

Estimation of the groundwater discharge through the edge of Changma alluvial fan in the Shule River Basin, northwestern China

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Abstract. In this paper, the groundwater discharge through the edge of Changma alluvial fan in the Shule River Basin is estimated. The Changma alluvial fan is generalized as an aquifer system including an unconfined aquifer, an upper semi-permeable layer and a confined aquifer. The vertical flow of groundwater in the unconfined aquifer and the elastic storage of the semi-permeable layer are neglected. The flow in the semi-permeable layer is assumed to be vertical. Analytical solution of the model is derived. From the top of the alluvial fan to the intersection of the unconfined aquifer and confined aquifer, the groundwater level decreases gradually and then increases suddenly at the intersection. The groundwater flow velocity and flux decrease from the intersection of unconfined aquifer and confined aquifer to the edge of alluvial fan. The recharge of Changma irrigation area from the unconfined aquifer is 0.82 billion m³/a. The quantity of evaporation of groundwater for each year is larger than 0.56 billion m³/a, which indicates that large amount of salt accumulated on the surface.

1. Introduction

Arid zones are exposed to extreme deficits of water due to low rainfall and relatively high evapotranspiration rates. As a result, various groundwater resources and environmental problems arise, which include groundwater depletion, desertification, land salinization, and degradation of vegetation (Edmunds et al. 2006; Aeschbach-Hertig and Gleeson, 2012; Lapworth et al. 2013). Particularly, the effective evaporation or transpiration of infiltrating rainfall can result in low groundwater recharge rates and saline soil water and groundwater. Salinity can negatively influence soil quality and sustainable agriculture, and it can threaten biodiversity, water quality and agricultural production. The Shule River Basin, located in the western part of the Hexi Corridor, is one of the most water-stressed endorheic basins of Northwest China (Guo et al., 2015; Wang et al., 2015). The links between evaporation and soil salinization processes are explored. The basin lies between the north Qilian Mountain in the south and Beishan Mountain in the north, and spreads from Huahai village of Yumen city in the east to Guazhou county in the west. The total area of the basin is approximately $4.13 \times 10^4 \text{ km}^2$, including the upper part of Changma and the piedmont alluvial basins. The altitude from the Changma dam 1850 m in southeast gradually reduced to about 1040m in west lake area in northeast. There is a complete typical alluvial fan in the front of Qilian Mountain, located in the upper part of Shule River Basin, which is called Changma alluvial fan. The middle-lower part of Shule River basin is covered by the oasis. In order to investigate the large amount of salt accumulation carried by the groundwater on the surface, it is necessary to



estimate the groundwater discharge through the edge of Changma alluvial fan in the Shule River Basin.

2. Mathematical Model and Analytical Solution

We consider an aquifer system in the Changma alluvial fan, including an unconfined aquifer, a confined aquifer and a semi-permeable layer, as shown in Figure 1. The unconfined aquifer is in the upper part of the alluvial fan, and the confined aquifer and semi-permeable layer are in the lower part of the alluvial fan, namely the fine soil plain area. In order to investigate the groundwater discharge through the edge of Changma alluvial fan, the following assumptions will be used to the aquifer system. (a) The flow in the unconfined aquifer and confined aquifer is horizontal, and that in the semi-permeable layer is vertical. (b) Each layer is homogeneous and isotropic. (c) The average thickness of unconfined aquifer is b_1 . (d) The semi-permeable layer and confined aquifer have horizontal interface with each other. The constant thickness of confined aquifer and semi-permeable layer are b_2 and b_3 , respectively. (e) The elastic storage of the semi-permeable layer is neglected.

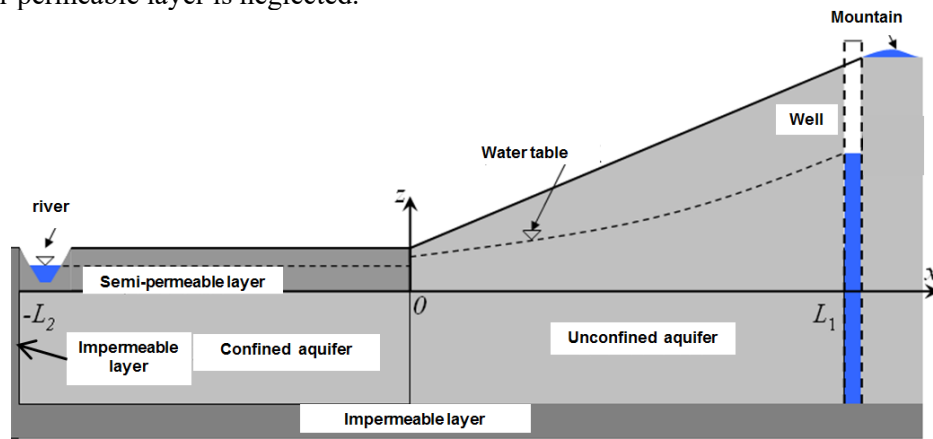


Figure 1 Conceptual model of a multi-layered aquifer system of alluvial fan.

