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Analysis of the Caucasus Mineral Waters' Field's Modeling

Ivan M. Pershin[1], Alexander V. Martirosyan[1] & Karina V. Martirosyan[1]

[1] North-Caucasian Federal University, branch in Pyatigorsk, 357500 Pyatigorsk, Russian Federation

Correspondence: Karina V. Martirosyan, North-Caucasian Federal University, branch in Pyatigorsk, 357500 Pyatigorsk, Russian Federation.

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Abstract

The purpose of this work is to make a review of the mineral water field's modeling approaches, to detect common factors of this approaches and to hold the general sustainability analysis of the shown models. In this work the analysis of a number of the geofiltrational models constructed in relation to mineral water fields of the Caucasus Mineral Waters region is carried out. At the model's creation the data on mineral water production from Kislovodskoe and Georgievskoe fields is used. It is shown how factors of external that impacted on the studied object can be included to geofiltrational model. For the each model the entry and boundary conditions, which correspond to a physical picture of difficult hydrolithospheric processes are specified. In relation to these fields the assessment of geofiltrational model's stability is carried out. Using of the experimental data obtained during operation of fields provides the accuracy of the modeling numerical calculations. Comparison of the model and actual results shows high reliability of settlement data. The conducted research allows the development of the general approach to creation of Caucasus Mineral Waters' region fields' geofiltrational models. Results of the modeling can be used for carrying out a synthesis of the distributed control system by hydrolithospheric processes of all complex of fields.

Keywords: system modeling, mathematical modeling, geofiltration models, aquifer pressure function, compressibility of formation, model's sustainability, synthesis of the distributed parameters hydrolitosphere processes control system

1. Introduction

The safety of the world's mineral water storages is one of the topical issues in nowadays' province of recourse's conservation. It is very hard task to organize free from danger exploitation mode's parameters, particularly on the territories where the difficult hydrogeological conditions are. One of this regions is Caucasus Mineral Waters (CMW). Objects of research will be the field Nagutskoe. The summarized flow rate of the wells is 3200 m3/s, but because of its difficult structure it becomes quite hard produced (Martirosyan and Martirosyan, 2014).

Technogenic changes of hydrogeological conditions in areas of intensive underground waters' production have considerable impact on conditions of the extensive territories' economic development (Elmahdi and McFarlane, 2009). It raises requirements to hydrogeological forecasting. For the perfomance of expected decisions the mathematical models describing processes of a geofiltration, geomigration and a mass transfer are built (Kresic, 2007.). The most widespread of them are geofiltrational models. At high level of compliance to hydrogeological object and basic data's adequacy, the using of this type models gives qualitative results (Yanukyan et al., 2013).

But it is a well-known fact, that hydrogeologic and hydrologic parameters used by the model are always just an approximation of their actual field distribution, which can never be determined with 100% accuracy (Martirosyan and Martirosyan, 2013). That means that it is necessary to pay a great attention to the equation's accurate, because it has a profound effect for the model's sustainability (Yanukyan et al., 2013).

It is offered to consider some approaches of the mineral water field's mathematical model's development and to mark out the main distinctions to compare the results of their practical application.

Production of drinking water from the earth interior can shortly become a necessity, therefore already now it is necessary to reflect of its stable production and rational using organization. In case of underground waters there is such concept as a "safe water intake". It is understood as the organization of such water production in case of which there are no serious geological changes of layers and the exploited aquifers exhaustion (Winter, 1998).

The miscalculation of productions admissible volume can lead to the water level reduction in the aquifer, owing to what there can be a water percolation from lower horizons or a soil flash. Similar changes of a hydrogeological structure can lead to fields' collapse that will make its coming exploitation impossible (Martirosyan et al., 2013).

For accidents prevention the hydrogeological objects control systems are used. On the basis of mathematical models putting into the system they are capable to count the technogenic processes development dynamics (trend) for some years forward, thereby giving an opportunity of waters production parameters adjustment.

Implementation of the similar systems is especially important for the territories sitting on hydromineral resources, as because of mineral and sulfur water medical properties, they are more rare and valuable resource (Kresic, 2007).

