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Model of urban groundwater level management in drainage systems

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Currently, it is proposed to design horizontal drains for the city of Fergana to reduce the negative impact of the rise in the level of groundwater on the environment, agricultural crops, buildings, and structures, as well as on underground communications. Groundwater depth measurements were carried out in observation wells in the city area and the results were analysed. The depth of groundwater level drop within the horizontal drainage effect is physically and mathematically modelled. For this, long-term data from observation wells were analysed and the hydraulic parameters of horizontal drainage were selected considering the hydrogeology of the area. Taking into account the terrain and characteristics of the soil layers, the possibility of diverting the collected water outside the city through the "Margilan Say" waterwork passing through the city centre has been developed. The differential equation of groundwater movement is solved by numerical calculation and the results are analysed graphically. According to the analysis of the results of numerical calculation, it is proved that it is possible to control the groundwater level with horizontal drainage. The adequacy of the results was assessed by comparing data collected in natural field conditions.

KEY WORDS: horizontal drainage, groundwater, depth of groundwater, coefficient of hydraulic conductivity, mathematical model.

Introduction

The rapid development of construction is exacerbating the engineering geological and environmental problems of groundwater. In many cases, for example, when excavating a foundation pit, soil deformation or cracking of the deep bottom, subsidence in underground construction by dewatering, piping or sand liquefaction, the problem of stability in the rock layer, concrete, iron and steel corrosion of manufactured fittings has always been one of the problems to be solved. Researchers and engineers are paying close attention to engineering geological and hydrogeological problems or construction disasters. There has been new information about groundwater engineering over the last decade (Tang et al., 2017).

Determining the impact of groundwater on the surrounding area is a major problem in groundwater hydrogeology (Mulligan and Ahlfeld, 2016). Urban groundwater collection and assessment are of great importance for irrigated agriculture and urban water supply, and this topic has been modelled by many researchers (e.g. Arnold et al., 1993; Sophocleous et al., 1999; Bredehoeft, 2011; Rossman and Zlotnik, 2013; Maxwell et al., 2014). The development and application of groundwater models is the basis for the application of modern and efficient methods of groundwater management. The study of groundwater flow systems has used mainly sandbox models, analogue models, and mathematical models (Istok, 1989; Arifjanov et al., 2021). Models often allow the physical and geological state of spatially variable aquifers to be determined, which is difficult to calculate and study. However, because this calculation is complex and time-consuming, such calculations are performed based on modern software. Over the years, many researchers have used a physical model of groundwater and a variety of mathematical methods to reduce computational time. Typically, the reduction in model time depends on the accuracy of the model (Gosses et al., 2018; Abdulkhaev et al., 2021). The mathematical model based on the groundwater process consists of an equation describing physical processes in the area, initial and boundary conditions of the flow.

Mathematical models can be solved analytically or numerically and are solved for steady and unsteady groundwater flow conditions (Anderson et al., 2015). Analytical models require a high degree of simplification of the problem that can be solved mathematically. Simple analytical solutions can be solved using a calculator, but more complex solutions are often obtained using a spreadsheet, computer program or special software (Barlow and Moench, 1998). Assumptions based on analytical solutions are justified for relatively simple

systems and therefore do not apply to many practical groundwater issues. Nevertheless, analytical solutions are still useful for some problems and provide important insights into the behaviour of groundwater systems. Analytical models can be useful tools for building more complex digital models, i.e., they are used to verify that the codes that solve the digital models are programmed correctly (Haitjema, 2006). The analytical element method provides analytical solutions to complex problems. The analytical element method is based on Green's functions and relies on computer code to locate certain types of analytical solutions called analytical elements (Strack, 1989; Haitjema, 1995). Currently, analytical element models are most commonly used in the two-dimensional and time-constant state of the groundwater flow problem (Haitjema 2006; Hunt 2006). Analytical element models are also useful for three-dimensional and time-variable modelling. Usually, numerical models based on the finite element or finite element method allow to calculate the movement of groundwater in three-dimensional porous media with complex initial and boundary conditions, stable and unstable flow (Anderson et al., 2015).
The rise of the underground water level in the centre of Fergana city, Beshbola, Yormazor and Joydam regions is causing many problems in residential areas. To solve this problem, deep ditches are being dug, and water is being collected, which causes various problems and inconveniences in the city. Therefore, it is relevant to design horizontal drainage for urban groundwater management and to develop a mathematical model of groundwater level change within the drainage effect.