In the alluvial fan aquifer system, large quantity of surface water infiltrates to recharge groundwater in the top of the alluvial fan. The groundwater flows through the upper unconfined aquifer to recharge the lower confined aquifer, and then it flows through the semi-permeable layer above the confined aquifer and discharges to the ground. The flow in the alluvial fan is steady-state over many years. The steady flow is caused by the head difference between the head in the top and that in the edge of the alluvial fan, which is independent of time. Let the datum of the aquifer system be the bottom of confined aquifer; the z -axis be vertical, positive upward; the x -axis be horizontal, positive right; and the coordinate origin be the intersection point of unconfined aquifer and confined aquifer. On the basis of the preceding assumptions, the following governing equations can be used to describe the head variation within the unconfined aquifer and confined aquifer. In the unconfined aquifer and confined aquifer,

$$T_1 \frac{d^2 h_s(x)}{dx^2} + W = 0, \quad 0 < x < L_1, \quad (1)$$

$$T_2 \frac{d^2 h_s(x)}{dx^2} + K_3 \frac{h_A - h_s(x)}{L_3} = 0, \quad -L_2 < x < 0, \quad (2)$$

where $h_s(x)$ is the hydraulic head [L] of the unconfined aquifer and confined aquifer; h_A is the constant hydraulic head [L] of the semi-permeable layer; L_3 is the thickness of saturated zone of the semi-permeable layer [L]; $T_1 = K_1 b_1$ is defined as the transmissivity of unconfined aquifer, in which K_1 is the hydraulic conductivity [LT^{-1}]; W is the recharge rate [LT^{-1}]; T_2 and K_3 are the transmissivity [$L^2 T^{-1}$] of the confined aquifer and the hydraulic conductivity [LT^{-1}] of the semi-permeable layer. The boundary conditions for the unconfined aquifer are Dirichlet boundary,

$$h_s(x) = h_c, \quad x = L_1, \quad t \geq 0, \quad (3)$$

$$h_s(x) = h_B, \quad x = 0, \quad t \geq 0, \quad (4)$$

where h_B and h_C are the boundary heads at $x=0$ and $x=L_1$, respectively. The boundary condition for the confined aquifer at $x=0$ is expressed as Equation (4), and that at $x=-L_2$ is Neumann boundary condition,

$$\frac{dh_s(x)}{dx} = 0, \quad x = -L_2, \quad t \geq 0. \quad (5)$$

The solution of Equations (1)-(5) can be solved to yield

$$h_s(x) = -\frac{W}{2T_1}x^2 + \left(\frac{h_C - h_B}{L_1} + \frac{WL_1}{2T_1}\right)x + h_B, \quad 0 < x < L_1, \quad (6)$$

$$h_s(x) = A \exp(ax) + B \exp(-ax) + h_A, \quad -L_2 < x \leq 0, \quad (7)$$

where $a = \sqrt{K_3/(T_2L_2)}$, $A = [(h_B - h_A)\exp(2aL_2)]/[\exp(2aL_2) + 1]$, $B = (h_B - h_A)/[\exp(2aL_2) + 1]$.

At the location $x=0$, according to the law of flow continuity, one has

$$T_2 \frac{dh_s(x)}{dx} \Big|_{x=0^-} = T_1 \frac{dh_s(x)}{dx} \Big|_{x=0^+}, \quad (8)$$

From Equation (8), one obtains

$$h_B = \left(h_A a T_2 \frac{\exp(2aL_2) - 1}{\exp(2aL_2) + 1} + \frac{T_1}{L_1} h_C + \frac{WL_1}{2} \right) / \left(a T_2 \frac{\exp(2aL_2) - 1}{\exp(2aL_2) + 1} + \frac{T_1}{L_1} \right). \quad (9)$$

Substituting Equation (9) back into Equations (6) and (7), one can obtain the steady state head in the unconfined aquifer and confined aquifer.

3. Analysis and Discussions

In this section, the analytical solutions, Equations (6) and (7) will be applied to the Changma alluvial fan of Shule River Basin, northwestern China. The following model parameter values are used: the thickness of saturated zone of the semi-permeable layer L_3 is 10m, the average thicknesses of unconfined aquifer b_1 and confined aquifer b_2 are 90m and 60m, and the length of unconfined aquifer L_1 and confined aquifer L_2 is 39900m and 21800m, respectively. The hydraulic conductivity values of K_1 , K_2 and K_3 are 30m/d, 30m/d and 0.0126m/d, respectively. The transmissivity of confined aquifer T_2 is 1800 m²/d. The hydraulic head values of h_A , h_B and h_C are 1414m, 1444.7m and 1935m, respectively. The groundwater level of the unconfined aquifer and confined aquifer is derived from the equations (6) and (7), and the results are shown in Figure 2. The depth of groundwater level in the unconfined aquifer is large, because of the scarce rainfall in the alluvial-proluvial plain. The results show that the groundwater level increases at the location $x=0$, because the groundwater flow becomes slow due to the low permeability of the aquitard. This is consistent with the fact that there is a large amount of spring water at the intersection of the unconfined aquifer and confined aquifer.