The development of hydrogeological object's control systems can be conditionally divided into several stages: control object description, mathematical model's development and testing, parameters adjustment, management systems synthesis (development) (Fitts, 2013).

It is offered to consider in more detail the second systems development stage – the development of a mathematical model. Nowadays simulation of geological objects took a form of the research's separate area, extremely important for regions with large volumes of underground waters, such as Caucasus Mineral Waters region.

Therefore it is offered to consider the concept of the hydrogeological objects mathematical simulation, explained in works I.M. Pershina and A.V. Malkov, which researches are conducted on the mineral water fields of this region. As Caucasus Mineral Waters region locates a row of mineral water fields, there is a favorable situation for carrying out the similar researches, which can be carried out from use of real operational data, that increases the technogenic processes reflection accuracy internally of the hydrolithospheric objects of this region.

2. Methods

Groundwater modeling is some form of the most projects dealing with groundwater development, protection and remediation. Model of underground waters fields can be divided into two components: geofiltrational model and mass transfer model.

Geofiltration model is a representation of object (field) in the form of two or three-dimensional cell array, which are characterized by a set of parameters, and include the operational data of wells (field) and the sheeted processes dynamic characteristics (Jakeman et al., 2012). Basic data for modeling includes: the layers amount data and their capacitor parameters, data for permeability and intra layers pressure, operational data etc. The mathematical filtration model is the differential equation that describing geofiltration process in specifically set space (Malkov and Pershin, 2007).

More complex challenge is model's parametrical providing. Geological objects is the systems with the distributed parameters, and justification of the hydrodynamic parameters' spatial distribution is a responsible task.

Certainly, in model forming the preliminary information about filtrational properties of the environment is also available. It is defined on the basis of the underground waters inflow testing, which is carried out in the course of the objects geological studying, however that is dot estimates which not always coincide with the geofiltration processes' average values characterizing (Meenal and Eldho, 2012). In this regard it is very important to have a verification technique, that allows us to make an adjustment of the model's parameters. In other words, available information about object's operation modes for the last periods is reproduced on model, and by means of special receptions the parameters adjustment is introduced, providing the maximum convergence of the actual and model data (Gavich, 1988).

As the purpose of work is the review of Caucasus Mineral Waters region's mineral water field's, it is offered to lower the equation of a mass transfer and further consider only the geofiltration equation.

This differential equation describes spatial process of a filtration which at certain assumptions can be presented as:

$$\eta * \frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial H}{\partial z}\right) \quad (1)$$

where $\eta *$ - compressibility of rock, 1/m;

k_x, k_y, k_z -hydraulic conductivities coefficients for the corresponding coordinates, m/day; $H(x, y, z, t)$ - pressure function.

At this stage the geofiltration problem is solved. Given equations describes geofiltration process with the best precision, but its problems are insufficient parametrical providing and high mathematical complexity. Due to these factors, for the purpose of the model's simplification it is possible to consider two-dimensional representation of the equation (1). In this case the differential equation takes the form:

$$\mu*\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(km_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(km_y\frac{\partial H}{\partial y}\right)+b_k\times\left(H_k-H\right)+b_n\times\left(H_n-H\right) \tag{2}$$

where $\mu*$ - compressibility of formation coefficient (the compressibility of formation coefficient equal's $\mu*=m\eta*$, where m – formation thickness, m);

b_k, b_n – migration parameter of the relatively confining stratum, that underlies in the roof or on the base, m/day;

H_k, H_n – pressures in abutting aquifers, m;

k_x, k_y, k_z – hydraulic conductivities coefficients for the corresponding coordinates.