Materials and methods

The rising groundwater level in the Fergana region (Fig. 1) in recent years has caused many problems. The groundwater level was measured, and the results were analysed from observation wells in the area. For areas above groundwater, the hydraulic parameters of the horizontal drainage were selected using the hydrogeology of the area. The selected hydraulic parameters and measurement results were taken as the initial data for the mathematical model, and the groundwater level in the urban area was calculated based on this model.
Central Fergana region is divided into 5 regions according to water permeability: (i) rapid seepage area (mountainous areas, where underground water is deep); (ii) the area located above the Big Fergana canal (including areas with poor drainage); (iii) the area with poor drainage (the area between the Katta Fargona kanali and the Janubiy Fargona kanali); (iv) central region (the region located below the Katta Fargona kanali); (v) non-flow area (flat area along the Syrdarya river bed).
Hydrogeological studies in the city of Ferghana show that the main factor of the rise of groundwater is mountain rivers (Shoxmardon soy, Isfayram soy), reservoirs (Karkidon reservoir), canals (Janubiy Fargona kanali) and water causes the water of the structures to soak into the ground and accumulate on the waterproof layer. According to engineering research, the area receives the most annual rainfall in the fall, winter, and spring months, as it receives more rain during this period and less during the summer months. The average annual

Fig. 1. The location of Fergana region within Uzbekistan and districts of Fergana city.

rainfall is 181.1 mm, and the daily rainfall is 0.496 mm. From July to September, the weather is dry, with less rainfall. The coefficient of hydraulic conductivity of the area is K=0.000436 m s^{-1}, and in most places, the depth of impermeable layer is 40 m.
Currently, rising groundwater levels in the area have a negative impact on buildings and structures, the environment, crop fields and underground communications. There are open horizontal canals and ditches in the city area, which are rapidly filling up and have a negative impact on the environment. Such structures occupy a large area when considered in general (Akmalov and Gerts, 2016). The best solution to these and similar problems is to collect groundwater through closed horizontal drains and supply it to irrigated areas outside the city. Studies of the hydrogeological condition of the area have proven that the topography is suitable for the discharge of the collected water out of the city through the "Margilan Say" waterworks passing through the city centre (Arifjanov et al., 2019; Arifjanov et al., 2021; Erkinjonovich et al., 2021).
The depth of groundwater table below the surface was measured from observation wells located in the studied area for 6 years (Fig. 2 and 3). According to the measured

