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# HORIZONTAL CIRCULAR PUMPING WELLS TO MINIMIZE SALINE WATER UPCONING: WATER RESOURCE DEVELOPMENT MEASURE FOR TROPICAL SAVANNA CLIMATIC NINH THUAN AREA, VIETNAM

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***The relevance.*** *The Southern central region of Vietnam, including Ninh Thuan province, has a tropical savanna climate and has been heavily suffering from drought and water salinization. Ninh Thuan province has faced severe droughts in recent years because of the increase of the frequency and intensity of extreme weather conditions, the water scarcity, and the salinity of the groundwater. The distribution of fresh and saline groundwater in Ninh Thuan plain has three zones: 1) zone of entire profile with fresh groundwater; 2) zone of the upper profile's with fresh groundwater and of the lower profile's with saline groundwater, and 3) zone of entire profile with saline groundwater. The groundwater abstraction facilities in the first zone are vulnerable to salinization from surrounding saline water, while in the second zone are vulnerable to the upconing saline water from below.*

***The aim:*** *to determine the optimal groundwater pumping in respect to given water level drawdown, to show that the horizontal circular wells are the best for minimization of saline water upconing, to determine the relationship between the saline water upconing height and the radii of the horizontal circular wells.*

***Objects:*** *tropical savanna climate, coastal plain, fresh and saline groundwater, aquifer with fresh water in the upper profile and saline water in the lower profile, circular groundwater wells, saline water upconing.*

***Methods:*** *finite element method, dynamic programming, Dagan–Bear model of saline water upconing, superimposition principle in dealing with multiple pumping points for identification of overall saline water upconing.*

***Results.*** *Different schemes of pumping fields with either vertical wells or horizontal circular wells with different radii were analyzed for saline water upconing. The time of saline upconing height in all the alternative schemes were determined. A very well regression curve of the relationship between the time saline water upconing to the horizontal circular wells and the circular well radii was obtained. The analysis results are extremely useful supporting well design in terms of minimization of saline water upconing.*

***Key words:***
*Tropical savannah climate, saline water upconing, dynamic programming, finite element, horizontal circular well.*

## Introduction

The Southern central region of Vietnam, including Ninh Thuan province, has been heavily suffering from drought and salinization. By the Köppen–Geiger climate classification system [1, 2] and a 1-kilometer resolution Köppen–Geiger climate map of H. Beck et al. [2] (Fig. 1), Ninh Thuan province has a tropical savanna climate, i. e., severe dry season, and prevailing drought conditions during the year, and is one of the provinces which are most affected by drought. Severe drought in recent years (2012 to 2016) led to reduced water availability for irrigated agriculture, especially for higher-value crops such as black pepper, coffee, dragon and grapefruits. In 2016, there was 5,770 ha of agricultural land in Ninh Thuan province, which is about 30 % of agricultural land, could not be planted due to water shortage and 5,500 households suffering from a shortage of domestic water [3]. In the context of the drought situation, the Asian development bank had financed a project to improve supply and water efficiency in drought-affected provinces in the central coast and central highlands of Vietnam, including Ninh Thuan province, one of the main objectives of which is a qualitative groundwater resource assessment because of the increase of the frequency and intensity of extreme weather conditions, the water scarcity and groundwater salinity of the area. The population in these regions is heavily relying on groundwater (GW) for domestic use and irrigating the high-value crops.

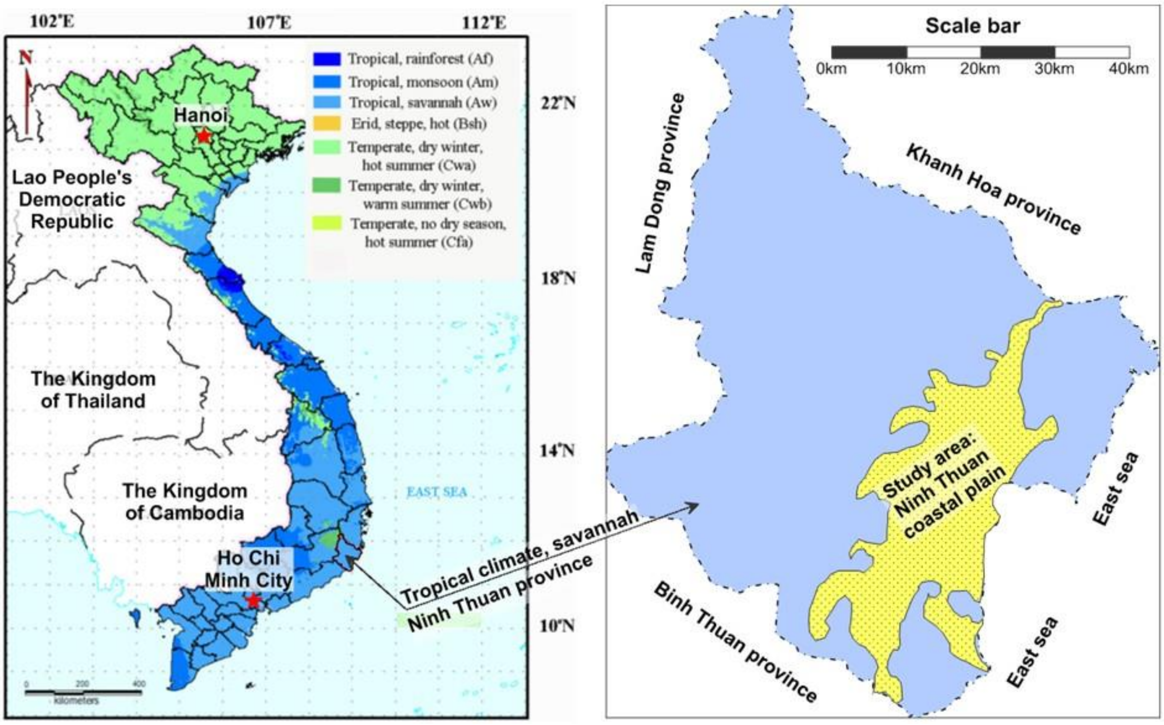


***Fig. 1.*** *Map of the study area in Köppen–Geiger climate classification for Vietnam*
***Рис. 1.*** *Карта района исследований по классификации климата Кёппена–Гейгера для Вьетнама*