3. Results

The approach described above has been applied by mainly hydrogeologist of the enterprise "Narzan" Dubogrey V.F. in the simulation of Kislovodskoe mineral water field (Dubogrey, 2013). He proposed a two-dimensional hydrogeological model of the field. The system of equations describing the process geofiltration has the following form:

$$\begin{cases}\mu_1*\dfrac{\partial H_1}{\partial t}=km_{1,x}\dfrac{\partial^2 H_1}{\partial x^2}+km_{1,y}\dfrac{\partial^2 H_1}{\partial y^2}+b_{1,2}\times\left(H_2-H_1\right)+W_a;\\ \mu_2*\dfrac{\partial H_2}{\partial t}=km_{2,x}\dfrac{\partial^2 H_2}{\partial x^2}+km_{2,y}\dfrac{\partial^2 H_2}{\partial y^2}+b_{2,3}\times\left(H_3-H_2\right)+b_{1,2}\times\left(H_1-H_2\right);\\ \mu_3*\dfrac{\partial H_3}{\partial t}=km_{3,x}\dfrac{\partial^2 H_3}{\partial x^2}+km_{3,y}\dfrac{\partial^2 H_3}{\partial y^2}+b_{2,3}\times\left(H_2-H_3\right),\end{cases} \tag{3}$$

where W_a - interstratial infiltration recharge, m^2/day.

In this model, the lower bound is represented by the closed and the top with the presence of infiltration. The initial conditions are given as follows:

$$t=0, Q=0, H=H_{cm}, \tag{4}$$

where Q - well's flow rate, m^3/day.

Boundary conditions are given over external boundary of the object as $Q=const;$ and inside of the object, between the aquifers as $Q=f(H)$.

In this system of equations used in the pressure function in interstratial aquifers, and also introduces W_a - interstratial infiltration recharge of the upper reservoir. The model (3) showed good repeatability.

Another approach to the Kislovodskoe mineral water field modeling was proposed by Atroschenko O.I. (Atroschenko, 2008). He presented a mathematical model of the aquifer in the form of partial differential equations having the following form:

$$\frac{\partial S}{\partial t}=\frac{1}{\eta*}\times\left(k_x\frac{\partial^2 S}{\partial x^2}+k_y\frac{\partial^2 S}{\partial y^2}+k_z\frac{\partial^2 S}{\partial z^2}\right)-F\frac{\partial S}{\partial x}-\hat{S}(t)\times\delta(x,y,z) \tag{5}$$

where S – depression of level, m;

k_x, k_y, k_z – hydraulic conductivities coefficients for the corresponding coordinates;

$\eta*$ - compressibility of rock;

F – motion speed of aquifer, m/sek;

$\hat{S}(t)$ – controlling action.

Physical meaning $\hat{S}(t)$ is the controlling action on the subject to management, submitted to the discretization points. In this points $\delta(x,y,z)=1$, but in another $\delta(x,y,z)=0$. $\hat{S}(t)$ is the well's flow rate (water intake from the well). F – nonlinear value, that defines the motion speed of aquifer, that is defined by the correlation of $F = F_0 - a\sin(S)$.

In this case, the boundary conditions are as follows:

$$\begin{aligned}
&S(x,y,z,0)=0;\\
&\frac{\partial S(x_1,y,z,t)}{\partial x}=0,\frac{\partial S(x_7,y,z,t)}{\partial x}=0;\\
&S(x,y_1,z,t)=0,\frac{\partial S(x,y_4,z,t)}{\partial y}=0;\\
&\frac{\partial S(x,y,z_1,t)}{\partial z}=0,\frac{\partial S(x,y,z_4,t)}{\partial z}=0.
\end{aligned} \tag{6}$$

This model is three-dimensional, the water intake acts as entrance influence from a well. In model the water level changing process is considered in water-bearing horizon.

As the last example it is offered to consider the system of the differential equations which is the mathematical model of a water infiltration process in aquifer of the Georgievskoe field (Malkov and Pershin, 2007). The similar mathematical model allows a prediction of a technogenic changes in a field as a whole and has the following appearance:

