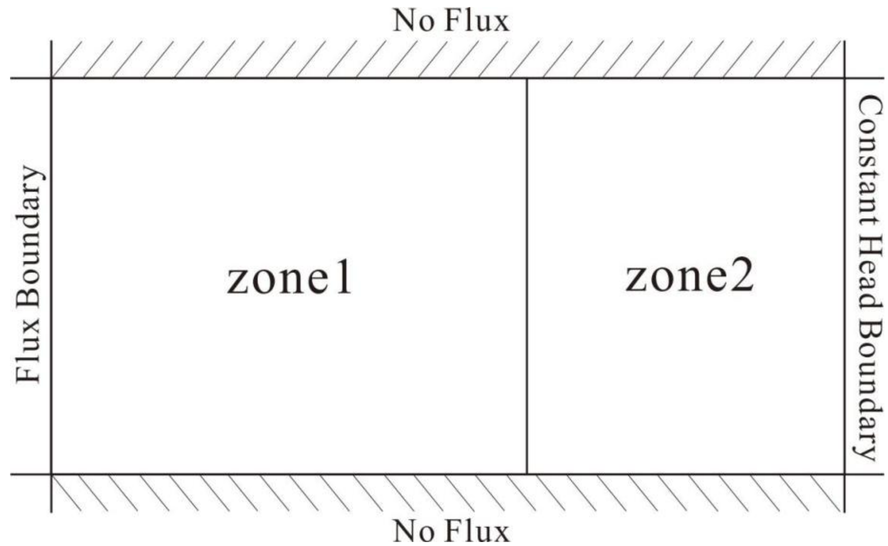


Figure 3. Model partitioning diagram

In the numerical simulation of the quasi-ideal model, the simulation duration is 7200 days, and the time step is 30 days. Different situations were simulated for comparison. First, we investigated the groundwater flow between zone 1 and zone 2 by setting up five pumping wells in the study area and continuously pumping during the simulation duration of 7200 days. Moreover, to explore the natural recovery ability of the wetland, the pumping wells were shut down when they were pumped up to 3600 days, and the recovery of the wetland was analyzed from day 3600 to day 7200 under the condition that a cone of depression had been formed due to groundwater overexploitation. The model was then analyzed for parametric uncertainty, and three different values of hydraulic conductivity K were set during the simulation by describing the effect of changes in the hydraulic conductivity on wetland water flow through indicators such as the reduced base flow, induced infiltration and total water reduction, as well as analyzing the effect of different hydraulic conductivities on wetland recovery capacity under the condition of closing the pumping wells at 3600 days.

Results

Simulation results when groundwater is not exploited

First, in the simulation time without pumping wells, since the initial head values in the study area were artificially set when the model was established, the overall initial head values decreased from west to east, while the head values at the eastern constant head boundary were equal to the initial head values set at the eastern boundary, and the western boundary was set as a flux boundary to continuously recharge the entire study area. Therefore, in the simulation time without pumping wells, the overall groundwater flow direction is from west to east, and the wetland is sufficiently recharged. At this time, the wetland will not be degraded, which is the first process of wetland–aquifer interaction.

Simulation results of groundwater exploitation

Five pumping wells were set up in the study area, and the well locations and pumping rates are shown in Table 1. The pumping times were all 7200 days. Since the time step was 30 days during the simulation, the Zone Budget module also output water volumes every 30 days.

Table 1 Location of pumping wells and pumping rate

Pumping well	X-axis coordinates /m	Y-axis coordinates /m	Pumping rate /m^3/d
PW1	11000	3000	5000
PW2	11000	4000	5000
PW3	11000	5000	5000
PW4	11000	6000	5000
PW5	11000	7000	5000

When the pumping time was 90 days, only the water level near five pumping wells dropped slightly, and a small groundwater flow to the wells could be observed, forming five small cones of depression, as shown in Figure 4. The water level at the location of the pumping wells was 8.0 m. The overall groundwater flow direction was still from west to east. According to the Zone Budget module, the base flow from zone 1 to zone 2 was 3023.1 m^3/d, which is 100.6 m^3/d less than the 3123.7 m^3/d at the simulation time of 60 days. The reason is that the installation of intermediate pumping wells leads to a reduction in water flow to the wetland (zone 2), which can be described as reduced base flow. At this time, a groundwater divide has formed between the pumping wells and the wetland (Figure 4, red dotted line), the water level in the wetland and cone of depression

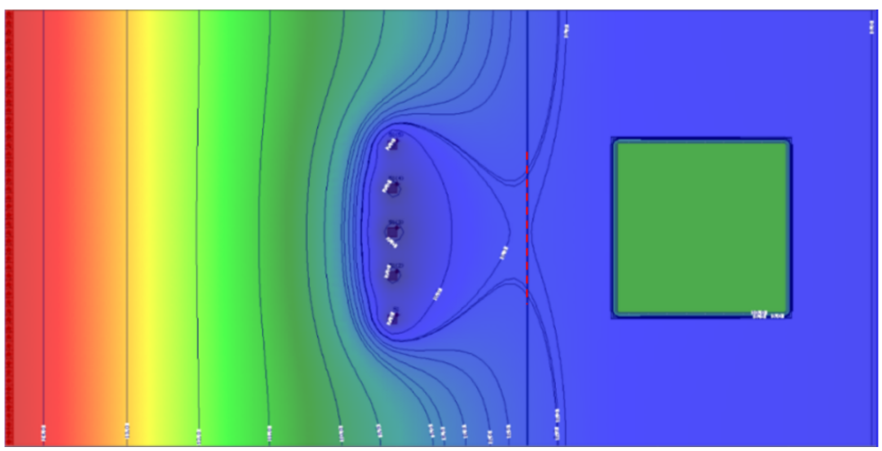


Figure 4. Contour of groundwater level for 270 days of pumping

is relatively low, and the water level in the middle location is higher than that on the two sides. As the pumping continues, the pumping time reaches 270 days, and the base flow from zone 1 to zone 2 is reduced to 1525.8 m^3/d. At this time, the area of the cone of depression also increases with the pumping time. The water level at the location of the pumping wells also decreased to 7.0 m, as shown in Figure 5. The figure also shows that the hydraulic gradient has reversed in the middle of the wetland and at the pumping well, and the groundwater flow direction has changed from east to west, which means that the groundwater divide has gradually spread to the wetland with increasing pumping time (Figure 5, red dotted line), and this process is the second process of wetland–aquifer interaction.