The coastal plain area of Ninh Thuan province belongs to an arid area (from low aridity to high aridity) with Aridity Index from 1 to less than 0,25, in average is 0,45 which is corresponding to susceptibility to desertification, which is even more effected by climate change to cause the conditions more severe: the area of desertification is 41,02 ha which is 12,21 % of the province area. Along with aridity, the groundwater resources are saline in a large portion of the coastal plain area of Ninh Thuan province and are vulnerable to salinization from surrounding saline water and by the upconing of below saline water to the abstraction facilities. The distribution of fresh and saline GW in Ninh Thuan plain has three zones with the following specific feature: 1) zone of entire fresh GW depth (the total dissolved solids (TDS) is less than 1 g/l); 2) zone with the upper part of fresh GW, and 3) zone of entire saline GW depth. The native deep groundwater is saline water that mostly had a marine origin, which is either trapped in the sediments during deposition or invaded in the sediments during marine transgressions. As a result of recharge to these aquifers, freshwater layers lay over saline water in the vertical section of the aquifers.

To support a sound scientific-based GW development, the GW extraction technique by horizontal GW wells in the area of distribution of fresh GW in the upper parts to minimize the saline water upconing would be very essential. This would be a water resource development measure for the so-called tropical savanna climatic Ninh Thuan area with severe water scatter and GW salinity situation.

Coastal aquifers always have saline water underneath the freshwater. This phenomenon substantially limits the GW pumping rates using traditional vertical wells because of the upconing of the fresh/seawater interfaces and the potential of seawater intrusion G. Dagan and J. Bear [4], J. Bear et al. [5]. Since horizontal wells often have much longer screens than vertical ones, they can intercept a significant amount of freshwater flow in a shallow coastal aquifer. A horizontal well distributes its pumping rate over a much longer screen longer than a vertical well, thus generates much less upconing of the fresh/seawater interface. Therefore, a horizontal well might be a better means for coastal aquifer development. The model of a horizontal well (in Russia, it is named a horizontal drain) was firstly considered by N.E. Zhukovskii (refer to V.N. Emikh, [6]): the author considered the horizontal drain and other drain schematization as a line of sink points. Later, horizontal wells have been applied to environmental geology and hydrogeology since the pioneering work of collecting wells [7].

The analyses of the saline water upconing phenomenon may be carried out depending on the assumption of an abrupt or transition interface between the fresh water and saline water. The assumption of an abrupt boundary between saline water and freshwater is said to be a good approximation for practical conditions and is used in most engineering problems. This boundary represents the average position of the transition zone with 50 % fresh water mixed with 50 % saline water. Again, the problem of water drainage in a freshwater lying above saline water was firstly studied by a Russian researcher, P.Ya. Polubarinova-Kochina (refer to V.N. Emikh [6]), who published a solution to the problem of GW flow in a freshwater lens lying above saline water for the condition that the infiltration rate is equal to the outflow. Subsequently, the GW horizontal well and fresh/saltwater interface have been further studied by Yu.I. Kapranov and V.N. Emikh [8] and V.N. Emikh [9], who solved a series of problems relating GW flow with horizontal wells in a fringe of freshwater supplied from infiltration.

Most of the studies are related to seawater intrusion refer to vertical wells, e.g., H.M. Hajtiema [10], Nguyen Van Hoang et al. [11]. The investigations on the saline water upconing under horizontal wells may be referred to [12], Nguyen Van Hoang et al. [13].

Horizontal wells are typically employed not only for the recovery of heavy oil [14], but also for groundwater remediation in recent years chiefly thanks to the ability of a single horizontal well to extend its radius of influence over a large lateral range, what is particularly beneficial in sites where the pollutants are spreading extensively horizontally [15], and the combination of a large diameter vertical well with horizontal wells near the bottom of the vertical well successfully abstract groundwater from aquifers with low permeabilities and ensures sustainable water supply in many arid and semi-arid regions [16]. An overall review of the hydraulic and economical advantages of the horizontal wells, including radial collector wells, the evolution of horizontal wells, their application fields, their construction techniques, their typical hydraulic conditions and design criteria, and how they can be modeled properly may be referred to the recent publication of S. Collins et al. [17].

Dagan and Bear saline water upconing model is to be used in the present study to supporting the selection of the most appropriate horizontal circular well in respect to the minimization of saline water upconing.

## Study area conditions

### Hydrogeological conditions of Ninh Thuan coastal plain

The coastal plain of Ninh Thuan province has an area of about 760 $km^2$, including about 200 $km^2$ of the coastal sand dune (Fig. 1, 2) and consists of Quaternary deposits. The most widely distributed is the Holocene aquifer (qh) and the Pleistocene aquifer (qp) which make up one hydraulic aquifer qh–qp with a single water level since there is no impermeable layer between qh and qp aquifers. Therefore, the two aquifers in combination form one hydraulic aquifer with one single water level. The qh–qp aquifer is the main aquifer having a potential water resource for socio-economic use, the features of which may be referred to the work of as follows.

The Holocene aquifer is the first one from the ground surface and consists of silt and sand with grit and gravel. The aquifer has a very thin thickness from less than a meter to about 10 meters, on average 5 meters. The aquifer is unconfined and has a water level depth from few decimeters to 6 meters, on average 2,5 meters. There is about 57 % of the Holocene aquifer area has high total dissolved solids (TDS) from more than 1 up to 14 g/l.

The Pleistocene aquifer has a total distributed area of about 362 $km^2$. There are 152 $km^2$ of the aquifer is underlying the Holocene aquifer, while the remaining 210 $km^2$ is exposed to the ground surface where the Holocene aquifer is absent. The Pleistocene aquifer consists of silt and sand with calcareous grit in the upper part and of medium to coarse quartz sand with gravel in the lower part. The aquifer has a very variable thickness from less than a meter to about 44 meters, on average 7 meters. The GW level is from few decimeters above the ground surface to 6 meters below the ground surface, on average 2,45 meters below the ground surface. There is about 52 % of the aquifer area has high TDS from 1,42 to 13 g/l. For the area of freshwater distribution, in general, the aquifer water has an adequate quality for domestic use.