$$\begin{cases}
\dfrac{\partial S_1}{\partial t}=\dfrac{1}{\eta_1 *}\left(\dfrac{\partial(k_{y1}\cdot\partial S_1)}{\partial x^2}+\dfrac{\partial(k_{y1}\cdot\partial S_1)}{\partial y^2}+\dfrac{\partial(k_{y1}\cdot\partial S_1)}{\partial z^2}\right)-F_{x1}\cdot\dfrac{\partial S_1}{\partial x};\\
\dfrac{\partial S_2}{\partial t}=\dfrac{1}{\eta_2 *}\left(\dfrac{\partial(k_{y2}\cdot\partial S_2)}{\partial x^2}+\dfrac{\partial(k_{y2}\cdot\partial S_2)}{\partial y^2}+\dfrac{\partial(k_{y2}\cdot\partial S_2)}{\partial z^2}\right)-\\
-F_{x2}\cdot\dfrac{\partial S_2}{\partial x}-\hat{S}(t)\cdot\delta(x_i,y_i,z_i);\\
\dfrac{\partial S_3}{\partial t}=\dfrac{1}{\eta_3 *}\left(\dfrac{\partial(k_{y3}\cdot\partial S_3)}{\partial x^2}+\dfrac{\partial(k_{y3}\cdot\partial S_3)}{\partial y^2}+\dfrac{\partial(k_{y3}\cdot\partial S_3)}{\partial z^2}\right)-F_{x3}\cdot\dfrac{\partial S_3}{\partial x};
\end{cases}$$
$$0<x<X_L, 0<y<Y_L, 0<z<Z_j; (j=1,2,3), \tag{7}$$

where j – aquifer's number.

Initial conditions are shown as:

$$S_j(x,y,z,0)=0; \tag{8}$$

Boundary conditions on the field limit are shown as:

$$\begin{aligned}
&\frac{\partial S_j(X_L,y,z,t)}{\partial x}=0, S_j(0,y,z,t)=0;\\
&\frac{\partial S_j(x,0,z,t)}{\partial y}=\frac{\partial S_j(x,Y_L,z,t)}{\partial y}=0;\\
&(j=1,2,3).
\end{aligned} \tag{9}$$

Boundary conditions on the border of aquifers are shown as:

$$\begin{aligned}
&k_{zj}\frac{\partial S_j(x,y,Z_L,t)}{\partial z}=k_{zj+1}\frac{\partial S_{j+1}(x,y,Z_{j+1},t)}{\partial z}\\
&\frac{\partial S_1(x,y,z=Z,t)}{\partial z}=0,\frac{\partial S_3(x,y,z=Z_3,t)}{\partial z}=0;\\
&0<x<X_L, 0<y<Y_L
\end{aligned} \tag{10}$$

4. Discussion

Let's consider the Caucasus Mineral Waters region's mineral water field's modeling results. When modeling either spatial or flat geofiltrational models are used. The general approach to modeling is presented in table 1.

Table 1. The modeling of the Caucasus Mineral Waters region's fields

	Kislovodskoe field Dubogrey V.F.	Kislovodskoe field Atroschenko O.I.	Georgievskoe field Malkov A.V., Pershin I.M.
Equations	Equation (3)	Equation (5)	Equation (7)
Initial and boundary conditions	Equation (4)	Equation (6)	Equation (8-10)
Object's size (m)	20000×20000	1500×500×1600	6300×1560×2600
Number of discretization interval	200×200	6×3×3	42×12×66
Size of discretization interval (m)	$\Delta x = 100$ $\Delta y = 100$	$\Delta x = 250$ $\Delta y = 166$ $\Delta z = 53$	$\Delta x = 150$ $\Delta y = 130$ $\Delta z = 20$
Hydraulic conductivity coefficients for the corresponding coordinates (m/day)	$k_{xj}, k_{yj}, k_{zj} = 0{,}2$	$k_{ijk} = 0{,}2 - 0{,}4$	$k_{xj}, k_{yj}, k_{zj} = 0{,}2$
Elastic capacity coefficients (1/m)	$\mu_{1,x} = \mu_{2,x} = \mu_{3,x} = 2\times10^{-5}$	$\eta_{const} = 2\times10^{-7}$	$\eta_1{*} = 1{,}5\times10^{-7}$ $\eta_2{*} = 2\times10^{-7}$ $\eta_3{*} = 2{,}25\times10^{-7}$
Error (%)	10-20	15	14

Generally there are two approaches to model's development:

1. To make the difficult model that considers all possible factors, that involve complexity of mathematical calculations and realization on the computer.

