
Numerical simulation of groundwater flowing to horizontal seepage wells under a river

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Abstract A horizontal seepage well, consisting of an interconnected vertical well, galleries, chambers and small-diameter radiating bores, is used to acquire relatively clean water that has been filtered through natural alluvial deposits in a riverbed. It has wide application, especially in arid and semi-arid areas. The lack of calculation formulae or models for horizontal seepage wells, up until now, has resulted in several false applications. Based on the analysis of groundwater flow characteristics, it has been concluded that several flow regimes coexist and hydraulic head loss exists in the horizontal seepage well. To avoid the difficulty of confirming the flux or head distribution in such a complex system, the model boundary of the whole horizontal seepage well has been moved to that of just the vertical well, and the well-aquifer system was treated as a heterogeneous medium, where the horizontal seepage well itself is a highly permeability medium. A mathematical model has been developed, based on the coupled seepage-pipe flow, by the introduction of equivalent hydraulic conductivity according to different flow regimes. Then a three-dimensional finite difference numerical model, based on the mathematical model, was developed and applied to a horizontal seepage well in China. The numerical model verified the groundwater flow characteristics of the horizontal seepage well.

Résumé Un puits d'infiltration horizontal, consistant en un puits vertical interconnecté, des galeries, des chambres et des forages radiaux de petits diamètres, est utilisé pour recueillir une eau relativement propre qui a été filtrée à

travers des dépôts alluviaux du lit d'une rivière. Ce système présente de nombreuses applications, notamment dans les zones arides et semi-arides. Le manque de formules de calcul ou de modèles de puits d'infiltration horizontaux, a conduit jusqu'à présent à plusieurs cas erronés. Sur la base de l'analyse des caractéristiques des écoulements des eaux souterraines, il a été conclu que plusieurs régimes d'écoulement et que des pertes de charge existent dans les puits d'infiltration horizontaux. Pour éviter la difficulté de la définition des flux ou de la distribution des charges dans un système aussi complexe, la limite du modèle a été restreint aux puits verticaux, et le système puits aquifère a été traité comme un milieu hétérogène où le puits horizontal d'infiltration lui-même est représenté par un milieu très perméable. Un modèle mathématique a été développé, sur la base de l'écoulement couplé infiltration-puits, avec l'introduction de la conductivité hydraulique équivalente suivant différents régimes d'écoulement. Ensuite un modèle numérique 3D aux différences finies, basé sur le modèle mathématique, a été développé et appliqué à un puits horizontal d'infiltration en Chine. Le modèle numérique vérifie les caractéristiques de l'écoulement des eaux souterraines du puits d'infiltration horizontal.

Resumen Un pozo filtrante horizontal, consistente de una interconexión entre un pozo vertical, galerías, cámaras y perforaciones radiales de diámetro pequeño, se usa para conseguir agua relativamente limpia, que se ha filtrado a través de los depósitos aluviales naturales en un lecho del río. Tiene una aplicación amplia, sobre todo en las áreas áridas y semiáridas. La falta de formulas del cálculo o modelos para los pozos de filtración horizontales, hasta ahora, ha producido varias aplicaciones falsas. Con base en el análisis de características de flujo del agua subterránea, se ha concluido que varios regímenes de flujo coexisten y existe la pérdida de cabeza hidráulica en el pozo filtrante horizontal. Para evitar la dificultad de confirmar la fluctuación o la distribución de cabeza en semejante sistema complejo, se ha desplazado el límite del modelo de la totalidad del pozo de filtración horizontal, hasta el límite del pozo vertical y el sistema del pozo-acuífero se trató como un medio heterogéneo, donde el pozo de filtración horizontal es en si mismo un medio de permeabilidad alta. Fue desarrollado un modelo matemático, basado en un acoplamiento del flujo entre la

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filtración-tubería, mediante la introducción de una conductibilidad hidráulica equivalente según los regímenes de flujo diferentes. Entonces se desarrolló y aplicó un modelo numérico tridimensional de diferencias finitas, basado en el modelo matemático, a un pozo de filtración horizontal en China. El modelo numérico verificó las características de flujo del agua subterránea del pozo de filtración horizontal.

Keywords Horizontal seepage well · Equivalent hydraulic conductivity · Mathematical model · Numerical modeling · Groundwater flow

Introduction

Horizontal seepage well design (Chen and Zhou 1995) has developed in recent years for the collection of river leakage. Such wells can maximize water resources by converting surface water to relatively cleaner groundwater via filtration through the natural alluvial deposits in the riverbed. A horizontal seepage well produces much more water than a single vertical well does near the river, and the water yielded from it is of better quality. A horizontal seepage well is a complex construction (Li and Yang 2003; Wang et al. 2004; Fu et al. 2004), consisting of an interconnected vertical well, galleries, chambers and small diameter radiating bores (the term “well pipe” is used hereafter to describe this four-part combination of what constitutes a horizontal seepage well). Different horizontal seepage wells may have different numbers of chambers; the dimensions of chambers, normally, are 3 m in length, 3 m in width and 3.5 m in height. There are normally several bores radiating from the top and side faces of each chamber, and these “radiating bores” partially penetrate

the main aquifer beneath the riverbed. The interval between chambers is about 50 m, and adjacent chambers are connected by galleries. The gallery cross section is typically about 1.7 m in height and 1.5 m in width. Provided the underlying rock is suitable for tunneling, the structural system of galleries-chambers-radiating bores is laid underneath the river; meanwhile the vertical well, with diameter of about 3 m, is located in the riverbank. The structural system of galleries-chambers-radiating bores is linked with the vertical well by a gallery, and the vertical well is the pumping site of the whole horizontal seepage well. Figure 1 is the sketch of a typical horizontal seepage well located in the Wulidian water-supplying field in the Wuding River valley of Suide city, northern Shaanxi province, China (Fig. 2), and will be used as an example in this study. The manner of water collection using a horizontal seepage well is different from that of a horizontal well, i.e. the water pumped from a horizontal seepage well is mainly from the radiating bores, while the water pumped from a horizontal well is from the conduit (corresponding to the gallery of the horizontal seepage well) itself.