In the study area (plain of Ninh Thuan province), underneath the Pleistocene aquifer in the Upper Cretaceous effusive formation consisting of dacite, rhyodacite, felsite and esitodacite and their tuff. The drilling data showed its maximal thickness of about 67 meters. The aquifer is very low permeable: two pumping tests in the aquifer gave transmissivity values of 1,18 and 1,28 $m^2$/d.

Fig. 2, *a* presents the distribution of fresh and saline GW in Ninh Thuan plain, which provides three zones: 1) zone of entire vertical profile with fresh water; 2) zone of the upper part with fresh water and the lower part with saline water; 3) zone of entire vertical profile with saline water, and the saline water's TDS is 5 g/l in average. Fig. 2, *b* presents a typical hydrogeological cross-section in the middle of the plain along with line AB from northwest to southeast. A central rectangular area with sides of 7 and 9 km (Fig. 2) has been selected for the analysis of the study regarding optimal groundwater abstraction, to minimization of saline water intrusion, i. e., saline water upconing and horizontal saline encroachment. In the analysis area, the average thickness aquifer is 26 m which consists of the upper half fresh water and the lower half saline water.

### Hydraulic parameters of qh–qp aquifer

The hydraulic conductivity (*K*) of the Holocene and Pleistocene was determined by field pumping tests. The results of 38 pumping tests in the Holocene aquifer and 17 pumping tests in the Pleistocene aquifer gave the average, minimal and maximal values of horizontal hydraulic conductivity of 1,86; 0,17 and 5,15 m/d for Holocene aquifer, and 1,61; 0,26 and 4,79 m/d for Pleistocene aquifer. There is no clear distinction between the hydraulic conductivity of the Holocene and Pleistocene aquifers. Statistical analysis has shown that the hydraulic conductivity of the Holocene and Pleistocene together follows a normal distribution with the mean of 1,55 m/d and standard deviation of 1,10 m/d. Therefore, the analysis is carried out for three cases of typical hydraulic conductivity values: average minus standard deviation (0,45 m/d), average (1,55 m/d), average plus standard deviation (2,65 m/d). Since there is no information on vertical hydraulic conductivity, a reference ratio between the horizontal ($K_h$) and vertical hydraulic conductivity ($K_v$) of 10 is used to get $K_v$. Therefore, the values of $K_v$ of the three modeling cases are 0,045; 0,155 and 0,265 m/d.

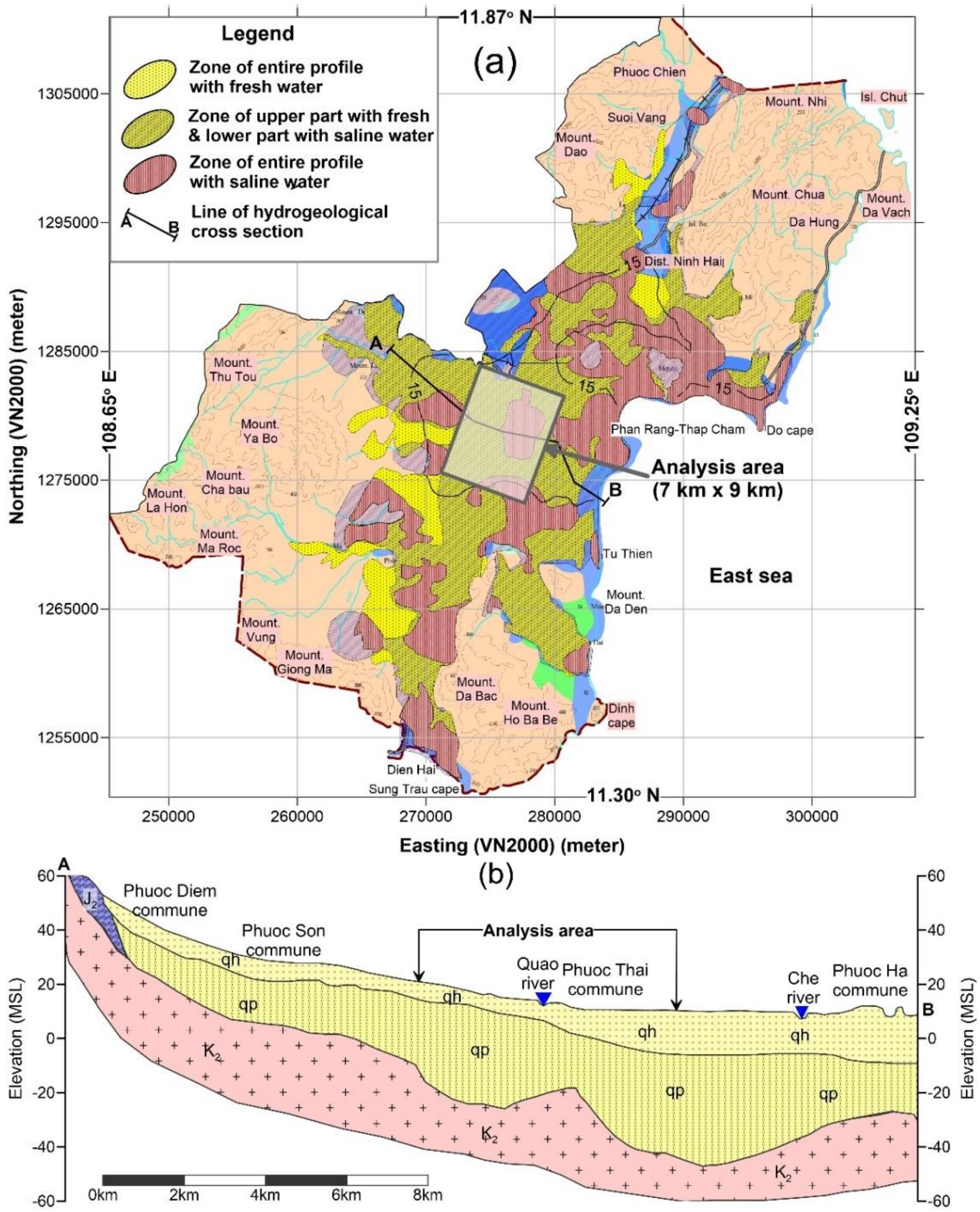


***Fig. 2.*** *Area of saline upconing and desalinization analysis (a) and hydrogeological cross-section along with line AB (b)*

***Рис. 2.*** *Район анализа засоления и опреснения (a) и гидрогеологический разрез по линии AB (b)*

### Methods

#### Dagan–Bear model of saline water upconing

G. Dagan, J. Bear [4] developed an analytical model to determine the saltwater upcoming from below saline water to the abstraction wells lain in the upper freshwater part. The aquifer has an upper part of fresh water and a lower part of saline water. The boundary between saline water and freshwater is said to be a horizontal plane and is an abrupt boundary with no transitional mixing. There exists a transition zone between fresh water and saltwater due to the mixing of these two types of water by hydrodynamic dispersion mechanism. This transition zone is also further developed because the abstraction of the lighter fresh GW above creates a cone of saline intrusion. This assumption of an abrupt boundary between saline water and freshwater is said to be a good approximation for practical conditions and is used in most engineering problems. This boundary represents the average position of the transition zone with 50 % freshwater mixed with 50 % saline water.