2. To make simpler mathematical model which must display the essence of occurring processes.

At an assessment of the model's adequacy, both existing, and projected, the limited subset of various states can be used. In this regard, for an assessment of received results reliability when modeling, great importance played the problem of the model's stability. As it is known that computing schemes can be formed on the opened and closed cycles.

In this case for calculations schemes with the closed cycle are used. When it using the model's stability depends on proceeding processes' physical parameters. Thus, using methods of the management theory, it is possible to choose parameters in the way, that the computing scheme will be steady.

If the carried-out results of the model's quality assessment showed that a number of its working parameters doesn't meet imposed requirements, it is necessary to execute model calibration.

Process of calibration has iterative character and consists of three main stages: global change (input of new processes, properties, algorithms), local change (changing of some laws of random variables modeling), changing of the special parameters called by the calibration (Gavich, 1988).

The approaches given above to underground waters dynamics modeling in total represents numerical geofiltrational modeling which actively took root into the practice of hydrogeological researches, significantly having pressed analog modeling. But, despite a large number of the works mentioning this task, the technique passed only initial steps of the development in hydrogeology. From the point of view of this technique implementation to the practice of hydrogeological researches there is a number of shortcomings:

- limitation of the researches directed on an assessment of practical accuracy of the main differential schemes in relation to standard hydrodynamic conditions that doesn't allow to carry out objective comparison of methods and technique schemes for identification of optimum limits of their applicability;

- lack of due justification of structure and opportunities of created programs that complicates their use for the solution of the other class problems, than for what they are made;

- limited number of works in which numerical methods would be used for independent research of underground waters dynamics complex problems. Numerical geofiltrational modeling is often applied where it is possible to manage approximate analytical estimates or analog means (Martirosyan, 2014).

All these circumstances in combination with deficiency of initial information traditional for hydrogeology substantially reduce interest to numerical modeling from hydrogeologists. But, despite it, in works of founders of differential methods it was repeatedly noted that their effective introduction requires participation of application engineers.

All presented models are steady rather set technological process and possess a low error. Analysis of the Kislovodsk field modeling results, presented in V. F. Dubogrey's works, also shows adequacy of the model. In this research he describes flat-space model of a field. Modeling is made concerning the provision of statistical level in the aquifers. Approbation of this technique showed its efficiency. The general error at calculation of drawdown in operational wells made 10-20% (Dubogrey, 2013). In turn, the computational error model of one of the field's aquifers developed Atroschenko O.I., is 15% (Atroschenko, 2008).

Results of the Georgievskoe field modeling shows the good convergence of the actual and model falls on observation wells. The mean square error of calculations is 14%.

The presented models are result of joint work of experts of both areas, than qualitative results of researches are caused.

In this work, results of modeling of Kislovodskoe field and Georgievskoe field are generalized.

The conducted researches show that creation of geofiltrational models according to the techniques given in this work, allows the receiving of rather reliable results. The data obtained as a result of modeling can be the basis for the organization of a control system by a field as there is a possibility of indignation size determination which brings production process in a condition of hydrolithospheric balance of a field. Respectively, there is a possibility of the organization of the compensation mechanism by the principle of feedback.

Synthesis of the regulator, allowing organizing of the balanced field’s management is the new investigation phase of a hydrolithosphere following creation of the field’s geofiltrational model (Malkov and Pershin, 2007). Process of regulator synthesis is connected with determination of the model’s parameters at which not only a compensation mechanism is using, but also stability conditions are satisfied. These researches become complicated that demand big computing capacities when performing numerical calculations. Accuracy increase in the model creation is connected with reduction of a discretization interval that at once is reflected in calculation time.

Thus, the models presented in this work are base for carrying out synthesis of the regulator of a condition of a field. Respectively, modeling accuracy on this step defines results of the subsequent investigation phases.

5. Conclusion

The analysis of geofiltrational models of the Kislovodskoe and Georgievskoe mineral water fields are carried out. Mechanisms of the various processes that proceeding in fields calculations are considered: infiltration recharge, water intake from a well. It is shown how the system from several water-bearing layers is modeled. Generalization of the modeling methods which are applied when studying the processes proceeding in mineral water fields is executed.