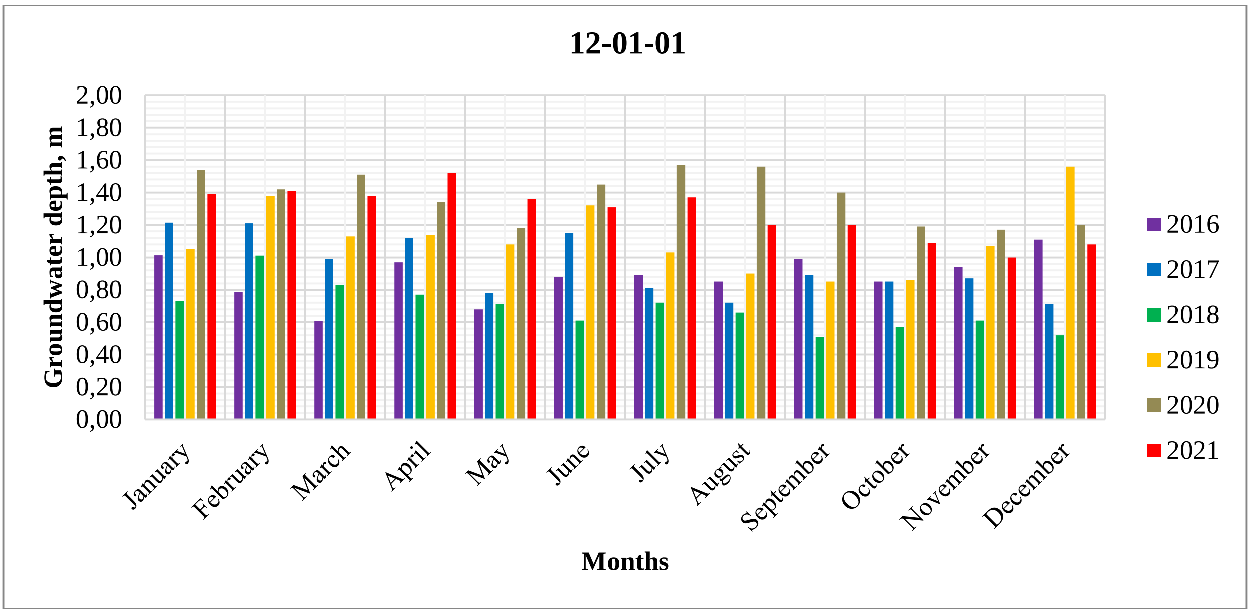

Fig. 2. The depth of groundwater table below the surface in the observation well No. 12-01-01 in the Yormazor area.

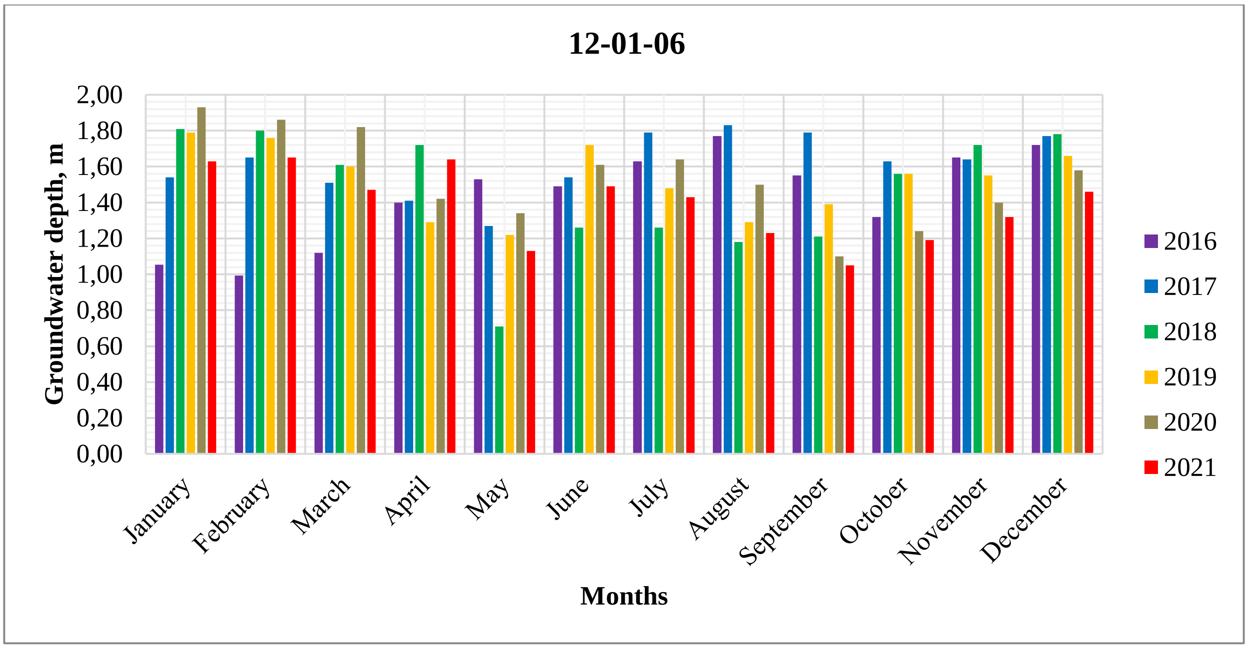

Fig. 3. The depth of groundwater table below the surface in the observation well No. 12-01-06 in the Yormazor area.

data, the depth of groundwater table below the surface in the observation well No. 12.01.01 varies from 0.4 to 1.5 m, and in observation well No. 12.01.06 varies from 0.7 to 1.9 m.
The specific filtration rate for imperfect horizontal drainage (Fig. 4) is:

$$q = \frac{K(H^2 - H_D^2)}{2\cdot(L + \Delta f_{(H_D)})} \quad (1)$$

where
H – the height of the groundwater table above the impermeable layer [m],
H_D – the height from the impermeable layer to the drainage centre [m],
K – coefficient of hydraulic conductivity [m s^{-1}],
L – the length of the affected area of horizontal drainage [m],
Δf_{HD} – additional filtration resistance.