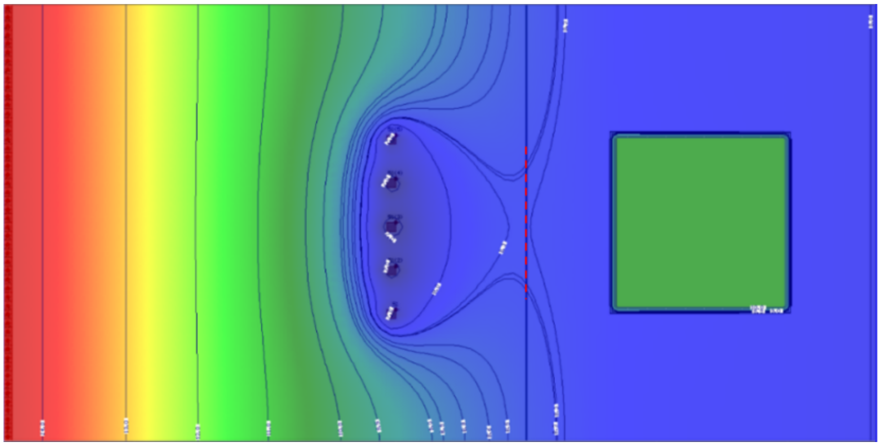


Figure 5. Contour of groundwater level for 270 days of pumping

When the pumping time is 300 days, the base flow from zone 1 to zone 2 becomes 1313.8 m^3/d; at the same time, some water flows from zone 2 to zone 1 with a volume of 41.12 m^3/d, which means that the water from the wetland recharges the piedmont plain aquifer, and the process can be described as induced infiltration. The area of induced infiltration is initially distributed in the center at the junction of zones 1 and 2. This is because the pumping wells are located in the middle of the study area, and the extent of the cone of depression formed during pumping is also roughly distributed in the middle. The inversion of the hydraulic gradient in the middle of the study area causes the groundwater flow direction to change from east to west, while the edge is relatively less affected by pumping, which can be clearly observed in Figure 5. Another reason for setting the pumping wells in the middle of the study area is that the south and north boundaries of the model are no-flux boundaries, and the contour of the groundwater level is perpendicular to the south and north boundaries. If the pumping wells are located too close to the no-flux boundaries, with the increase in pumping time, the formed cone of depression will definitely affect the groundwater flow direction at the south and north boundaries, which does not match the set boundary conditions.

As the pumping process continues, the area where the hydraulic gradient is inverted becomes increasingly larger, while the infiltration volume of zone 2 flowing to zone 1 increases, and the base flow of zone 1 flowing to zone 2 decreases. The base flow from zone 1 to zone 2 is reduced to 0.69 m^3/d when pumping is carried out for 1440 days. At this time, due to the reversal of the hydraulic gradient, the infiltration from zone 2 to zone 1 increased to 2661.5 m^3/d, and the water level at the location of the pumping wells dropped to 5.0 m. When pumping was carried out for another 30 days and the simulation duration was 1470 days, the base flow from zone 1 to zone 2 became 0, which means that the groundwater divide formed between the wetland and the piedmont plain due to pumping had spread to the wetland boundary, as shown in Figure 6. The groundwater in

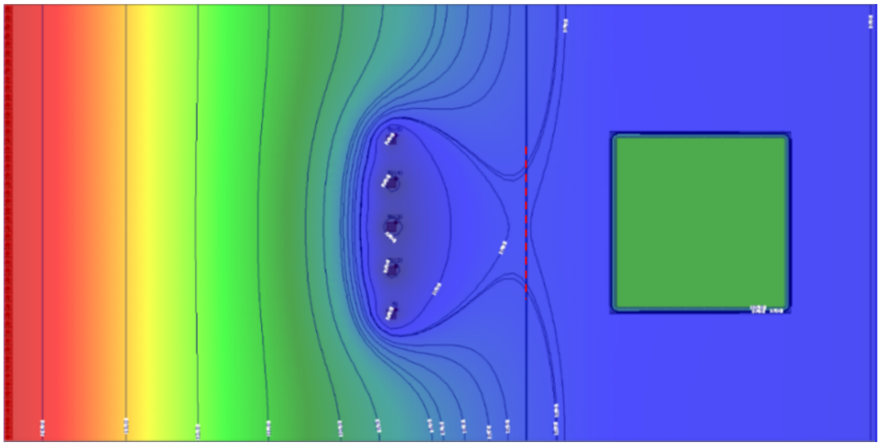


Figure 6. Contour of groundwater level for 1470 days of pumping

the piedmont plain area is no longer recharged to the wetland, and the amount of water recharged from the wetland to the piedmont plain aquifer was 2702.9 m^3/d. This process is the third process of wetland–aquifer interaction. Figures 7 and 8 show the relationship between base flow and induced infiltration with time. In the next numerical simulation, the third process is continued, and the induced infiltration from the wetland to the piedmont plain aquifer gradually increases. The induced infiltration increases to 6386.4 m^3/d at 7200 days.

To visually observe the groundwater divide formed between the piedmont plain and the wetland due to groundwater exploitation, three calculation points are set up to observe the water level change between the piedmont plain and the wetland in order to determine the specific location of the groundwater divide. The coordinates of the five calculation points are shown in Table 2.

Table 2 Location of head observation wells

Well number	X-axis coordinates/m	Y-axis coordinates/m
OB1	9200	5000
OB2	9500	5000
OB3	11800	5000

Through the simulation results and the simulated water level of the calculation point, we can observe the formation of the groundwater divide and the gradual expansion of the divide to the wetland. The profile of model row 25 and the enlarged local position are shown in Figure 7 (to better observe the groundwater divide movement, the model profile has been magnified 120 times vertically).

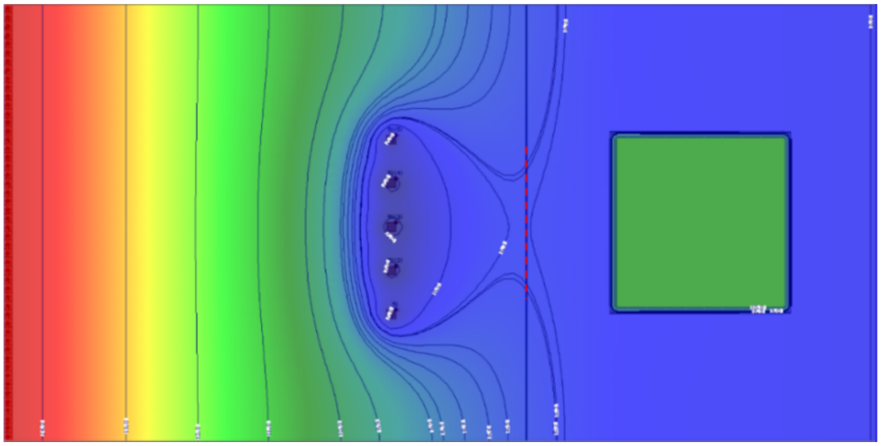
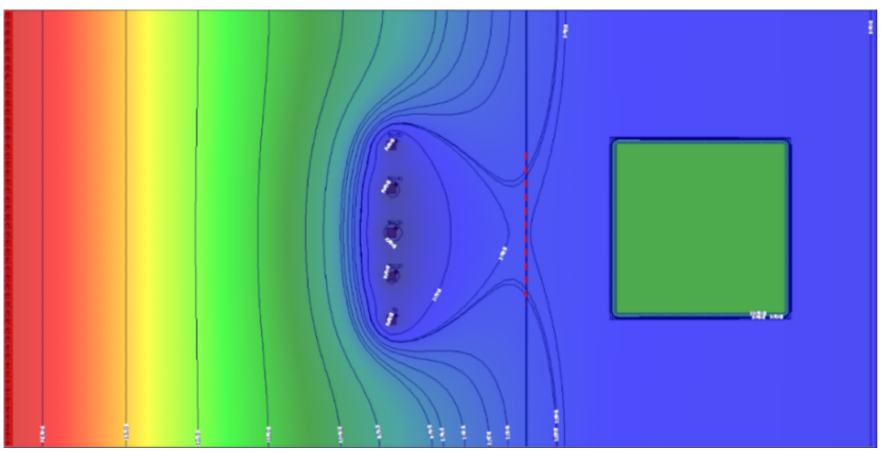
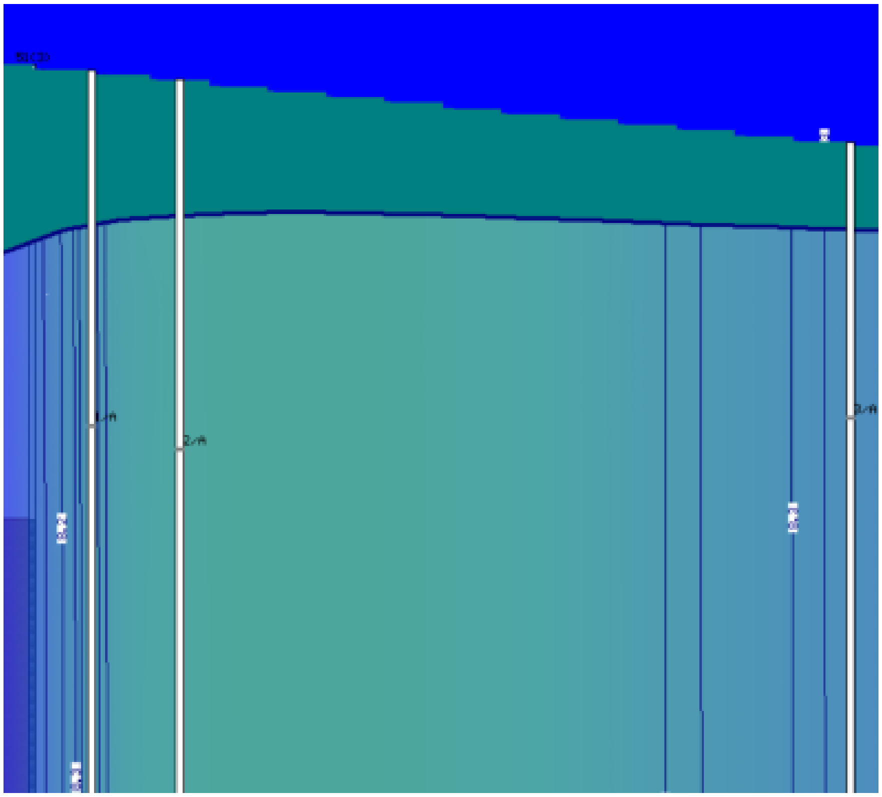