The algorithm of infiltration model’s stability assessment is described. During of the process’ research, specification of the model’s parameters that allows the achieving of considered scheme stability is carried out. It is shown that this algorithm can be applied to all considered models of the fields without restrictions.

The considered models are reliable as researches were conducted on the basis of the enterprises which are engaged in the development of modeled fields. Existence of a large volume of a field’s statistical data provides the possibility of computing algorithm practical approbation. It is noted that the mechanism of the mineral water field’s analysis, offered by authors, allows the regularities’ of their functioning revealing.

In future this algorithm can be used on the every mineral water field in the world, but know some equation problems of it must be solved. The greatest future plan is to develop automatic control system to provide the safety of exploitation process for all mineral water fields of the region.

References

Atroshenko, O. I. (2008). System synthesis of debit management of mineral water supply well. Vestnik of ISPEU 3. Retrieved December 4, 2014, from http://www.vestnik.ispu.ru/sites/vestnik.ispu.ru/files/publications/90-94_0.pdf

Dubogrey, V. F. (2013). Mathematical model of the geofiltrarion of the Kislovodsk carbonic-acid mineral waters deposit. National forum "Narzan 2013". Pyatigorsk: RIA-KMV, pp. 276-287.

Elmahdi, A. D., & McFarlane, A. (2009). A decision support system for sustainable groundwater management. Case study: Gnangara sustainability strategy. In proceedings of the 2009 Water Resources Management Conference, WIT Press, pp: 327-339.

Fitts, C. R. (2013). Groundwater science. Oxford: Academic Press, pp: 121-125.

Gavich, I. K. (1988). Hydro-geodynamics. Moscow: NEDRA, pp. 57-62.

Jakeman, A. J., Voinov, A. A., Rizzoli, A. E., & Chen, S. H. (2012). Environmental modeling, software and decision support. State of the Art and New Perspectives. Amsterdam: Elsevier, p. 18.

Kresic, N. (2007). Hydrogeology and Groundwater Modeling, Second Edition. CRC Press, pp: 499-503.

Malkov, A. V., & Pershin, I. M. (2007). Distributed controller synthesis for the hydrolitosphere processes management systems. Moscow: Science world, pp. 235-240.

Martirosyan, A. V., & Martirosyan, K. V. (2013). Modeling of information system "Caucasus Mineral Water's hydromineral resources". In the proceedings of 4th International Scientific and Practical Conference "Science and Society", SCIEURO, pp: 158-165.

Martirosyan, A. V., & Martirosyan, K. V. (2014). Ensuring sustainable model of mineral water deposits operating modes on the example of the deposit Nagutskaya. *Intersectorial scientific and technical journal « Subsurface resources management - XXI century», 6a*, 89-93.

Martirosyan, K. V., Martirosyan, A. V., & Kapylova, T. S. (2013). The model of mineral water deposits sustainable management using the decision support system. *World Applied Sciences Journal, 27*(1). Retrieved October 4, 2014, from http://www.idosi.org/wasj/wasj27(1)13/17.pdf

Meenal, M., & Eldho, T. I. (2012). Simulation–optimization model for groundwater contamination remediation using meshfree point collocation method and particle swarm optimization. Sadhana Academy proceedings in engineering sciences. Retrieved May 5, 2014, from http://www.ias.ac.in/sadhana/Pdf2012Jun/351.pdf

Winter, T. S., Harvey, J. W., Franke, O. L., & Alley, W. M. (1998). Ground Water. Denver: U.S. Goverment printing office, pp: 33-39.

Yanukyan, E. G., Martirosyan, A. V., & Martirosyan, K. V. (2013). Application of the Bayesian network for the development of decision support system "Sanatorium-and-spa resorts". In proceedings of the 3rd International Scientific and Practical Conference "Science and Society", SCIEURO, pp: 58-66.

Yanukyan, E. G., Martirosyan, A. V., & Martirosyan, K. V. (2013). The development of the field's output control model with the Bayesian networks application. *Fundamental research, 11*, 1158-1162.