Since the soil of the study area consists of 2 different layers, the coefficient of hydraulic conductivity is found as follows:

$$K = \frac{K_1 h_1 + K_2 h_2}{h_1 + h_2} \quad (2)$$

The additional filtration resistance is found as follows (Averyanov, 2015):

$$\Delta f_{H_D} = 0.73 \cdot H_D \cdot \frac{2\cdot H_D}{\pi H_D \cdot d} \quad (3)$$

where
d – drainage diameter [m].

The ordinate Z from the impermeable layer to the depression line at a distance x from the centre of the drain is found as follows:

$$Z = \sqrt{(H_D^2 + (H^2 - H_D^2)\cdot \frac{x}{L}} \quad (4)$$

The time taken for groundwater to recede in the area affected by drainage is as follows (Averyanov, 2015):

$$t = \sqrt{\frac{L^2}{3\cdot\frac{K}{S_S}\cdot h_a}} \quad (5)$$

where
S_s – soil water removal coefficient [m^{-1}],
h_a – the average capacity of the area where groundwater levels are declining [m].

The following formula is used to determine the average capacity of an area where groundwater levels are declining:

$$h_a = \frac{S}{2} \quad (6)$$

where
S – the height from the centre of the drain to the groundwater table [m].

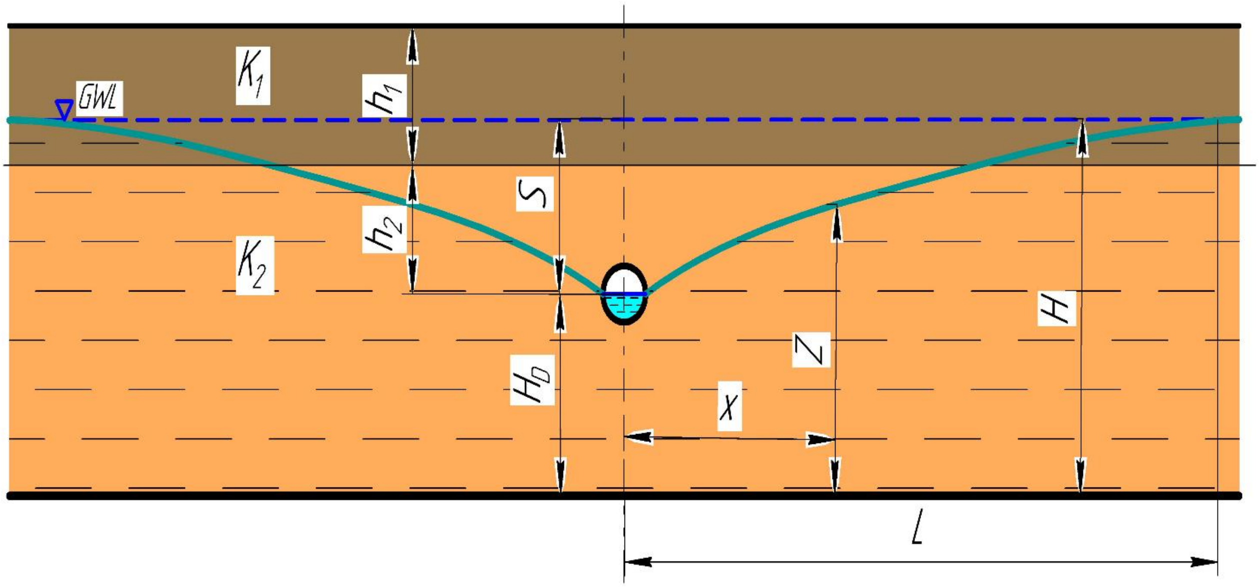

Fig. 4. Scheme of hydrodynamically imperfect horizontal drainage; GWL – groundwater level, x – length from the centre of the drainage, h_1 – thickness of the first layer, h_2 – distance between the top of the second layer and drainage centre, S – distance between GWL and drainage centre, HD – distance from impermeable layer to drainage, H – thickness of the aquifer, K_1 and K_2 – coefficient of hydraulic conductivity of the first and second layer, respectively, L – the length of the affected area of horizontal drainage, Z – the difference between impermeable layer and depression line at a distance x.