The horizontal seepage well technique has been employed in many river-valley water-supplying projects with great success. It attracts more and more attention because of its advantages over conventional/horizontal wells such as high yield, low power consumption, ease of management, and low total cost of the water supply. It has particular practical significance in arid and semi-arid areas. For example, a horizontal seepage well located in Yulin city, northern Shaanxi province, China, has a yield excess of 16,000 m³/d. Another horizontal seepage well located in Zhenchuan county, northern Shaanxi province, has a yield of up to 4,500 m³/d; by contrast, a conventional vertical well in the same place can produce

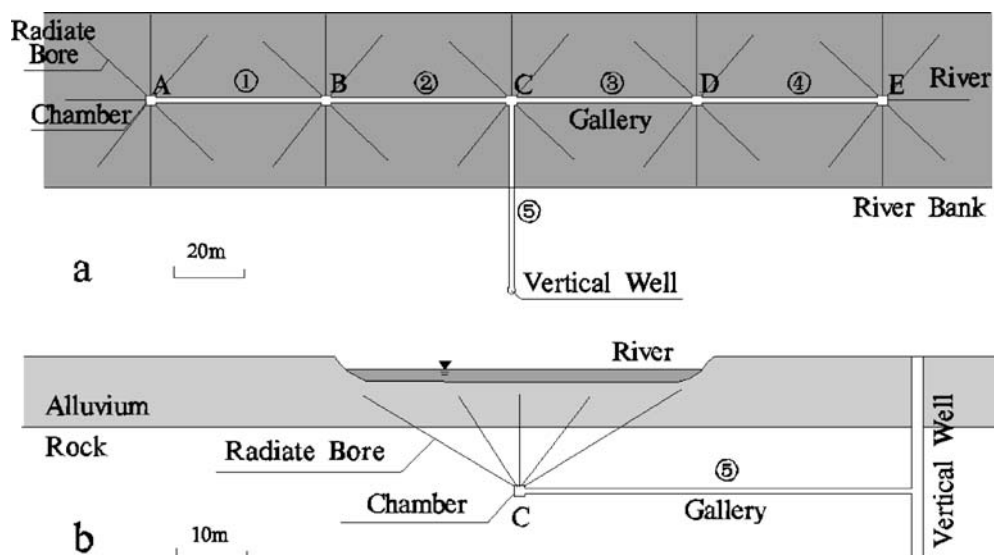


Fig. 1 Sketch of a horizontal seepage well structure in **a** plan view, and **b** in cross section, for chamber C. The numbers (1), (2), (3), (4), (5) represent segments 1, 2, 3, 4, 5 of the galleries. A, B, C, D, E represent the chambers; the dimensions of each chamber are 3 m in length, 3 m in width and 3.5 m in height. Each gallery,

between two adjacent chambers, is about 50 m; the gallery cross section is 1.7 m in height and 1.5 m in width. The diameter of the vertical well is 3 m. The diameter of each radiating bore is approximately 0.1 m

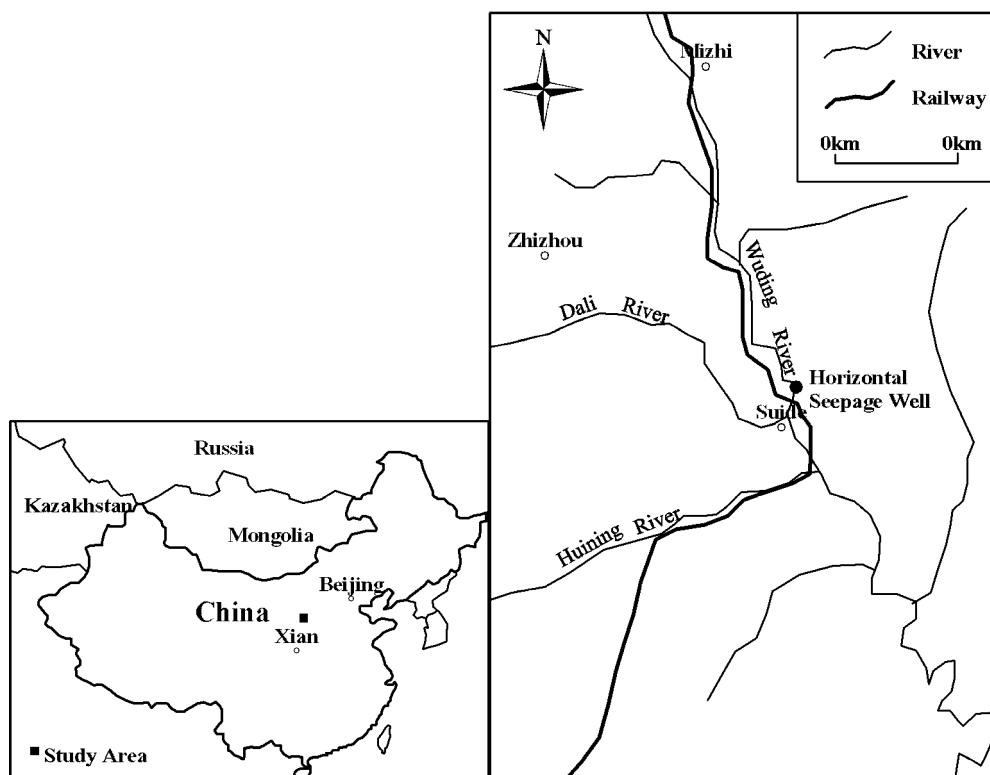


Fig. 2 Map of the horizontal seepage well location in the Wuding River valley, Suide city, China

no more than approximately $100 \text{ m}^3/\text{d}$. Horizontal seepage wells can filter suspended solids in river water by flow to the well via the natural alluvial deposit in the riverbed, and, therefore, has an advantage over direct pumping from the river. However, the pumpage of horizontal seepage wells under certain drawdown conditions can only be roughly estimated according to the information acquired during exploration and there have been no available formulae or models for the horizontal seepage well mechanism. This shortcoming has jeopardized any water-supplying project that has employed horizontal seepage well technology. In fact, there are quite a few applications that cannot reach the expected yield; in the worst case, the well had to be abandoned because its yield was no more than $100 \text{ m}^3/\text{d}$. Therefore, finding a method to accurately calculate the potential yield of horizontal seepage wells according to the exploration data is urgent, and it should be possible or easier to compare different designs (size, number of chambers, etc.) under different conditions.