Figure 7. Model 25 row profile and local enlarged position

When the pumping time is 30 days, as shown in Figure 8 (a), the location of the groundwater divide is 500 m from the pumping well. The water levels of the three calculation points are 8.74 m, 8.91 m, and 8.19 m, which could quantitatively describe the formation of the groundwater divide. When pumping is carried out for 150 days, as shown in Figure 8 (b), the location of the groundwater divide gradually approaches the wetland boundary, 1700 m away from the pumping well. When the pumping time is 270 days, as shown in Figure 8 (c), the groundwater divide extends to the wetland boundary, and the surface water of the wetland begins to recharge the groundwater. In the remainder of the simulation time, wetland surface water supplies groundwater to the piedmont plain. Table 3 shows the groundwater levels between the pumping well and the wetland at the three calculation points at different simulation times.

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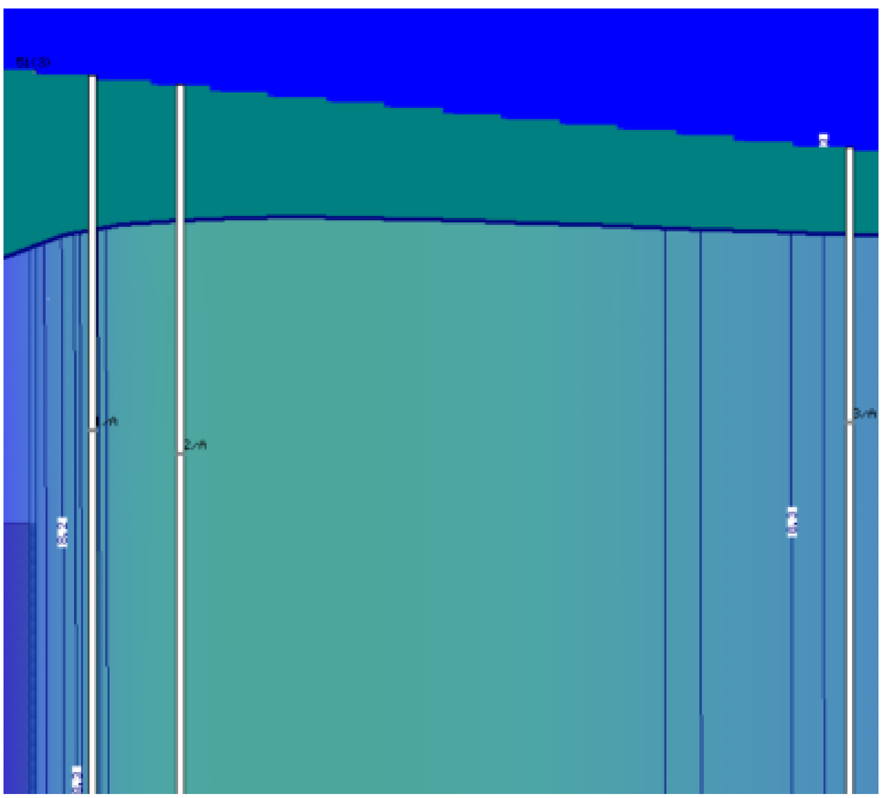
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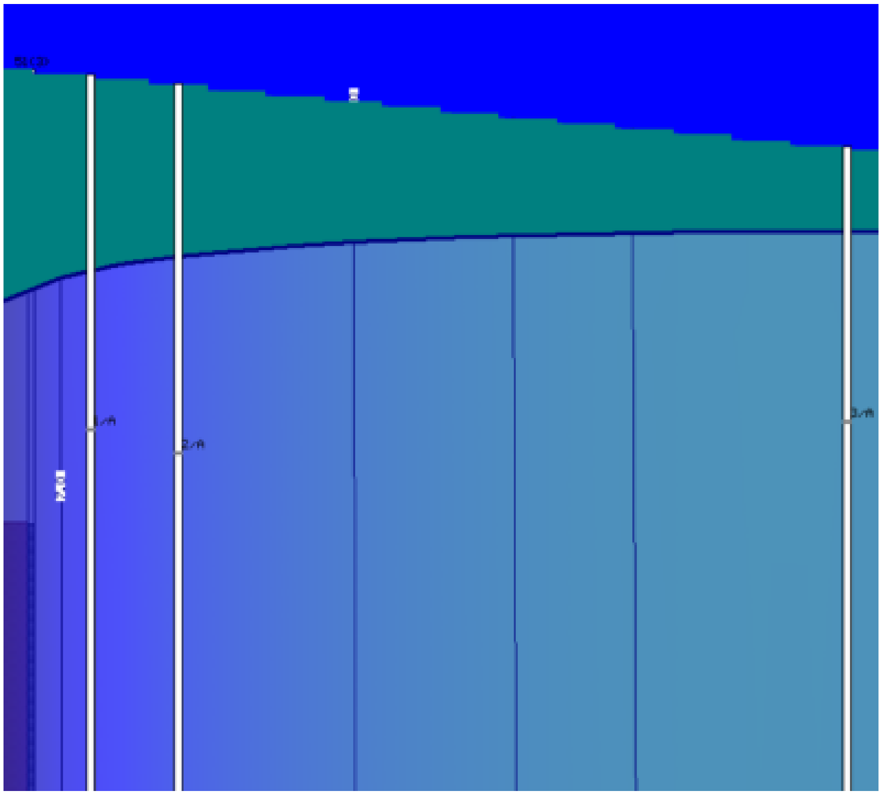
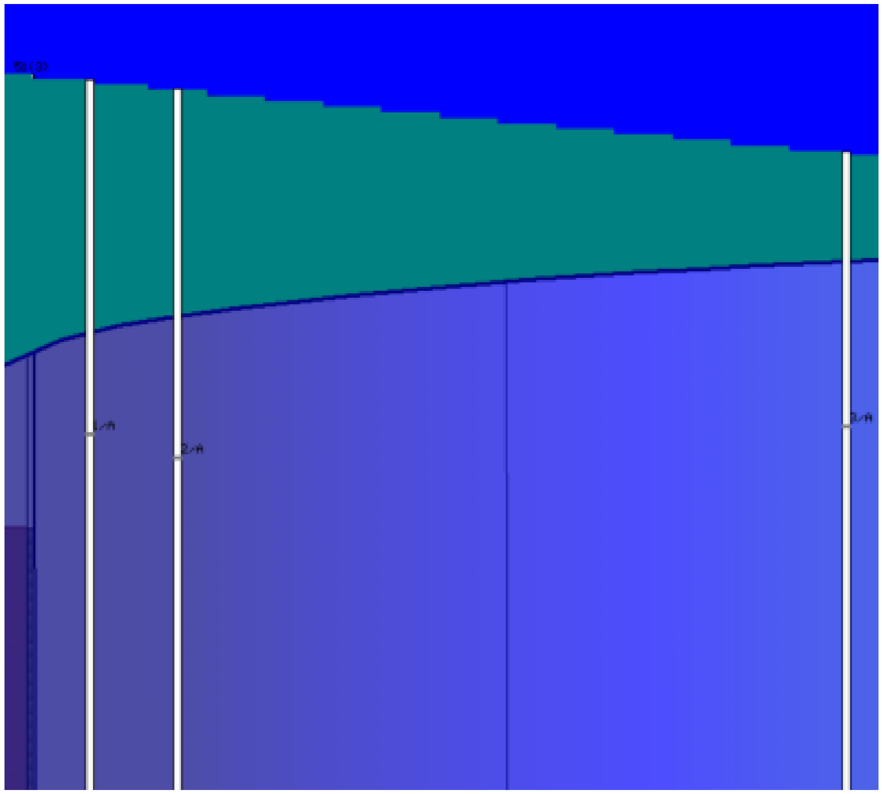
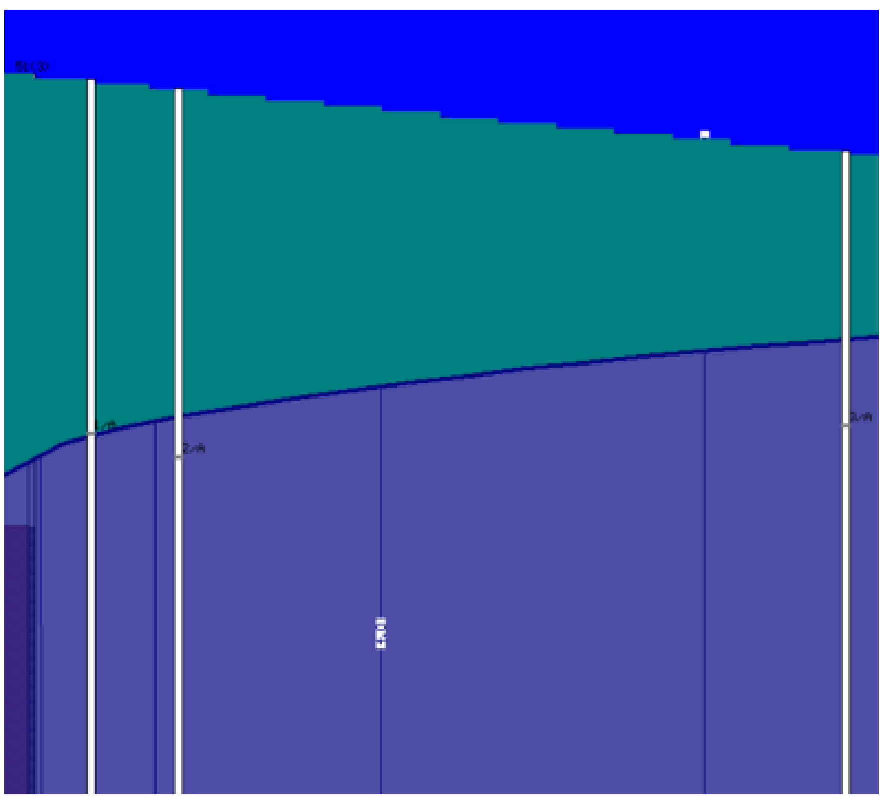
(a)30d (b)60d (c)90d







(d)270d (e)1500d (f)7200d

Figure 8. Water level between pumping well and wetland at different simulation time

Table 3 Water level at different simulation time

Calculation point	Water level(m) 30d	Water level(m) 60d	Water level(m) 90d	Water level(m) 270d	Water level(m) 1500d	Water level(m) 7200d
OB1	8.74	8.35	8.10	7.18	5.24	2.57
OB2	8.91	8.64	8.44	7.61	6.03	3.15
OB3	8.19	8.25	8.27	8.32	7.57	5.24

Figure 9 shows the change in water quantity in the wetland aquifer system, where the reduced base flow Q_2 is obtained from the following equation:

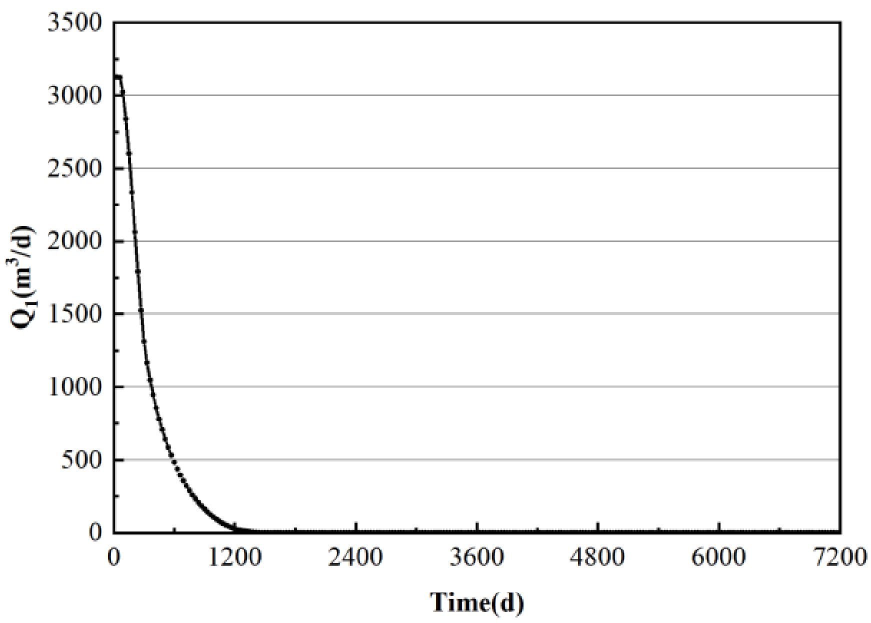
Q_2=Q_0-Q_1

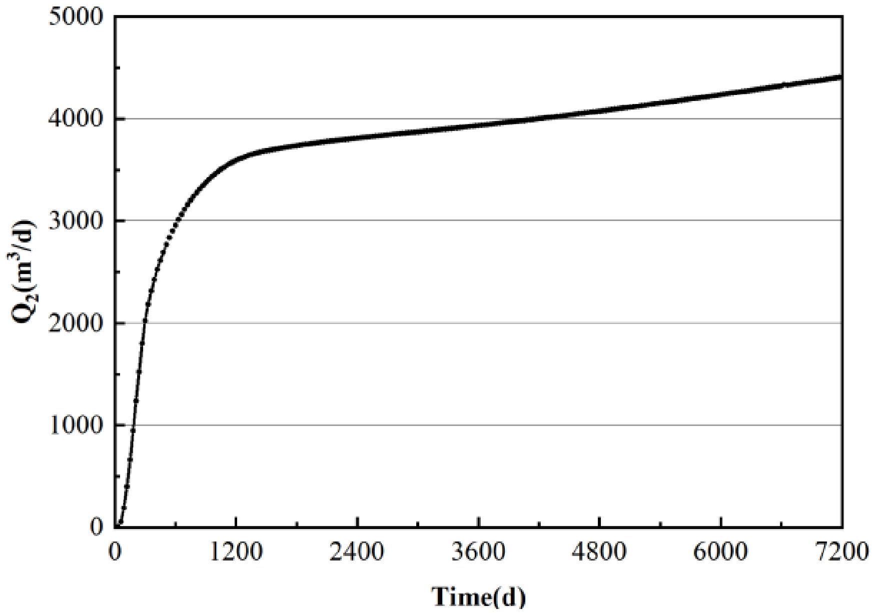
where Q_0 is the base flow when groundwater is not exploited, Q_1 is the base flow when groundwater is exploited, and Q_2 is the reduced base flow.

Total water reduction is the sum of reduced base flow and induced infiltration and represents the total water reduction in the wetland, which is obtained from the following equation:

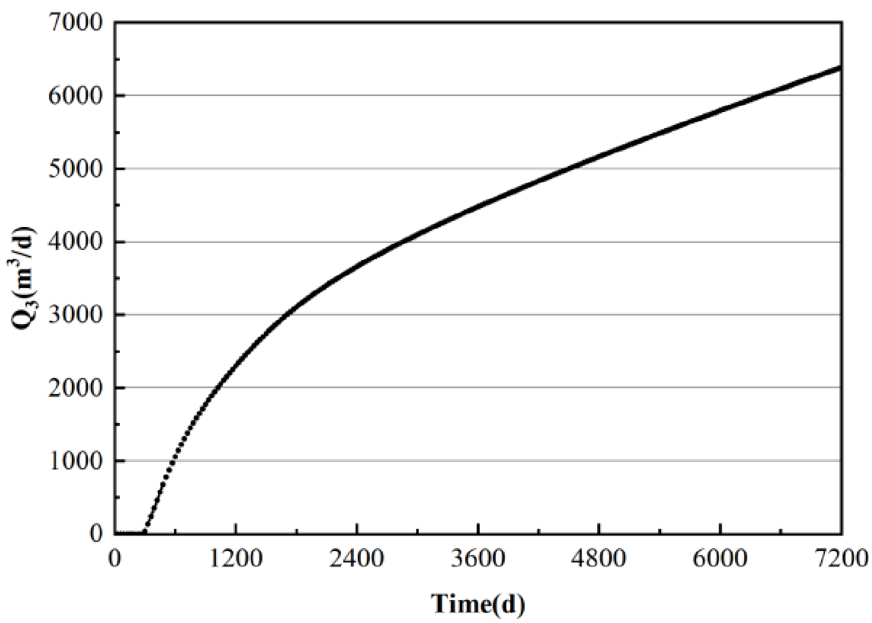
Q_4=Q_2+Q_3

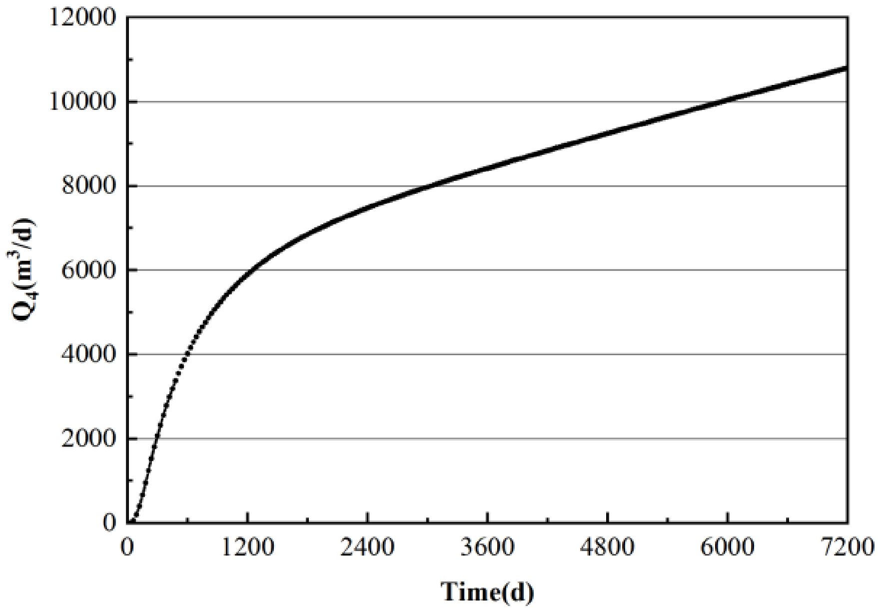
where Q_4 is the total water reduction in the wetland, Q_2 is the reduced base flow, and Q_3 is the induced infiltration.





(a) Base flow reduction process (b) Reduced Base flow increase process





(c) Infiltration increase process (d) Total water reduction process

Figure 9. Water quantity change when pumping water all the time

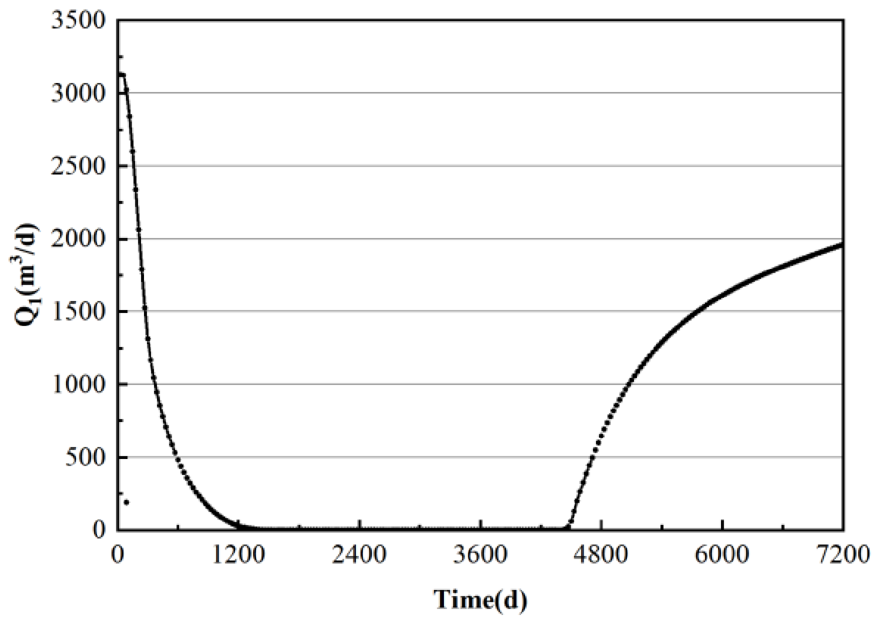
where Q_1 is the base flow, Q_2 is the reduced base flow, Q_3 is the induced infiltration, and Q_4 is the total water reduction.