Suppose that there is an abstraction point in the upper fresh GW portion lying above saline water (Fig. 3, *a*). With the notation $\zeta_f(r,t)$ (Fig. 3, *b*) for freshwater pressure and $\zeta_s(r,t)$ for saline water pressure. The following is an equation (1) describing the boundary surface between the fresh and saline water [4]:

$$\begin{aligned}&n\left(\alpha_f\frac{\partial\Phi_f}{\partial t}-\alpha_s\frac{\partial\Phi_s}{\partial t}\right)-\alpha_f\left(\nabla\Phi_f\right)^2+\\&+\alpha_f\left(\nabla\Phi_f\bullet\nabla\Phi_s\right)^2-\frac{\partial\Phi_f}{\partial z}=0\\&n\left(\alpha_f\frac{\partial\Phi_f}{\partial t}-\alpha_s\frac{\partial\Phi_s}{\partial t}\right)+\alpha_s\left(\nabla\Phi_f\right)^2-\\&+\alpha_f\left(\nabla\Phi_f\bullet\nabla\Phi_s\right)^2-\frac{\partial\Phi_s}{\partial z}=0\end{aligned}\quad \text{on the boundary } \zeta=z. \quad (1)$$

In which: $n$ is the effective porosity; $\alpha_f=\gamma_f/(K\Delta\gamma)$; $\alpha_s=\gamma_s/(K\Delta\gamma)$; $\Delta\gamma=\gamma_s-\gamma_n$; $\Phi_f=K\zeta_f(x,y,z\ t)$; $\Phi_s=K\zeta_s(x,y,z,t)$; $\gamma_f$, $\gamma_s$ are unit weights of fresh and saline water, respectively; $K$ is the hydraulic conductivity.

The determined $\zeta_f(r,t)$ and $\zeta_s(r,t)$ in (1) give the coordinate $\zeta(r,t)$ of the fresh-saline boundary (Fig. 3):

$$\zeta(r,t)=\alpha_s\Phi_s(r,t)-\alpha_f\Phi_f(r,t). \qquad (2)$$

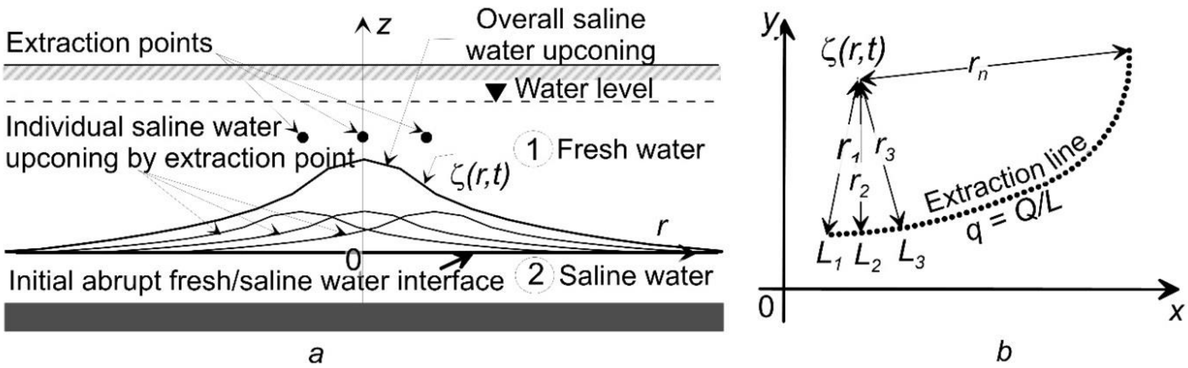


***Fig. 3.*** *Saline water upconing superimposition: a) pumping points; b) horizontal well*
***Рис. 3.*** *Подъем соленой воды: a) насосные станции; b) горизонтальная скважина*

The authors have used method of small perturbations to get $\Phi_f(r,t)$ and $\Phi_s(r,t)$ in (1) and (2) as follows:

$$\begin{aligned}\Phi_f(r,t)&=\Phi_f^0(r,t)+\varepsilon\Phi_f^1(r,t)+\varepsilon^2\Phi_f^2(r,t)+...=0;\\\Phi_s(r,t)&=\Phi_s^0(r,t)+\varepsilon\Phi_s^1(r,t)+\varepsilon^2\Phi_s^2(r,t)+...=0.\end{aligned} \qquad (3)$$

In which: $\Phi^0_f(r,t)$ and $\Phi^0_s(r,t)$ are corresponding to the steady pressures of $\zeta_f(r,t)$ and $\zeta_s(r,t)$, respectively; the remaining terms are the deviations from the steady values (or average values) with $\varepsilon$ characterizing the offsets which mathematically is significantly less than one. Although the method can deal with second-order or higher linearization, the authors have limited the first order linearization in (3) to have:

$$\zeta(r,t)=\frac{\gamma_f Q}{2\pi(\gamma_s-\gamma_f)\sqrt{K_r K_Z}}\times\int_0^\infty\left(\begin{aligned}&\frac{\cosh\left[\lambda(a-d)\right]}{\sinh(\lambda a)}\times\\&\times\left\{1-\exp\frac{-\lambda K_Z(\gamma_s-\gamma_f)t}{n[\gamma_f\coth(\lambda D)+\gamma_s\coth(\lambda S)]}\right\}\end{aligned}\right)J_0(\lambda r)d\lambda. \qquad (4)$$

In which: $Q$ is the point pumping rate; $K_v$ and $K_Z$ are the vertical and horizontal hydraulic conductivities, respectively; $t$ is the time from pumping beginning; $D$ is the total aquifer thickness; $a$ and $b$ are the thicknesses of fresh and saline water portion, respectively; $d$ is the initial distance from the fresh-saline boundary to the pumping point (Fig. 3, *a*).