Models for other pumping engineering designs that are similar to horizontal seepage wells such as horizontal wells and radiating wells, can be used as reference for the development of a calculation model for horizontal seepage wells. The early study of flow to horizontal wells was done by Hantush (1961) and Hantush and Papadopoulos (1962). They, and most later researchers (such as Beljin 1992; Cleveland 1994; Zhou and He 1997; Zhan et al. 1994; Zhan and Cao 2000; Kawecki 2000; Langseth et al. 2004), treat a horizontal well as a uniform-flux or uniform-head boundary. However, the applicability of these methods had not been strictly proven. Tarshish (1992) proposed a

hypothetic model which considered that the head loss is proportional to the square of average flow velocity in a horizontal well. Chen et al. (2003) and Zhan and Wan (2003) proposed a coupled seepage-pipe flow model and equivalent hydraulic conductivity (Chen 1995; Chen and Lin 1998a; Chen and Jiao 1999; Chen et al. 1993) to depict the flow to a horizontal well.

In this study, a mathematic model of groundwater flowing to a horizontal seepage well was described, based on analysis of the flow characteristics of a horizontal seepage well. Then a three-dimensional finite difference numerical model was developed to calculate the potential yield of a horizontal seepage well.

The flow characteristics and mathematical model of a horizontal seepage well

When a horizontal seepage well is working, several different flow regimes may coexist in the well-aquifer system at the same time (Chen et al. 2003). The flow regime in the aquifer medium is often a laminar flow with low Reynolds number ($Re < 1 \sim 10$). In this flow regime, the relationship between the hydraulic head loss and the seepage velocity is linear, and the flow obeys the Darcy law. Because the well pipe (combination of vertical well, galleries, chambers and small diameter radiating bores) has great hydraulic radius and great pumpage, the flow regime in the well pipe is often a turbulent flow with a high Reynolds number. In the well pipe, the relationship curve between the hydraulic head loss and the flow

velocity may exist as five components (Chen et al. 2003): laminar flow component, in which the hydraulic head loss is in proportion to the flow velocity u ; smoothing turbulent flow component, in which the hydraulic head loss is in proportion to $u^{1.75}$; turbulent flow component, in which the hydraulic head loss is in proportion to u^2 ; and two transition components between these three components.

In the well-aquifer system, groundwater flows into the well pipe from all directions, and groundwater flow has obvious three-dimensional flow characteristics. The water flowing in the well pipe will cause hydraulic head loss; therefore, the head in the well pipe is not evenly distributed, and a unique head boundary condition cannot be adopted to describe the well-pipe boundary. Meanwhile, because the pumping site is the vertical well where the hydraulic head is the lowest, and the water flows into each chamber through radiating bores at different rates, the hydraulic condition in the well-aquifer system is very complicated. If the well pipe was treated as a boundary, the boundary condition cannot strictly be confirmed (Chen et al. 2003).

According to flow character analysis of horizontal seepage wells, the well-pipe boundary condition cannot be confirmed easily. However, if the well-aquifer system is treated as a heterogeneous medium in which the well pipe is treated as a highly permeability medium, and the boundary of the whole horizontal seepage well is moved to that of just the vertical well, then this boundary condition can be confirmed easily. So the problem of the horizontal seepage well pumping is simplified as a problem of a single well working in a heterogeneous medium. The key to solving the problem is to confirm the hydraulic conductivity of the well pipe.

Because laminar flow (linear flow) and turbulent flow (non-linear flow) may coexist in the well-aquifer system at the same time, and in order to couple the different flow regimes in different media with each other, the equivalent hydraulic conductivity proposed by Chen et al. (1993) and C. Chen (Beijing Geology college, personal communication, 1966) can be adapted for the well pipe.

According to the research findings by Chen (1966), Chen and Lin (1998b) and Bear (1972), the hydraulic conductivity (K) for the well pipe with a laminar flow component can be denoted as:

$$K_l = \frac{d^2 g}{2c\nu} = \frac{d^2 g}{32\nu} \quad (1)$$

$$d = \frac{4A}{\chi}$$

Where g is gravity acceleration, d is the equivalent diameter of the well pipe, A is the area of flow section in the well pipe, χ is the wetted perimeter of the well pipe (Fig. 3), ν is kinematic viscosity of water, and c is an empirical shape factor, where $c=16$.

For turbulent flow, according to the Darcy-Weisbach equation (Li and Xu 2000), hydraulic head loss (ΔH) is:

$$\Delta H = f \times \frac{l}{d} \times \frac{u^2}{2g} \quad (2)$$

Where f is coefficient of friction, l is length of flow path, and u is the average flow velocity in the well pipe. The relation between seepage velocity v and average flow velocity in porous media is $v=nu$, where n is the medium porosity. In the well pipe, $n=1$. Then, Eq. (2) can be rewritten as:

$$v = \frac{2gd}{fv} \times \frac{\Delta H}{l} = K_n \times J \quad (3)$$

$$K_n = \frac{2gd}{fv} \quad (4)$$

This means that the relation between seepage velocity and hydraulic gradient in the well pipe has the same expression of Darcy's law, where v is the seepage velocity in the well pipe, K_n is the equivalent hydraulic conductivity in the well pipe, and $J = \frac{\Delta H}{l}$ is the hydraulic gradient. Compared to the K_l in Eq. (1), K_n is not a constant but a function of seepage velocity.