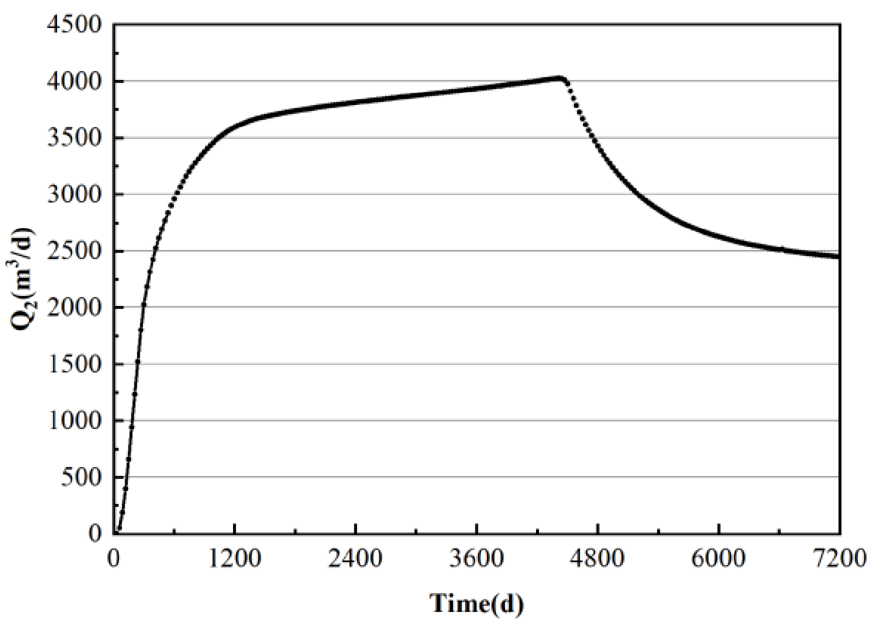
To simulate the natural recovery of the wetland when groundwater pumping is stopped after groundwater exploitation, we made some changes based on the original model. The simulation duration of the model is still 7200 days, and the pumping duration is 3600 days. When the simulation is carried out for 3600 days, the five pumping wells are closed until the end of the full simulation. After pumping is stopped, the water exchange between the wetland and the piedmont plain aquifer is similar to the inverse of the three wetland–aquifer interaction processes during the pumping period.

When pumping was stopped at 3600 days, the base flow from zone 1 to zone 2 was 0, the infiltration from zone 2 to zone 1 was 4480.1 m^3/d, and the water level at the location of the pumping wells was 4.0 m. When pumping was stopped, the induced infiltration gradually decreased, and after 840 days of pumping cessation, the infiltration from zone 2 to zone 1 became 104.75 m^3/d. At this time, the base flow from zone 1 to zone 2 changes from 0 to 6.45 m^3/d, which means that the groundwater cone of depression formed due to pumping is gradually recovering and the water level is gradually rising. The base flow also increases slowly from 0. When pumping was stopped for 930 days, the induced infiltration became 0, and the base flow became 130.11 m^3/d. Until the end of the simulation, the base flow slowly recovered to 1960 m^3/d.

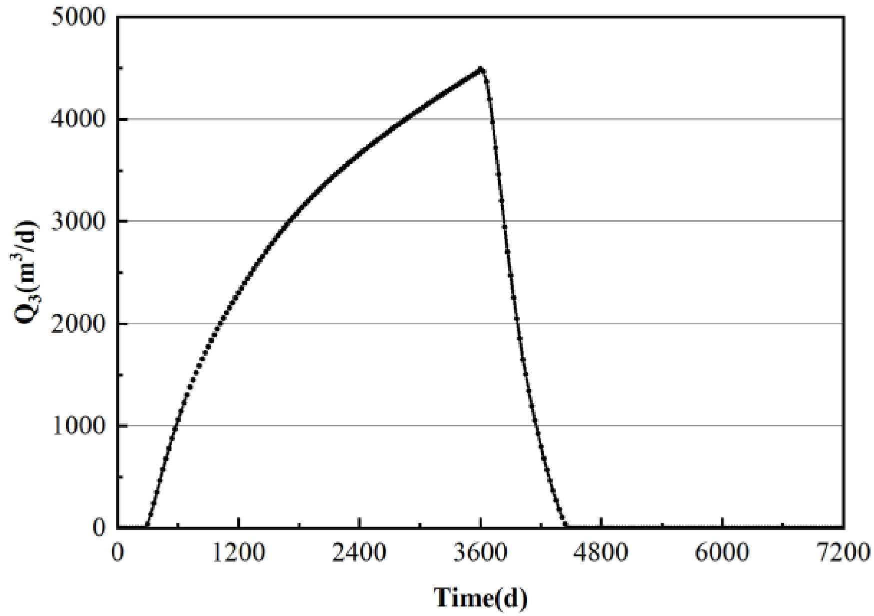
Similarly, in the numerical model for the cessation of pumping after 3600 days, we plotted the curves of base flow, reduced base flow, induced infiltration and total water reduction with time, as shown in Figure 10. It is possible to observe when the base flow and infiltration appear and disappear, which could quantitatively describe the base flow and infiltration.

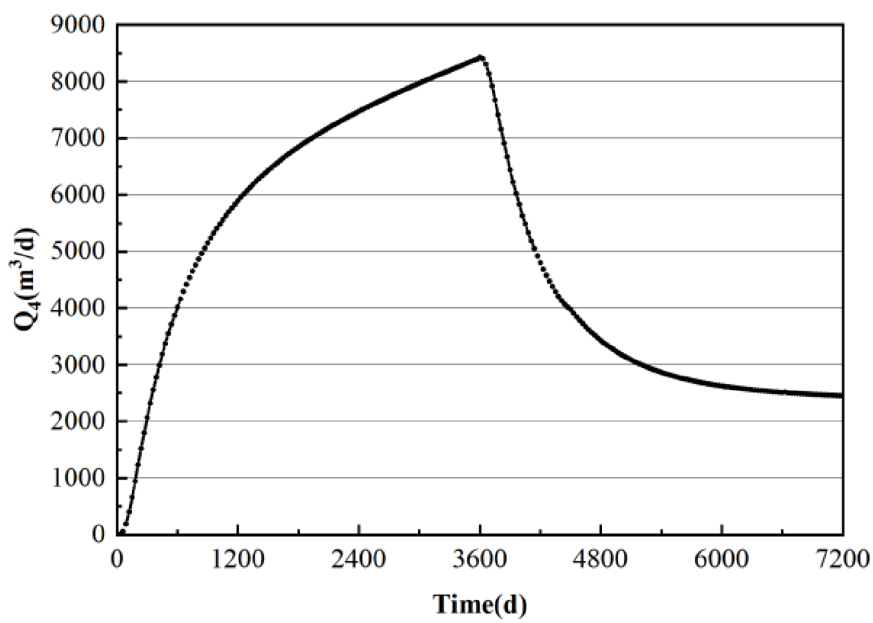
To investigate the effects of different hydraulic conductivities on the reduced base flow, induced infiltration and total water reduction in this quasi-ideal model, different hydraulic conductivities K=15, 20, and 25 m/d were used in the original model, and the pumping duration was also set to 3600 days. Pumping was stopped after 3600 days to observe the changes in the reduced base flow, induced infiltration and total water reduction under different conditions.