The superimposition principle may be used for dealing with multiple pumping points, by which the overall upconing is (Fig. 3, *a*):

$$\zeta(r,t)=\sum_{i=1}^{n}\zeta_i(r,t). \qquad (5)$$

In which: $i$ is the numbering of pumping point ($i$=1, $n$); $n$ is the number of pumping points; and $\zeta_i(r,t)$ is the upconing caused by the pumping point $i$.

In the case of the horizontal drain, the saline water upconing can be determined by the following line integral (Fig. 3, *b*):

$$\zeta(r,t)=\int_{L_1}^{L_n}\zeta_q\left[r(l),t\right]dl. \qquad (6)$$

In which: $\zeta_q[r(l),t]$ is as by (4) with the unit rate ($q$) of the horizontal drain ($m^3$/day/1m of length); $L_1$, $L_n$ are the two ends' coordinates of the curvilinear horizontal drain (expressed in terms of given coordinates $x$, $y$); $r(l)$ is the distance (m) from calculation point to a point-well in the drain.

In a word, the overall upconing caused by multiple pumping points and by a pumping line is determined by (5) and (6), respectively. A computer program written in Fortran language had been compiled to perform this analysis.

### Dynamic programming (DP) in the determination of groundwater pumping in respect to permissible drawdown in temporally changing recharge

The DP in the determination of GW optimal pumping rates when specified target optimal GW levels are given in terms of space and time by the work of B.A. Makinde-Odusola, M.A. Marino [18]. The target optimal GW level is the GW level which is to be determined by criteria on sustainable environmental maintenance such as the maximal permitted ground surface subsidence due to GW level drawdown in the GW exploitation, or the maximal GW level drawdown corresponding to the sustainable GW exploitation, or the GW level field which does not allow seawater intrusion during the GW exploitation, etc.

In a brief, the control vector $Q_T$ (optimal pumping rates) from the time $T$ to the time $T$+1 is determined by the following:

$$\{Q_T\} = \{ f_T(\phi_{opt,T}, \phi_{est,T}) \}. \qquad (7)$$

In which $f_T$ is a function in terms of estimated optimal water level $\phi_{est,T}$ and given optimal water level $\phi_{opt,T}$ at time step $T$. If $\phi_{est,0}$ values are known, then the optimal pumping rate $Q_0$ can be successively determined by eq. (7), and then $\phi_{est,1}$ is estimated by GW flow model. This procedure continues until all temporal $Q_t$ and $\phi_{est,t}$ values are determined. This procedure can be summarized as follows:

$$\phi_0 \,\&\, \phi_{opt,0} \to Q_0; \phi_0 \,\&\, Q_0 \to \phi_{est,1};$$
$$\phi_{est,1} \,\&\, \phi_{opt,1} \to Q_1; \phi_{est,1} \,\&\, Q_1 \to \phi_{est,2}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (8)$$
$$\phi_{est,T-2} \,\&\, Q_{T-2} \to \phi_{est,T-1};$$
$$\phi_{est,T-1} \,\&\, \phi_{opt,T-1} \to Q_{T-1}; \phi_{est,T-1} \,\&\, Q_{T-1} \to \phi_{est,T}.$$

It is worthwhile to note that the initial water levels $\phi_0$ in (8) are considered as the initially estimated water levels $\phi_{est,0}$.

The described DP has been performed by exact arithmetic operations. Thus, if the temporal critical heads have been specified at all nodes of the numerical mesh, then the estimated heads at each time step should be the same as the critical heads (the differences are caused by the computational round-off errors if there are any).

To determine the pumping rates of the proposed wells at given water level values, DP coupled to GW FE modeling has been applied [19]. The current paper's first author programmed DP embedding with GW FE modeling for a confined aquifer and an unconfined confined aquifer [20].

### Results

#### Extraction area and pumping field layout

The selection of the extraction area, pumping field layout, and pumping rates are firstly based on the concept of the GW safe yield, and then on the adoptable saline upconing to the abstraction wells. By D.K. Todd [21], the safe yield is the amount of water that can be withdrawn from it annually without producing undesired results in terms of economics, water rights, and water quantity and quality. In terms of water quantity, safe yield is either the recharge or the rate of movement of GW through the basin, whichever is lesser [21].

Following the estimate of the GW recharge from the precipitation by Nguyen Van Hoang et al. [3], the average recharge is 44,9 % of the precipitation minus evaporation. This is corresponding to the total annual recharge from precipitation of 163,382 $m^3$ in an area of 1 $km^2$. As the main objective of the study is the minimization of saline water upconing to the extraction wells, a relatively shallow well drawdown is to be maintained. The authors subjectively selected the permissible drawdown to be the maximal GW fluctuation between the annual lowest and highest levels, i.e., 3,5 m.

One of the methods of determination of GW potential is the method proposed by M. Masket, Ph.M. Botrever (refer to [22]), by which the region of GW potential assessment is divided into a mesh of sub-areas where pumping fields are located in the centers. The pumping fields are assigned as large wells with equivalent radii. Pumping rates of the equivalent large wells are then determined via the designated water level drawdowns along with the areal and side recharges of the sub-areas.

Therefore, an extraction area of a 1×1 km square is selected for analysis. The whole study area is divided into a mesh of 1×1 km squares (Fig. 4). Within the extraction square, the qh–qp aquifer is either entirely saline or is fresh in the upper aquifer's half (e.g., the right and the left squares are shown shaded grey in Fig. 4, respectively).