To confirm the hydraulic conductivity in the well pipe, one needs to confirm the average flow velocity in the well

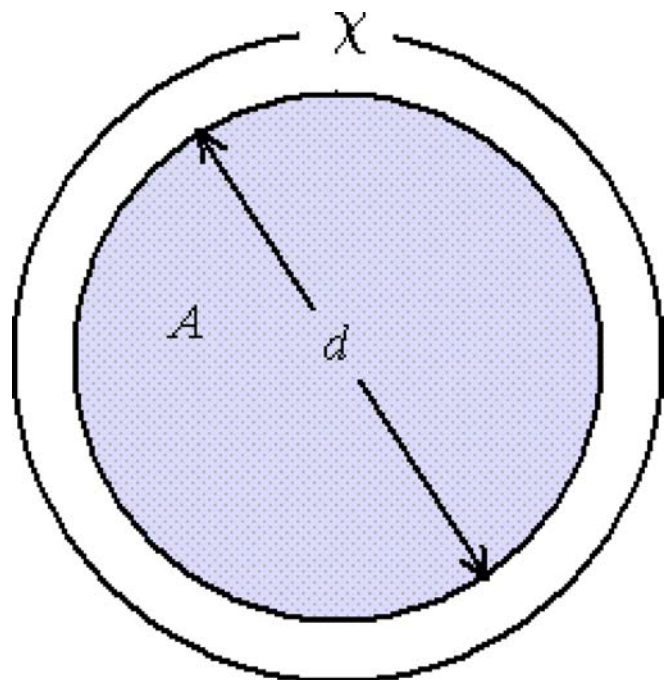


Fig. 3 Schematic sketch of the symbols in Eq. (1). d is the equivalent diameter of the well pipe, A is the area of flow section in the well pipe, χ is the wetted perimeter of the well pipe

pipe and the coefficient of friction first. For laminar flow, the coefficient of friction can be calculated by (Li and Xu 2000):

$$f = \frac{64}{Re} = \frac{64\nu}{ud}$$

Where $Re = \frac{ud}{\nu}$ is the Reynolds number, ν is kinematic viscosity of water.

For turbulent flow with $3,000 < Re < 100,000$, the coefficient of friction is (Li and Xu 2000):

$$f = \frac{0.316}{Re^{0.25}} \quad (6)$$

By substituting Eq. (5) for Eq. (2), the hydraulic head loss ΔH is proportional to $u^{1.75}$ while $3,000 < R < 100,000$.

For turbulent flow with $Re > 100,000$, the coefficient of friction is independent of the Reynolds number, but depends, however, on the wall coarseness of the well pipe (Li and Xu 2000).

$$f = \frac{1}{4} \left(\log_{10} 3.71 \frac{d}{e} \right)^{-2} \quad (7)$$

where e is the inner wall coarseness height of the well pipe. Here the hydraulic head loss ΔH is proportional to u^2 .

Substitute the f terms for different Re numbers in the Eq. (4), (where $\nu = nu$, $n=1$):

$$K_n = \begin{cases} \frac{gd}{32\nu} & Re < 2300 \\ \frac{2gd}{0.316} \cdot \left(\frac{d}{\nu}\right)^{0.25} \cdot \frac{1}{\nu^{0.25}} = \phi(\nu^{-0.25}) & 3000 < Re < 100000 \\ 8gd \cdot \left(\log_{10} 3.71 \frac{d}{e}\right)^2 \cdot \frac{1}{\nu} = \varphi(\nu^{-1}) & Re > 100000 \end{cases} \quad (8)$$

Where ϕ means K_n is the function of $\nu^{-0.25}$, φ means K_n is the function of ν^{-1} .

From Eqs. (4) and (8), it can be concluded that the hydraulic head loss is in proportion to the flow velocity u for laminar flow; in proportion to $u^{1.75}$ for smooth turbulent flow, and in proportion to u^2 for turbulent flow.

By adapting the equivalent hydraulic conductivity for a turbulent flow regime, the flow law of a turbulent flow regime has the same expression of Darcy's law. Then the flow law in five flow regimes of the well-aquifer system (one laminar flow area in the aquifer and four turbulent flow areas in the well pipe) can be described using the expression of Darcy's law, and the well pipe can be treated as a cylinder medium with high permeability. In this way, the pipe flow in the well pipe can be coupled with the seepage flow in the aquifer. According to this, the steady-state mathematic model for groundwater flowing to the horizontal seepage well in a river valley can be developed. In this model other sources and sinks, besides the river leakage, are ignored, so the water table is a flow plane in a steady-state flow:

$$\left\{ \begin{array}{l} \frac{\partial}{\partial x} \left(K_{he} \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{he} \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{ve} \frac{\partial H}{\partial z} \right) = 0 \quad (x, y, z) \in D \\ H(x, y, z)|_{\Gamma_1} = H_1(x, y, z) \quad \text{first kind boundary condition (Bear, 1972)} \\ \frac{\partial H}{\partial \mathbf{n}}|_{\Gamma_2} = q \quad \text{second kind boundary condition (Bear, 1972)} \\ \frac{K_r}{M_r} (H_r - H) = q_r \quad \text{river boundary (Bear, 1972)} \\ \left. \begin{array}{l} H = z \\ \frac{\partial H}{\partial \mathbf{n}_p} = 0 \end{array} \right\} \quad \text{water table boundary (Bear, 1972)} \\ \left. \begin{array}{l} H(x, y, z) = H_s \\ \lim_{r \rightarrow r_w} \int_0^{2\pi} \left[\int_0^M r K \frac{\partial H}{\partial r} dz \right] d\theta = Q_s \end{array} \right\} \quad \text{vertical well boundary, } \begin{cases} \text{constant drawdown pumping} \\ \text{constant flow rate pumping} \end{cases} \\ K_e = \begin{cases} K & \text{hydraulic conductivity in aquifer medium, laminar flow} \\ K_l & \text{equivalent hydraulic conductivity in "Well Pipe", laminar flow} \\ K_n & \text{equivalent hydraulic conductivity in "Well Pipe", turbulent flow} \end{cases} \end{array} \right\} \quad (9)$$