The groundwater velocity is 0.38m/d at the location $x=0$ according to the Darcy's law. The quantity of recharge of Changma irrigation area from the unconfined aquifer is 0.82 billion m³/a, which is less than the average annual runoff of the Shule river (0.86 billion m³/a). It is demonstrated that the recharge of Changma irrigation area is mainly from the upper unconfined aquifer. A large amount of groundwater discharge to the surface through the aquitard, as well as in the form of spring water. It forms the surface runoff, and then flows into the Shule river or evaporates into the atmosphere. The average annual runoff is 0.26 billion m³/a from the year 1953 to 2000 (including the spring water, flood and irrigation water), which is recorded by the Panjiazhuang Hydrological Station located in the middle reaches of Shule river. Therefore, the quantity of evaporation of groundwater for each year is larger than 0.56 billion m³/a. A large amount of salt carried by the groundwater will be accumulated on the surface. It will also be brought back to the groundwater with the surface water infiltration. As a result, the TDS and salinity of groundwater increase and the quality of groundwater in the irrigation area become worse.

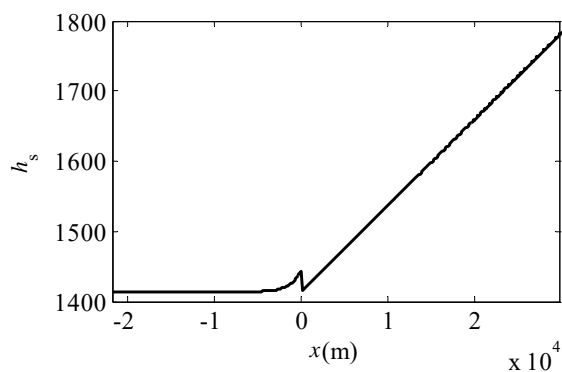


Figure 2 The steady state head in the unconfined aquifer and confined aquifer.

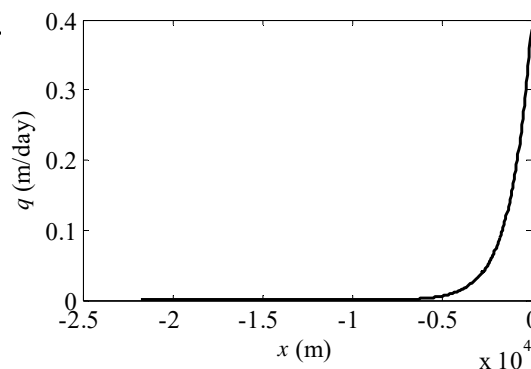


Figure 3 Change of the leakage flux with distance from the confined aquifer to aquitard.

Figure 3 shows the change of the leakage flux with distance from the confined aquifer to aquitard. The results demonstrated that the groundwater flow velocity and flux decrease from the intersection of unconfined aquifer and confined aquifer to the edge of alluvial fan. Therefore, it is inferred that the salt accumulation is large in the intersection of unconfined aquifer and confined aquifer. In the confined aquifer, the TDS and salinity of groundwater are not too high, due to the larger velocity of groundwater flow. However, a large amount of salt on surface will be carried back into the confined aquifer in the edge of alluvial fan, affected by the irrigation infiltration. As a result, the TDS and salinity of groundwater will increase, and the quality of groundwater become worse.

4. Summary

This paper estimated the groundwater discharge through the edge of Changma alluvial fan in the Shule River Basin, northwestern China. The Changma alluvial fan is generalized as an aquifer system, which includes an unconfined aquifer, a confined aquifer and a semi-permeable layer. The unconfined aquifer is in the upper part of the alluvial fan, and the semi-permeable layer and the confined aquifer are in the lower part of the alluvial fan. The vertical flow of groundwater in the unconfined aquifer and the elastic storage of the semi-permeable layer are neglected. The flow in the semi-permeable layer is assumed to be vertical. Exact steady analytical solution of the model is derived. The groundwater level decreases from the top of the alluvial fan to the intersection of the unconfined aquifer and confined aquifer. However, it increases at the intersection of the unconfined and confined aquifers, due to the low permeability of the aquitard. The groundwater flow velocity and flux decrease from the intersection of unconfined aquifer and confined aquifer to the edge of alluvial fan. The quantity of recharge of Changma irrigation area from the unconfined aquifer is 0.82 billion m^3/a , and the quantity of evaporation of groundwater for each year is larger than 0.56 billion m^3/a . As a result, a large amount of salt carried by the groundwater will be accumulated on the surface.

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