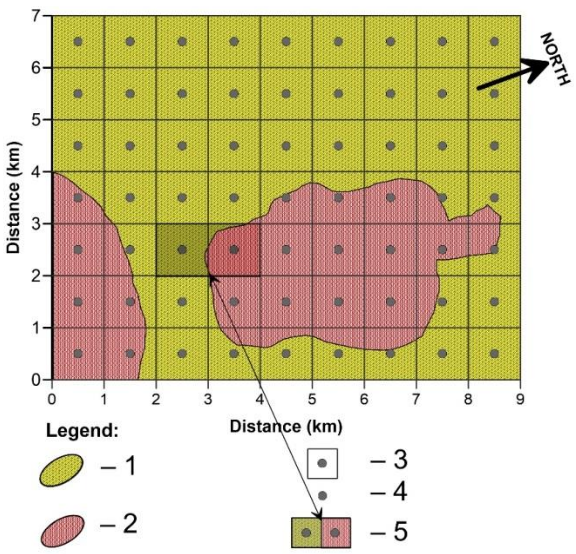


***Fig. 4.*** *Mesh of extraction squared areas and analysis extraction areas: 1 – zone of 13-m upper part with fresh and lower part with saline water; 2 – zone of entire profile with saline water; 3 – extraction square area; 4 – well field; 5 – two adjacent extraction areas under analysis*

***Рис. 4.*** *Сетка областей добычи воды и ее анализ: 1 – зона 13-метровой верхней части с пресной и нижней соленой водой; 2 – зона всего профиля с соленой водой; 3 – зона квадрата добычи; 4 – поле скважины; 5 – две смежные анализируемые области*

#### Pumping rates

The abstraction well fields are arranged in the central areas of the extraction squares with the same abstraction rate. This ensures that the saline water does not encroach on the abstraction fields in the squares with fresh water in the upper aquifer's half. The abstraction rate of the well field is determined by the above-described DP.

In this work, the target optimal GW is corresponding to the GW level drawdown in the pumping well equal to the maximal GW level fluctuation in a year, i.e., 3,5 m. The well field of 4 vertical wells in 30-m square vertices is selected for the determination of the well optimal pumping rates. The estimated optimal temporal well pumping rate is 59,47 $m^3$/day, i. e., the total pumping of the well field of 4 wells is 238 $m^3$/day, or 86,826 $m^3$/y. The annual abstraction amount is equal to 53 % of the annual precipitation. Therefore, during the dry seasons, the abstraction is from the aquifer storage, and during the rainy seasons, the rainwater recharge supplies the abstraction and raises the water level.

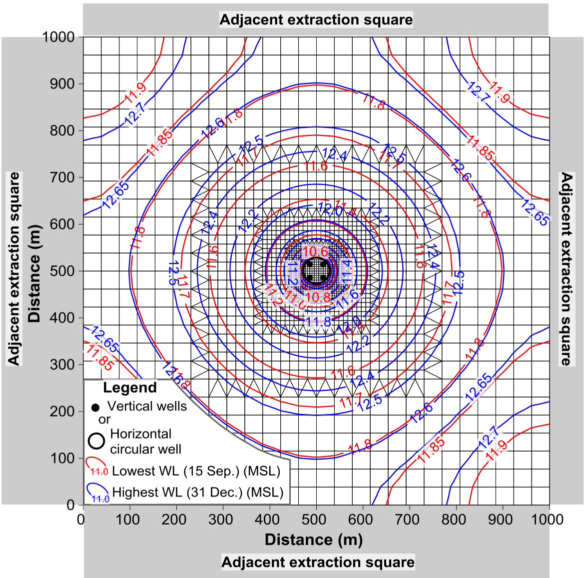


***Fig. 5.*** *GW level field due to estimated optimal GW extraction*

***Рис. 5.*** *Поле уровня ГВ, обусловленное оценкой оптимальной добычи ГВ*

The dynamic water level has almost a stable level and has the lowest and the highest level on 15 Sep. and 31 Dec., respectively. Fig. 5 presents the lowest and the highest water level field on 15 Sep. and 31 Dec. at the 5th simulation year with the average initial water level of 13 m (MSL).

### Saline water upconing in well field

Upconing to abstraction wells in case of 4 vertical wells and cases of horizontal circular wells of different radii is analyzed for supporting the selection of the abstraction scheme which would ensure that the well does not face salinization from below. The concept is that: 1) in the fresh GW extraction areas, the saline upconing is as far as possible from the wells' filters and the GW is pumped in the upper shallow portion which is replenished by the precipitation during rainy seasons (Fig. 6, *a*), and 2) in the saline GW extraction areas, the saline GW is abstracted from the above-MSL aquifer portion and in the upper shallow portion which is subsequently replenished by the precipitation during rainy seasons (Fig. 6, *b*).

Fig. 6, *a*, *c* presents the case with four vertical wells and with horizontal circular well, respectively, of the analysis conditions. Six cases of horizontal circular wells with radii 15, 20, 25, 30, 35 and 40 m have been analyzed. The upconing for representative cases of 4 vertical wells, 15-m and 40-m radius circular horizontal wells are presented in Fig. 7 respectively. Fig. 8, *a* presents saline water upconing height and time to horizontal circular well with different radii, while Fig. 8, *b* presents the relationship between time of 9-m saline water upconing height and radii of horizontal circular wells which shows a power trend of almost complete regression.