Where K_e is the equivalent hydraulic conductivity, H is head, H_1 is the head of the first type of boundary, q is the specific flow rate per unit area of the second type of boundary, K is hydraulic conductivity, K_h is horizontal hydraulic conductivity, K_v is vertical hydraulic conductivity, K_r is vertical hydraulic conductivity of medium in riverbed, q_r is specific river leakage, M_r is the thickness of medium in riverbed, $\mathbf{n}$ is the exterior normal vector of the second boundary, $\mathbf{n}_p$ is the exterior normal vector of the water table, (r, θ) is the auxiliary coordinate for a constant flow rate pumping well, M is the vertical length of well, r_w is the radius of well, D is the seepage domain. A similar equation can be found in Chen et al. (2003).

This mathematical model can be solved by numerical methodology. It is noteworthy that to calculate the equivalent hydraulic conductivity K_e , three variables—the average flow velocity u , the Reynolds number and the coefficient of friction f —need to be confirmed first. However, the Reynolds number Re depends on the average flow velocity u , the average flow velocity u depends on the coefficient of friction f , and confirmation of the coefficient of friction f depends on the Reynolds number Re . Therefore, an iterative scheme must be employed to calculate these three variables, and then the equivalent hydraulic conductivity K_e of the well pipe.

Numerical simulation of hypothetical model of a horizontal seepage well

Hydrogeological structure of the hypothetical model

The structures of the aquifer and horizontal seepage well in the hypothetical model are based on the data associated

with the Wuding River valley in Suide city,. The model domain is conceptualized as a rectangle river valley (Fig. 4), which is 10 km E–W (along the river), and 1 km N–S; the width of river is 50 m.

The aquifer consists of Quaternary alluvium and a weathered zone of Triassic sandstone and mudstone. The grains of Quaternary alluvium always deposit evenly to get higher stability; this has caused the alluvium to have a high horizontal permeability and low vertical permeability. Therefore the medium is considered as a heterogeneous (homogeneous with a single hydraulic conductivity for each layer) and axial symmetrical anisotropy. The total thickness of aquifer (both Quaternary and weathered Triassic) is 8.50 m, with 5.25 m/d horizontal hydraulic conductivity and 1.00 m/d vertical hydraulic conductivity. To simulate the three-dimensional flow field around the horizontal seepage well, the total thickness of model layers is considered as 40 m, including part of the Triassic rock under the weathered zone; the Triassic rock thickness is 31.50 m, and hydraulic conductivity is 0.233 m/d. The Triassic rock is considered an aquiclude, due to its compact formation and lack of fissures, and forms the base of the aquifer (depth from ground surface is greater than 40 m).

The eastern and western boundaries are treated as the first type of boundary with a constant head of 40 m; it is 5 km from the horizontal seepage well to each boundary. The southern and northern boundaries are treated as second-type boundaries, with zero flow rate through the boundaries. Considering the interface of the alluvium with loess and Triassic rock, the flow rate from loess and Triassic rock to alluvium is rather small and can be ignored. The river is treated as a third type of boundary, where the thickness of deposit in the riverbed is 1 cm and

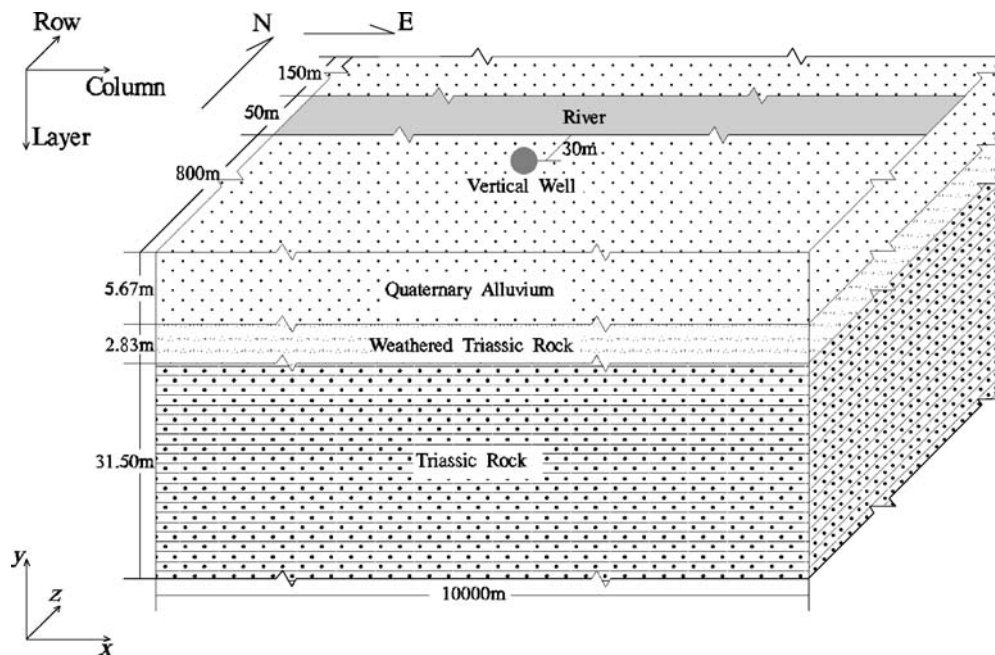


Fig. 4 Sketch of hydrogeological structure of the hypothetical model

its vertical hydraulic conductivity is 0.025 m/d. The river stage is also 40 m, the same as the eastern and western boundaries. The top of the model domain is the water table. No more sources and sinks are considered besides the river leakage.