Using the above formulas, the water consumption received by the horizontal drainage of length L was calculated.

Mathematical model

The relationship and mass conservation law expressed in Darcy's law represent the process of groundwater flow. The Laplace equation is used to express the flow of groundwater by the method of finite separations. The two-dimensional Laplace equation appears as follows:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{Q}{T \cdot \Delta\omega} = 0 \qquad (7)$$

where

T – transmissivity coefficient, which depends on the coefficient of hydraulic conductivity and the thickness of the layer, $T = K_h \cdot b$, [m^2 s^{-1}].

K_h – the coefficient of hydraulic conductivity in the horizontal direction, [m s^{-1}],

b – the thickness of the layer, [m],

$\Delta\omega$ –elementary surface, [m^2],

Q – water consumption, [m^3 s^{-1}].

The general water balance equation was expressed by S. F. Averyanov as follows:

$$Q = Q_{com} + Q_{e.g} + Q_{at} - Q_{dr} - (Q_{eva} + Q_{pla}) - Q_{exit} \qquad (8)$$

where

Q_{com} – the amount of water coming into the area, [m^3 s^{-1}],

$Q_{e.g}$ – amount of surface water, [m^3 s^{-1}],

Q_{at} – waters formed from atmospheric precipitation, [m^3 s^{-1}],

Q_{dr} – the amount of water collected from the area through drains, [m^3 s^{-1}],

Q_{eva} – the amount of evaporation from the soil surface, [m^3 s^{-1}],

Q_{pla} – the absorption of water from the ground by plants, [m^3 s^{-1}],

Q_{exit} – the amount of groundwater that has flowed out of the area, [m^3 s^{-1}].

After determining the boundaries of the study area, the selected area is divided into segments. Each node in the segment has 4 adjacent points, and the secondary product on the *x*- and *y*-axes can be written as (Fig. 5 and 6) (Istok, 1989):

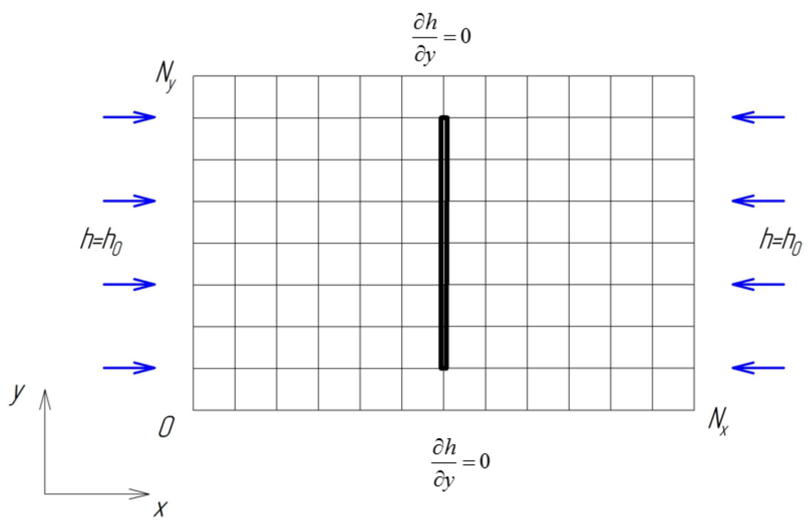

Fig. 5. Dividing the area of interest into a net.

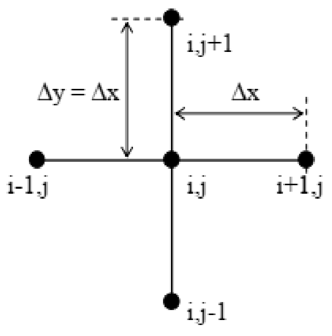

Fig. 6. Internal nodes of the finite element mesh.

$$\frac{\partial^2 h}{\partial x^2} = \frac{h_{i-1,j} - 2h_{i,j} + h_{i+1,j}}{(\Delta x)^2} \tag{9}$$

$$\frac{\partial^2 h}{\partial y^2} = \frac{h_{i,j-1} - 2h_{i,j} + h_{i,j+1}}{(\Delta y)^2} \tag{10}$$