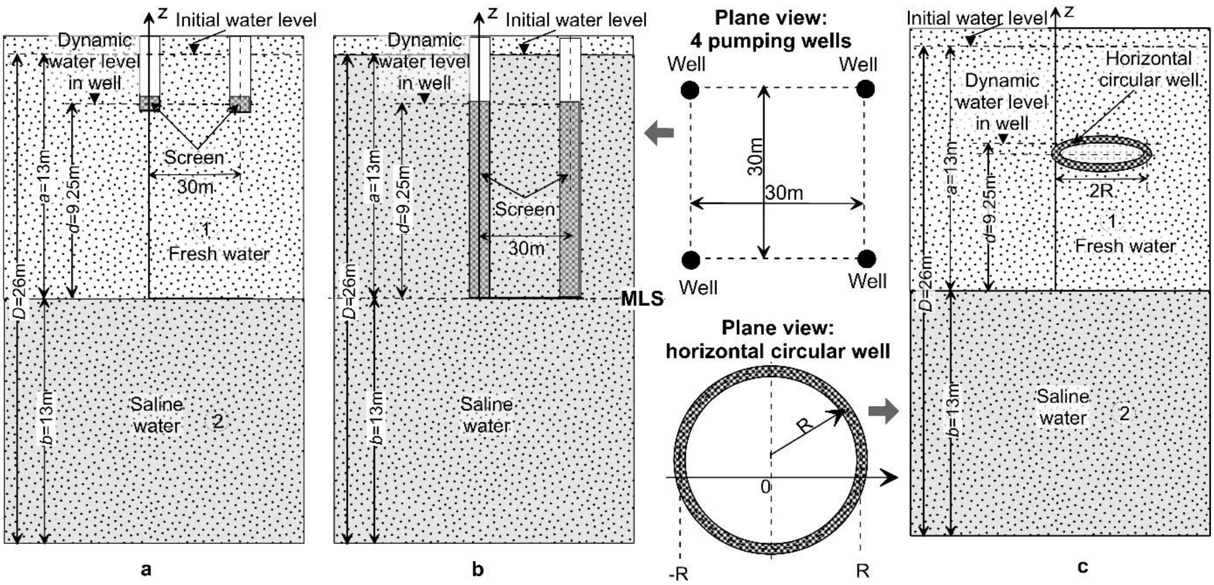


***Fig. 6.*** *Plane and section view: four vertical wells and horizontal circular well: a) wells in fresh-saline profile; b) wells in entire saline profile; c) horizontal circular well in fresh-saline profile*

***Рис. 6.*** *Вид сверху и в разрезе: четыре вертикальные скважины и горизонтальная кольцевая скважина: a) скважины в пресно-солевом профиле; b) скважины по всему солевому профилю; c) горизонтальная кольцевая скважина пресно-солевого профиля*

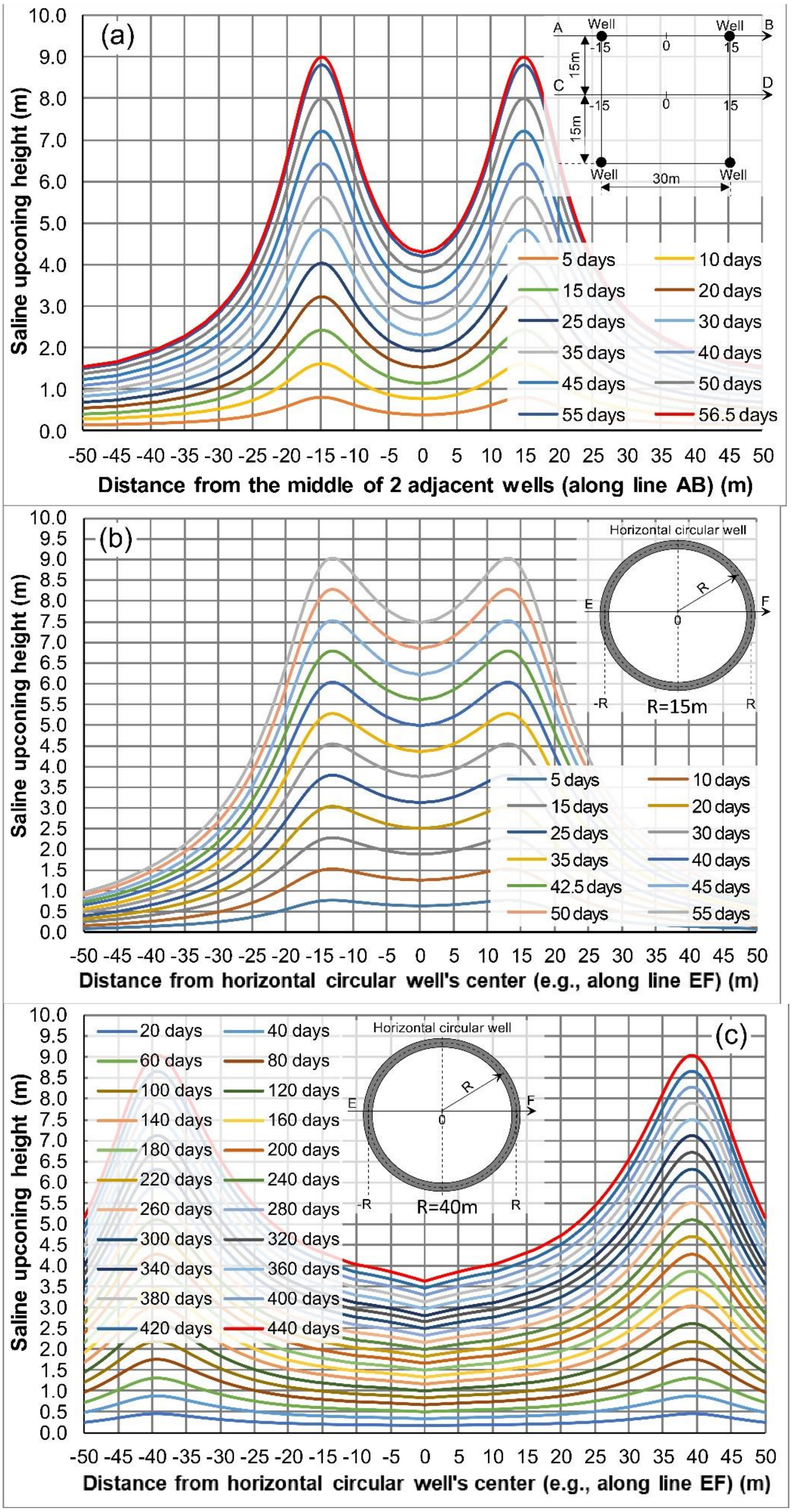


***Fig. 7.*** *Saline water upconing to vertical wells (a), to 15-m radius horizontal circular well (b) and to 40-m radius horizontal circular well (c)*

***Рис. 7.*** *Подъем соленой воды к вертикальным скважинам (a), к горизонтальной кольцевой скважине радиусом 15 м (b) и к горизонтальной кольцевой скважине радиусом 40 м (c)*