During the initial stage of horizontal seepage well pumping, the pumpage is from the storage in the well pipe. This first causes a head decrease in the well pipe, which then causes a head decrease in the aquifer. When the head in the aquifer is lower than the river stage, surface water will leak into the aquifer and into the well pipe through the radiating bores. As pumping continues, the proportion of river leakage in the pumped water increases gradually. The horizontal seepage well pumping can reach steady state if the pumping intensity is reasonable and if the horizontal seepage well pumps only river leakage. The mathematical model of this problem can be described by Eq. (8), and can be solved by a three-dimensional finite difference numerical method.

Numerical modeling

To reflect the complicated structure of horizontal seepage wells and to calculate the flow field caused by pumping of horizontal seepage wells, a high-resolution grid of cubic cells was applied to the model domain. The model has 207 columns, 60 rows, and 12 layers. The maximum interval in the horizontal plane is 200 m, far from the horizontal seepage well, and the minimum interval in the horizontal plane is 0.75 m, near the horizontal seepage well.

The vertical well, which is a mixed layer well, is located in cell (41, 104) in the horizontal plane and is 3 m×3 m in dimension; the distance to the water line of the river is 30 m (see Fig. 4). The cells of the vertical well were set as a constant head boundary with 35 m constant head, to simulate the constant drawdown pumping with a 5-m constant drawdown.

In the vertical plane, the model has 12 layers. The aquifer is divided into two layers, the Quaternary alluvium and the weathered zone of Triassic rock; the thickness of the upper layer is set to 5.67 m and the thickness of lower layer is 2.83 m. The Triassic rock, the aquiclude, was

divided into 10 layers. The chambers of the horizontal seepage well are in layer 7 and layer 8 from the top, with thicknesses of 1.8 and 1.7 m respectively. The galleries of the horizontal seepage well are in layer 8 from the top. In this finite difference model, galleries are rectangular with a 1.5 m×1.7 m (width × height) cross section, and chambers are rectangular with 3 m×3.5 m (width × height) cross section. Considering the diameter of radiating bores is only approximately 0.1 m, to simulate the effect of a radiating bore within the grid (with minimum interval 0.75 m), a weighted average hydraulic conductivity, taking account of the cross sectional areas of radiating bores, was employed as the vertical hydraulic conductivity in the area where radiating bores are distributed. Considering that the equivalent hydraulic conductivity of radiating bores is far greater than the actual hydraulic conductivity of the area where radiating bores are distributed, the weighted average hydraulic conductivity was approximately calculated by:

$$K_w = \frac{K_b A_b}{A_d}$$

Where K_w is the weighted average hydraulic conductivity, K_b is the equivalent hydraulic conductivity of radiating bores, A_b is the total cross sectional area of radiating bores, and A_d is the cross sectional area of the medium where radiating bores are distributed.

Considering that the inner face of the well pipe is lined, the hydraulic conductivity of the cells adjacent to the well pipe was set at a small value, which is 0.005 m/d in this model. The flow field at steady state is shown in Figs. 5, 6 and 7, showing where the galleries, chambers and vertical well are located, respectively. These figures indicate that groundwater flowing to the horizontal seepage well has obvious three-dimensional flow characteristics. The vertical well has a minimum head of 35 m and the head is different in the well pipe, but has a constant value. The water flows from the radiating bores into the chambers of the horizontal seepage wells. It is indicated that there is a high head gradient around the well pipe and this reflects the effects of the well pipe's lining. Figures 6 and 7 shows

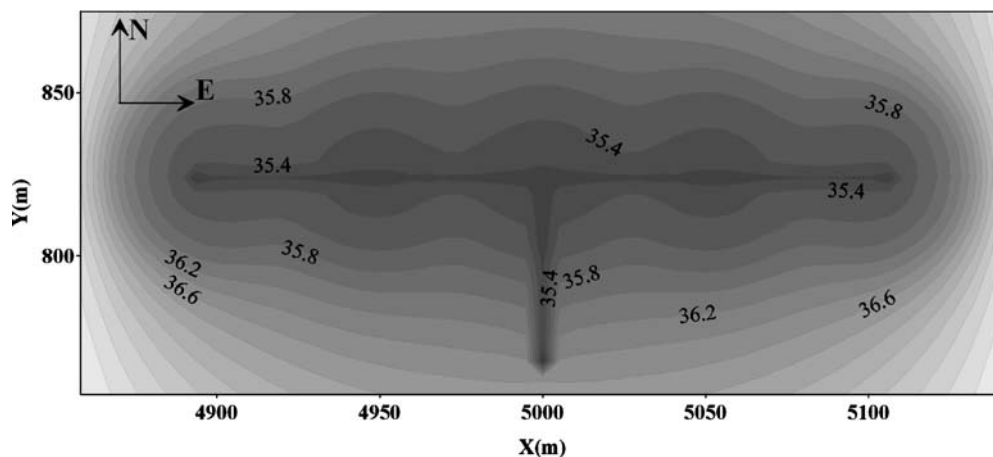


Fig. 5 Plan view of water-head contour map, showing where galleries are located in the x and y planes. Contour interval is 0.2 m

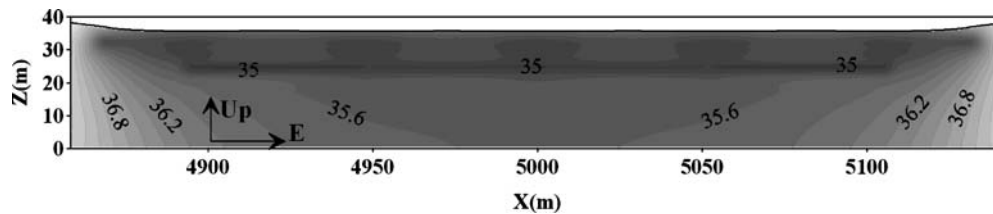


Fig. 6 Cross sectional view of the water-head contour map, showing where underground chambers are located in the X and Z planes. Contour interval is 0.2 m

that a single chamber can gather water from the river over a wide area.