By substituting Equations (9) and (10) to Equation (7), we obtain a limited difference equation:

$$\frac{h_{i-1,j} - 2h_{i,j} + h_{i+1,j}}{(\Delta x)^2} + \frac{h_{i,j-1} - 2h_{i,j} + h_{i,j+1}}{(\Delta y)^2} \pm \frac{Q_{i,j}}{T(\Delta x)^2} = 0 \tag{11}$$

$$h_{i-1,j} + h_{i,j-1} - 4h_{i,j} + h_{i+1,j} + h_{i,j+1} \pm \frac{Q_{i,j}}{T(\Delta x)^2} = 0 \tag{12}$$

We find $h_{i,j}$ from Equation (12) as follows:

$$h_{i,j} = \frac{h_{i-1,j} + h_{i,j-1} + h_{i+1,j} + h_{i,j+1}}{4} \pm \frac{Q_{i,j}}{4T(\Delta x)^2} \tag{13}$$

If the calculation is repeated many times, the number of iterations is expressed in terms of m:

$$h_{i,j}^{m+1} = \frac{h_{i-1,j}^{m} + h_{i,j-1}^{m} + h_{i+1,j}^{m} + h_{i,j+1}^{m}}{4} \pm \frac{Q_{i,j}}{4T(\Delta x)^2} \tag{14}$$

The above equation is valid for the internal nodes of the bounded region. If we assume that $h_{i,j-1} = h_{i,j+1}$ for the boundary on the x -axis, we make the following changes to Equations (13) and (14) for the boundary nodes on the x -axis:

$$h_{i,j} = \frac{h_{i-1,j} + h_{i+1,j} + 2h_{i,j+1}}{4} \pm \frac{Q_{i,j}}{4T(\Delta x)^2} \tag{15}$$

or

$$h_{i,j}^{m+1} = \frac{h_{i-1,j}^{m} + h_{i+1,j}^{m} + 2h_{i,j+1}^{m}}{4} \pm \frac{Q_{i,j}}{4T(\Delta x)^2} \tag{16}$$

For all boundary nodes, changes are made as in Equations 15 and 16. The following initial and boundary conditions are used to solve the problem numerically:

$$h(0;y) = h_0, \qquad h(x;0) = \frac{\partial h}{\partial y} = 0, \qquad h(x;N_y) = \frac{\partial h}{\partial y} = 0,$$

$$h(N_x;y) = h_0, \qquad \left.\frac{\partial h}{\partial y}\right|_{(x,0)} = h_{i,0} = h_{i,1}, \qquad \left.\frac{\partial h}{\partial y}\right|_{(x,N_y)} = h_{i,Ny} = h_{i,Ny-1}$$

where

h_0 – initial depth of groundwater, [m],

N_x, N_y – the number of nodes on the x and y axis, respectively.

In the calculation, the groundwater level in all parts of the region was assumed to be 2 m, and the infiltration coefficient was 0.496 m d^{-1}. Based on the above conditions, the differential equation (16) is solved numerically.

Results and discussion

Groundwater levels have risen in the Beshbola, Joydam and Yormazor districts of Fergana (Fig. 1). The use of horizontal drains to reduce groundwater is one of the most effective methods. Based on the above initial and boundary conditions, a mathematical model of the groundwater table under the influence of drainage was developed. The results of the numerical calculation are presented in the form of a graph in Fig. 7. The colours in the graph show the change in the groundwater level within the drainage area.

In fact, it can be seen that the groundwater level has risen significantly during the months of heavy rainfall. The depth of groundwater table below the surface fluctuated from 0.4 to 1.5 m in observation well