(a) Base flow reduction process (b) Reduced Base flow increase process





(c) Infiltration increase process (d) Total water reduction process

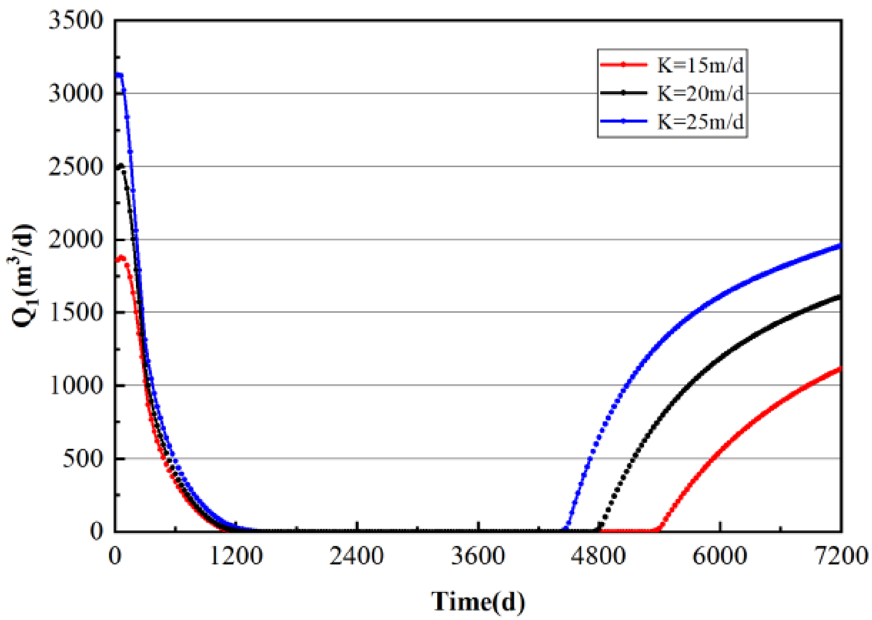
Figure 10. Water quantity change when stopping pumping for 3600 days

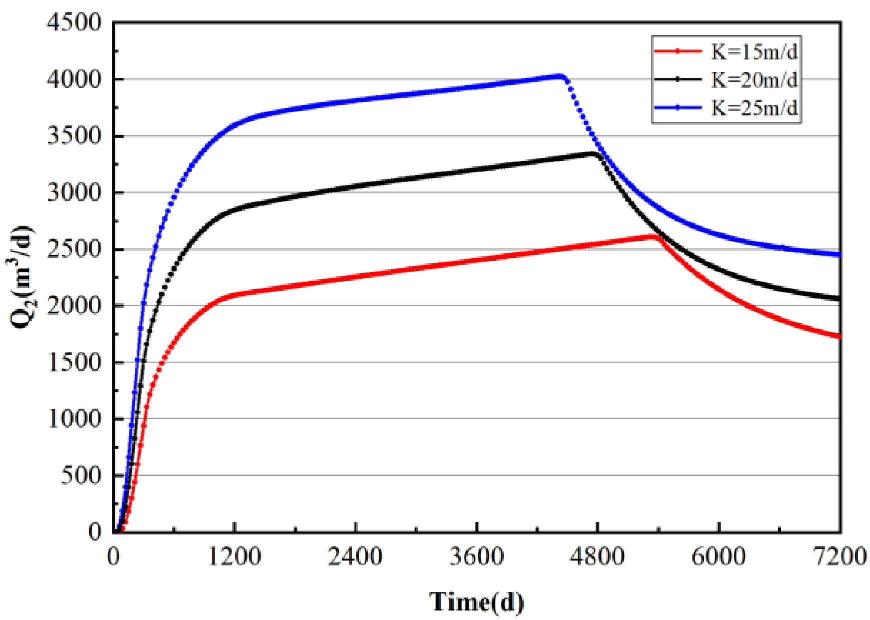
At 3600 pumping days, when K = 15, 20, and 25 m/d, the base flow from zone 1 to zone 2 decreased to 0 for 1260 days, 1320 days and 1470 days, and the infiltration times were 330 days, 300 days and 300 days. The infiltration volumes were 7.56 m^3/d, 9.11 m^3/d and 41.12 m^3/d, respectively.

In the 3600 days when pumping was stopped, when K=15, 20, and 25 m/d, the base flow from zone 1 to zone 2 reappeared for 5340 days, 4740 days, and 4440 days, respectively, and the time when the induced infiltration was 0 was 5430 days, 4860 days and 4530 days, respectively.

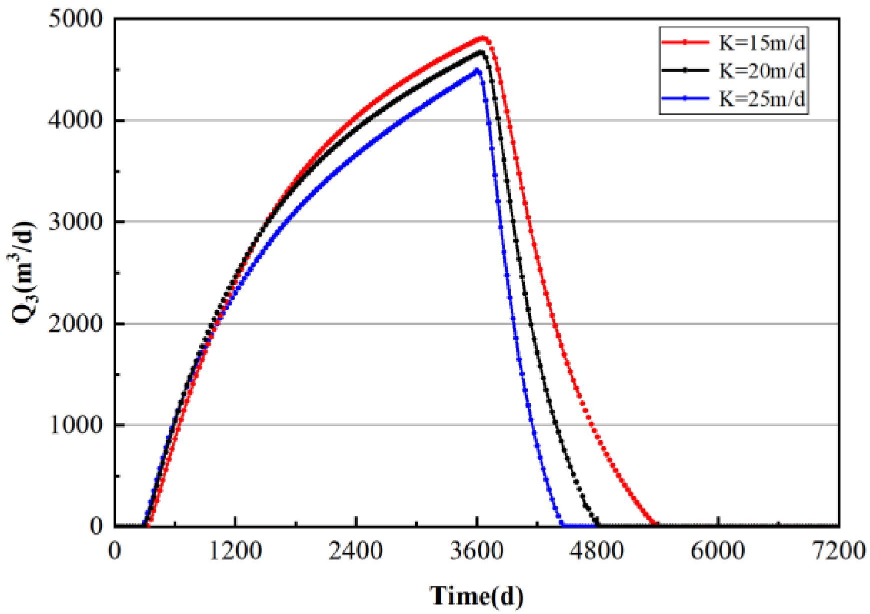
The cone of depression formed during pumping is also related to the difference in hydraulic conductivity. When K=15, 20, and 25 m/d, the water levels in the water level observation wells located 30 m away from the pumping wells are 2.73 m, 4.14 m, and 5.11 m, respectively, when pumping for 1500 days, which means that the smaller the hydraulic conductivity is, the faster the water level in the center of the cone of depression drops.