The calculation shows that this horizontal seepage well can yield $3,447.70 \text{ m}^3/\text{d}$ in total when the drawdown of the vertical well is 5 m. The water inflows of the five chambers of the horizontal seepage well (from W–E) are: 722.31 , 675.64 , 643.06 , 675.64 , $722.31 \text{ m}^3/\text{d}$, respectively. Due to the lining of galleries and the vertical well, the water inflow is only $7.46 \text{ m}^3/\text{d}$ from the galleries, and $1.28 \text{ m}^3/\text{d}$ from the vertical well. By comparison, the actual yield of the real horizontal seepage well, located in the Wulidian water-supplying field located in Wuding River valley of Suide city, China (Fig. 2), is $3,294 \text{ m}^3/\text{d}$ in total, with a 4.92 m vertical well drawdown, and $3,552 \text{ m}^3/\text{d}$ in total with a 13.09 m vertical well drawdown. This comparison proves that the proposed model is reliable in calculating the pumpage of a horizontal seepage well. The river leakage is limited due to the fact that the vertical hydraulic conductivity of a riverbed is rather small. When the head of the vertical well dropped to 35 m, the head underneath the river also dropped significantly, due to pumping from the horizontal seepage well. This caused the groundwater head to separate from the river head near the horizontal seepage well, and the river (above the horizontal seepage well) reached its maximum leakage. Under this condition, the water inflows of five chambers are different; the middle chamber (C) has minimum inflow due to the interferer of the five chambers, and the outside chambers (A and E) have maximum inflow because they can capture the runoff in the aquifer far from the horizontal seepage well.

The Reynolds number (Re) distribution and equivalent hydraulic conductivity (K_n) distribution along the galleries

are illustrated in Figs. 8 and 9, respectively. Figure 8 shows that there are three different flow regimes in the horizontal seepage well: laminar flow appears in chambers A and E, laminar-smooth turbulent transitional flow appears in galleries 1,2,3,4 and chambers B and D, and smoothing turbulent flow appears in gallery 5 and chamber C. The equivalent hydraulic conductivity along the galleries and chambers are 6.42×10^9 to $2.11 \times 10^{11} \text{ m/d}$. According to the water inflow of each chamber, assuming there are 10 radiating bores in each chamber, then the minimum flow rate of a radiating bore can be $64.306 \text{ m}^3/\text{d}$, and the maximum flow rate is $72.231 \text{ m}^3/\text{d}$. The range of Reynolds numbers in radiating bores is from 6,718.63 to 7,546.63. This means the flow regime in the radiating bores is laminar-smooth turbulent transitional flow and the equivalent hydraulic conductivity is $5.91 \times 10^7 \sim 6.45 \times 10^7 \text{ m/d}$; the average hydraulic conductivity in the area where radiating bores are distributed is $51.95 \sim 16,381.99 \text{ m/d}$.

Because the equivalent hydraulic conductivity along the gallery cells is high and the cross-sectional area of the galleries is also high, the head loss in the galleries and chambers is rather small under the small pumpage of the horizontal seepage well. Therefore the head in the gallery and chambers is approximately equal, and the total head loss along the gallery is only 0.0002 m. However, the head loss in the radiating bores, which have a small cross-sectional area and high velocity, cannot be ignored. Figures 6 and 7 show that the head in the medium where the radiating bores are distributed decreases downwards.

As a result of the effects of the gallery lining, the water inflow to the galleries is small in relation to the total yield of the horizontal seepage well. Even so, the flux along the galleries is not evenly distributed (Fig. 10). The water

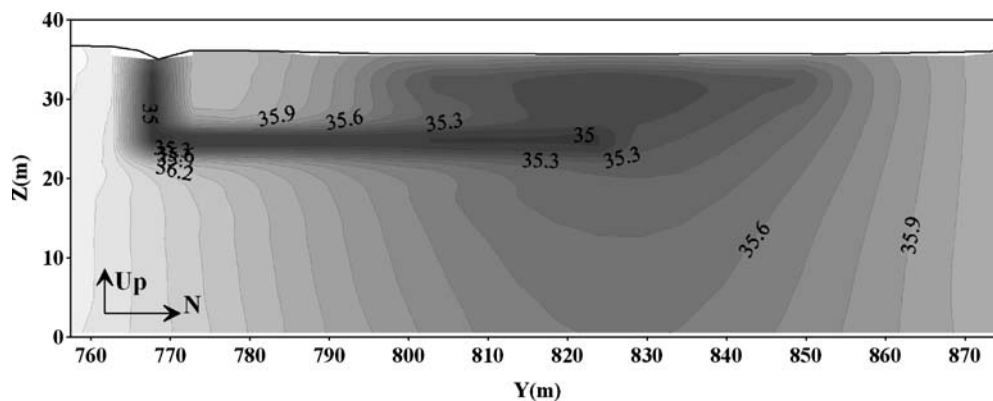


Fig. 7 Cross sectional view of the water-head contour map, showing where the vertical well is located in the Y and Z planes. Contour interval is 0.1 m