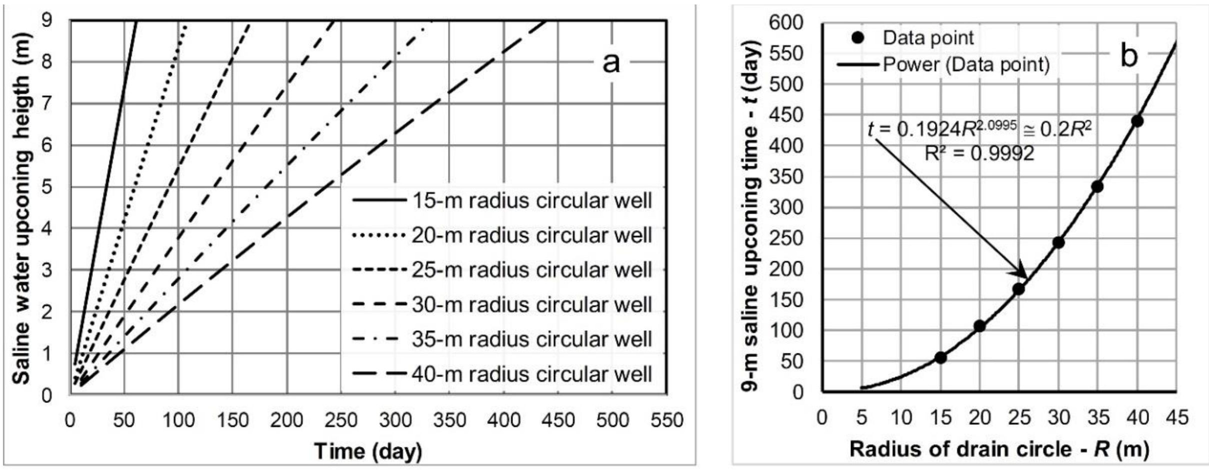


***Fig. 8.*** *a) saline water upconing height and time to horizontal circular well with different radii; b) 9-m saline water upconing height time trend*

***Рис. 8.*** *a) высота и время подъема соленой воды до горизонтальной круглой скважины различного радиуса; b) временной тренд высоты подъема соленой воды до 9 м*

### Conclusions

The severe drought, the water scatter, and complicated distribution of fresh and saline GW in both space and depth in Ninh Thuan coastal plain require special GW exploitation schemes. The application of DP had provided the temporal GW abstraction rates of the pumping fields in regards to the temporal recharge to GW from the precipitation. The equal GW extractions from the regular extraction areas can eliminate horizontal saline water encroachment on the freshwater abstraction fields, and to dewatering of the saline water in the saline water extraction areas. The GW abstraction schemes by vertical wells would cause saline water upconing to the wells in a relatively short time less than two months. The abstraction scheme by the horizontal circular well can dramatically increase the time the saline water upconing to the well. A 15-m radius horizontal well would double the time of saline water upconing to the well in comparison with the scheme of four vertical wells. The time saline water upconing to the horizontal circular wells is nearly perfectly proportional to the 2nd power of the well radius, or more exactly is nearly equal to a fifth of the 2nd power of the well radius (Fig. 8, *b*). The GW recharge by precipitation during Sep.–Dec. would replenish the aquifer's upper part both in fresh and saline extraction areas. The GW recharge by precipitation would either push down the saline upconing surface in the freshwater extraction areas or form a freshwater layer on the top of the saline water extraction areas.

Further investigation and study towards the aquifer's specific yield, effective porosity, site-specific hydraulic conductivity (both vertical and horizontal), dispersivity, and hydrodynamic dispersion are highly recommended during the GW extraction facilities' design and construction stages. It provides data and information necessary for amending and making corresponding modifications in regards to the well radius selection, well depth location, etc. The monitoring of water level and water salinity in depth below the horizontal wells is necessary to be implemented. It helps to predict possible unexpected salinization to take prevention measures. Finally, numerical modeling of salinization in regards to both saline water upconing and horizontal encroachment is very worthwhile to be carried out to get a deeper insight into the transitional saline intrusion of the designed horizontal circular wells.

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# ГОРИЗОНТАЛЬНЫЕ КОЛЬЦЕВЫЕ НАСОСНЫЕ СКВАЖИНЫ ДЛЯ МИНИМИЗАЦИИ ЗАБОРА СОЛЕНОЙ ВОДЫ: МЕРА ПО ОСВОЕНИЮ ВОДНЫХ РЕСУРСОВ ДЛЯ КЛИМАТИЧЕСКОЙ ЗОНЫ ТРОПИЧЕСКОЙ САВАННЫ НИНЬТХУАН, ВЬЕТНАМ

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***Актуальность.*** *Южный центральный регион Вьетнама, включая провинцию Ниньтхуан, имеет тропический климат саванны и сильно страдает от засухи и засоления воды. В последние годы провинция Ниньтхуан столкнулась с сильными засухами из-за увеличения частоты и интенсивности экстремальных погодных условий, нехватки воды и солености грунтовых вод. Распределение пресных и соленых грунтовых вод на равнине Ниньтхуан имеет три зоны: 1) зона всего профиля со свежими грунтовыми водами; 2) зона верхнего профиля со свежими грунтовыми водами и нижнего профиля с засоленными грунтовыми водами и 3) зона всего профиля с засоленными грунтовыми водами. Отводящие сооружения подземных вод в первой зоне уязвимы к засолению из-за окружающей соленой воды, а во второй зоне уязвимы к восходящей соленой воде снизу.*
***Основная цель исследования:*** *определить оптимальную откачку грунтовых вода с учетом заданного снижения уровня воды, показать, что горизонтальные кольцевые скважины оптимальны для минимизации подъёма соленой воды, определить зависимость между высотой подъёма соленой воды и радиусом горизонтальной скважины.*
***Объекты:*** *климат тропической саванны, прибрежная равнина, пресные и соленые грунтовые воды, водоносный горизонт с пресной водой в верхнем профиле и соленой водой в нижнем профиле, кольцевые скважины под грунтовыми водами, подъем соленой воды.*
***Методы:*** *метод конечных элементов, динамическое программирование, модель подъема соленой воды Дагана–Беара, принцип наложения при работе с несколькими точками откачки для определения общего восходящего потока соленой воды.*
***Результаты.*** *Проанализированы различные схемы откачки воды как вертикальными скважинами, так и горизонтальными кольцевыми скважинами разного радиуса для забора соленой воды. Определено время подъема солевой массы на высоту во всех альтернативных схемах. Получена очень хорошая кривая регрессии зависимости между временем поступления соленой воды в горизонтальные круглые скважины и радиусами круглых скважин. Результаты анализа чрезвычайно полезны при проектировании скважины с точки зрения минимизации подъема соленой воды.*

***Ключевые слова:***
*Тропический климат саванны, подъем соленой воды, динамическое программирование, конечный элемент, горизонтальная кольцевая скважина.*

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