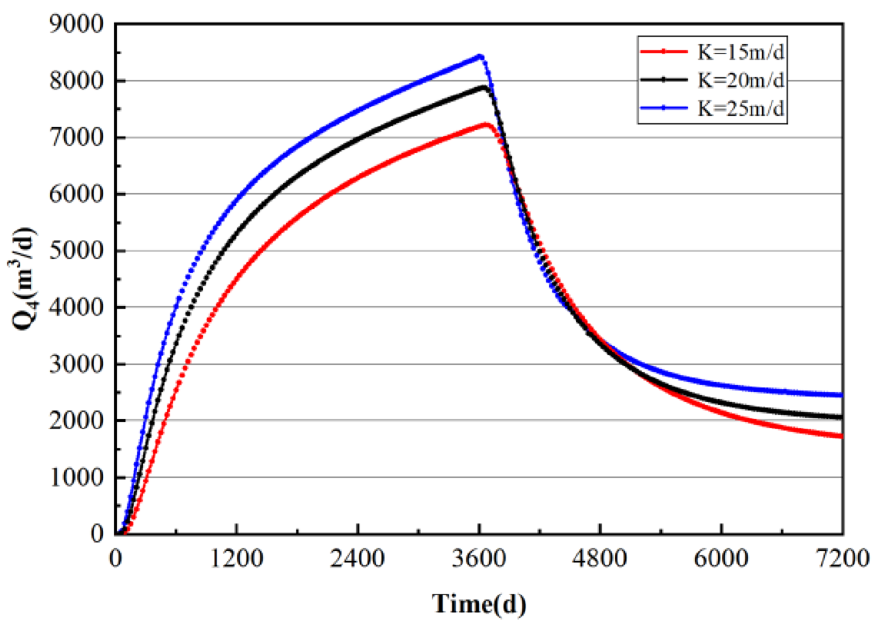
Similarly, we plotted base flow, reduced base flow, induced infiltration, and total water reduction versus time for the three different hydraulic conductivities, as shown in Figure 11. In the reduced base flow curve with time, the greater the hydraulic conductivity of the aquifer, the greater the reduced base flow, and the earlier the reduced base flow decreases when pumping is stopped at 3600 days, and the reduced base flow





(a) Base flow reduction process (b) Reduced Base flow increase process





(c) Infiltration increase process (d) Total water reduction process

Figure 11. Water quantity change of different hydraulic conductivity

volume until the end of the simulation is also proportional to the size of the hydraulic conductivity. Different from the reduced base flow, the value of induced infiltration is inversely proportional to the size of the hydraulic conductivity, and the time when the induced infiltration becomes zero after pumping is stopped is also inversely proportional to the size of the hydraulic conductivity. In general, the total water reduction is directly proportional to the size of the hydraulic conductivity.

Under the condition that water is pumped throughout the simulation period, the groundwater divide between the pumping wells and the wetland caused by groundwater exploitation in the wetland–aquifer interaction model is quantitatively portrayed based on the water exchange between zone 1 and zone 2, and the base flow from the piedmont plain aquifer to the wetland is continuously reduced until it becomes zero, while the reverse groundwater recharge from the wetland is induced to the piedmont plain aquifer. During the full simulation period, the reduced base flow increased rapidly in the early stage and was relatively flat in the later stage. The reduced base flow responded to pumping immediately, while the induced infiltration began to occur only when the groundwater divide spread to the wetland boundary and groundwater in zone 2 flowed to zone 1, with a certain lag. The longer the pumping time, the more dominant the effect of induced infiltration on wetland degradation.

In the model with cessation of pumping after 3600 days, the situation for the first 3600 days was the same as that of pumping for the entire time. The natural recovery process of the wetland after pumping cessation is an inverse wetland–aquifer interaction process. The gradual reduction of induced infiltration from zone 2 to zone 1 and the recovery of base flow from zone 1 to zone 2 characterize both the reappearance of the groundwater divide between the wetland and the pumping well and the disappearance of the groundwater divide with increasing pumping time. The groundwater flow direction in the whole simulation area resumed to flow from west to the east again. After the cessation of exploitation, the effect of reduced base flow on wetland degradation shows a certain lag after pumping cessation. In contrast, the effect of induced infiltration on wetland degradation responds instantly. At the end of the simulation, the only cause of wetland degradation is the reduced base flow.

Numerical simulations with different hydraulic conductivities showed that the effect of reduced base flow on wetland degradation is proportional to the hydraulic conductivity in the process of groundwater exploitation and natural recovery of wetlands. However, the inflection point at which the reduced base flow decreases with increasing pumping time is inversely proportional to the hydraulic conductivity, and the effect of induced infiltration on wetland degradation decreases with increasing hydraulic conductivity in this model. The total water reduction of wetlands increases with increasing hydraulic conductivity.

Conclusion

(1) Groundwater exploitation will form a cone of depression, and the water level around it will flow toward the center of the pumping well, which leads to the inversion of the groundwater hydraulic gradient between the wetland and the piedmont plain, and the base flow of the piedmont plain aquifer recharging the wetland decreases rapidly. A groundwater divide is formed between the wetland and the piedmont plain. With the increase in pumping time, the cone of depression continuously expands, and the groundwater divide gradually moves toward the wetland until it expands to the wetland boundary. At this time, the surface water of the wetland begins to recharge the piedmont plain groundwater and induces infiltration from the wetland to the piedmont plain. After pumping stops, the water level of the original cone of depression gradually rises due to recharge from the western boundary, and the lowest point of the cone of depression level gradually moves toward the wetland until the groundwater flow direction in the study area returns to west–east.

(2) The impact of groundwater overexploitation on wetland degradation is mainly divided into two parts. One part is the reduced base flow from the piedmont plain aquifer to the wetland, which leads to the reduction in groundwater recharge received by the wetland. The other is the expansion of the cone of depression, which induces the groundwater in the wetland to infiltrate into the piedmont plain aquifer, leading to a reduction in wetland surface water. The reduction in base flow tends to occur rapidly and correspondingly with groundwater exploitation, while induced infiltration has a certain lag. At the beginning of pumping, the effect of reduced base flow on wetland degradation dominates, but with pumping time, the effect of induced infiltration on wetland degradation exceeds that of reduced base flow. After stopping pumping, the effect of induced infiltration on wetland degradation responds immediately and decreases rapidly, while the effect of reduced base flow on wetland degradation still increases briefly for some time and then slowly decreases but its effect lasts for a long time.

(3) The different hydraulic conductivities of aquifers also have an impact on wetland degradation. The effect of reduced base flow on wetland degradation is proportional to the hydraulic conductivity, and the effect of induced infiltration on wetland degradation decreases with increasing hydraulic conductivity. In general, according to the numerical simulations under different hydraulic conductivities, the total water reduction of wetlands increases with increasing hydraulic conductivity. In actual wetland areas, if groundwater exploitation is not restricted or artificial supply measures are not taken, the amount of wetland water will gradually decrease until it is exhausted.

Declarations

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