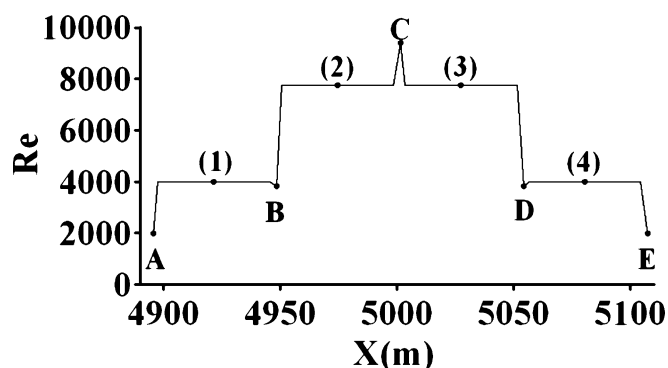


Fig. 8 The Reynolds number (Re) distribution along the gallery cells. The numbers (1), (2), (3), (4) represent segments 1, 2, 3, 4 of the galleries. A, B, C, D, E represent the chambers. The labels on the X axis are the X coordinates, in which $X=5,000$ m represents the location of chamber C (the same in Figs. 9 and 10). The Reynolds number along gallery 5, which exceeds 19,000, is not shown in this figure

inflows of each chamber are also not evenly distributed; the water inflow of the chamber near the vertical well is smaller than the inflow far away from the vertical well, due to the interference of the five chambers. Therefore, the galleries and chambers cannot be treated as uniform rate sink points.

Discussion

The conductivity (K_r) and thickness (M_r) of the riverbed material have significant impact on the productivity of the horizontal seepage well because they affect the specific river leakage, which in turn affects the inflow into each chamber. When the ratio K_r/M_r decreases, the specific river leakage will decrease and, in contrast, the drawdown in the aquifer will increase. When the head in the aquifer is separated from the river bottom, the specific river leakage reaches its maximum. Here, if the head of

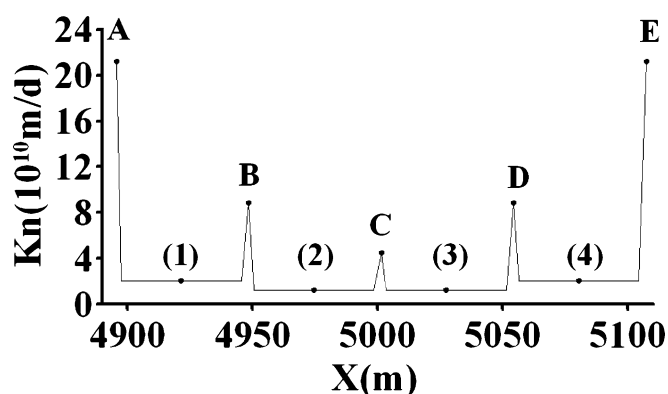


Fig. 9 The equivalent hydraulic conductivity (K_n) distribution along the gallery cells. The numbers (1), (2), (3), (4) represent segments 1, 2, 3, 4 of the galleries. A, B, C, D, E represent the chambers. The equivalent hydraulic conductivity distribution along gallery 5, which is no more than 6.43×10^9 m/d, is not shown in this figure

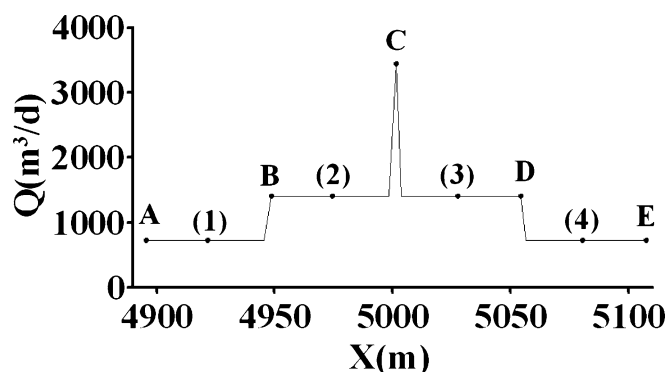


Fig. 10 The flow rate distribution (Q) along the gallery cells. The numbers (1), (2), (3), (4) represent segments 1, 2, 3, 4 of the galleries. A, B, C, D, E represent the chambers. The flow rate along gallery 5, which has little increase, is not shown in this figure

groundwater is dropped still further, the inflow into the chambers would not increase significantly.

According to the calculating model, if the river above the horizontal seepage well has reached its maximum leakage, adding more chambers will increase the productivity of the horizontal seepage well. However, the interference between chambers will increase with increasing numbers of added chambers; although the total pumpage is increasing, the inflows to each chamber will decrease. Therefore, it is not economical to construct a horizontal seepage well with more than five to seven chambers of this condition. When the ratio K_r/M_r of the riverbed material is great, the maximum specific river leakage will also be great; fewer chambers cannot cause the head of the aquifer to separate from the river bottom. Therefore, the river above the horizontal seepage well has not yet reached its maximum leakage. Under this condition, adding more chambers can increase the productivity of the horizontal seepage well significantly.

In this model, the cross-sectional area of the galleries is great and the productivity of the horizontal seepage well is relatively small. This will result in a small velocity and a small head loss along the galleries. If the cross-sectional area of the galleries is reduced, or conditions are managed such that there is maximum specific river leakage (for example, by placing the horizontal seepage well under the part of the river with the greatest specific river leakage), the productivity of the horizontal seepage well will be great and the velocity and head loss along the galleries will also be high.

Conclusion

This article presents a coupled model of groundwater flow to a horizontal seepage well without adopting the commonly used assumptions of uniform-flux or uniform-head boundaries. The model combines the aquifer and horizontal seepage well within a heterogeneous porous medium by assigning an equivalent hydraulic conductivity, defined by the Reynolds numbers, inside the horizontal

seepage well. Laminar, transitional, and turbulent flow regimes inside the horizontal seepage well were considered.

Using a hypothetical numerical model of a horizontal seepage well under a river, the calculation results show that the flux or head distribution along the horizontal seepage well cannot be treated as either a uniform-flux or a uniform-head boundary condition; even the head along the galleries is approximately equal.

Further analysis showed that the conductivity (K_r) and thickness (M_r) of the riverbed material above the horizontal seepage well have a significant effect on the productivity of the system; adding more chambers or increasing the drawdown in the vertical well cannot increase the productivity of a horizontal seepage well when the head of the aquifer is separated from the river bottom.

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