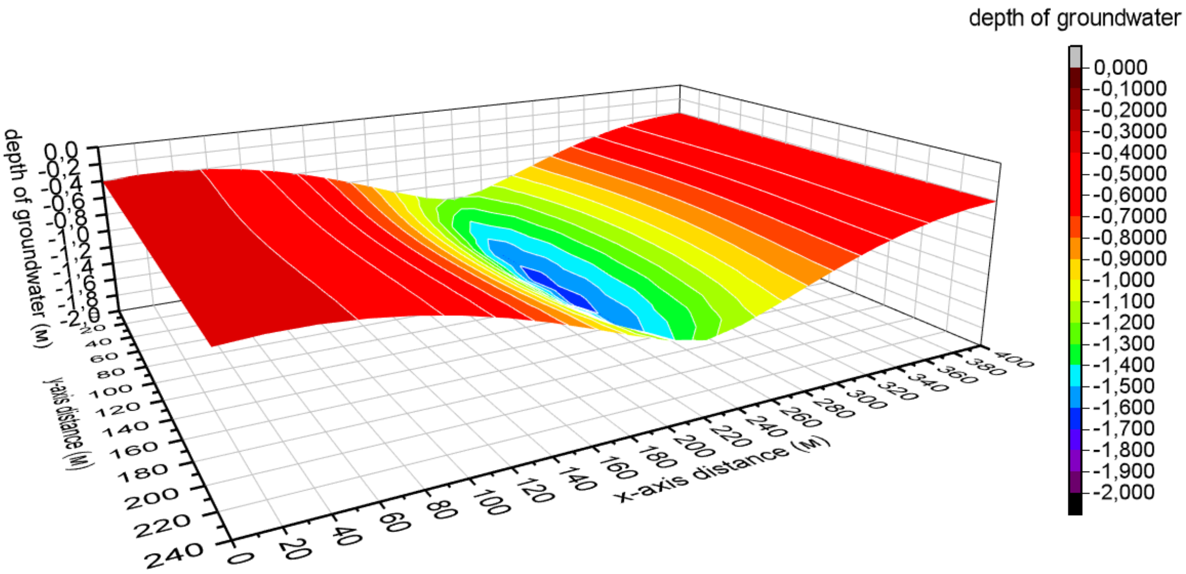

Fig. 7. Changes in the depth of groundwater in the area of drainage influence.

No. 12.01.01, and from 0.7 to 1.9 m in observation well No. 12.01.06 (Fig. 2 and 3).

In the initial case, the level of underground water is 0.4 m, and this value was obtained based on the results of measurements in observation wells. The area of the modelled area is 400x300 m, and the change of groundwater at every 10 cm depth is highlighted in different colours.

Based on the Fig. 7, it is possible to construct a depression curve and predict the depth of the groundwater level at a distance x from the drain.

Conclusion

In recent years, the rise in the level of underground water in residential areas and urban areas has caused many problems. In the central parts of the city of Fergana, in the regions of Yormazor, Beshbola and Joydam, the level of groundwater table below the surface is 1–1.5 meters. To solve this problem, deep pits are dug and water is collected. The ditches built in different parts of the city are causing various problems and inconveniences. It is planned to manage urban groundwater table through horizontal drainage, improve the environmental condition of the city, and reduce the negative impact of underground water on buildings and engineering communications in the city. Collected water is supplied to agricultural fields outside the city through the Margilan stream.

The use of horizontal drains is one of the most effective ways to reduce groundwater. The hydrogeology of the area, field research experiments, initial and boundary conditions, mainly the change of the groundwater level within the framework of the drainage effect, are physically and mathematically modelled. Numerical results of physical and mathematical calculations are presented in graphic form for the convenience of scientists. Each change in groundwater level is highlighted in the graph with colours and lines. According to the results of the analysis, it has been proven that it is possible to control the level of groundwater through horizontal drains in the places where the groundwater has risen.

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References

Abdulkhaev, Z. E., Madraximov, M. M., Axmadjon O’g’li, M. S. (2021): Reducing the Level of Groundwater. In The City of Fergana. International Journal of Advanced Research in Science, Communication and Technology 2(2): 67–72.

Akmalov, Sh. B., Gerts, J. V. (2016): Using Remote Sensing Very High Resolution Data in Observation of Open Drainage System Conditions in Syrdarya Province. Irrigatsiya va Melioratsiya (2): 26–29.

Anderson, M. P., Woessner, W. W., Hunt, R. J. (2015): Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic press.

Arifjanov, A., Samiev, L., Yusupov, S., Khusanova, D., Abdulkhaev, Z., Tadjiboyev, S. (2021): Groundwater Level Analyse in Urgench City with Using Modflow Modeling and Forecasting System. In E3S Web of Conferences, EDP Sciences, 3010.

Arifjanov, A., Otaxonov, M., Abdulkhaev, Z. (2021): Model of Groundwater Level Control Using Horizontal Drainage. Irrigation and Melioration 2021(4): 21–26.

Arifjanov, A., Otaxonov, M., Samiev, L., Akmalov, S. (2019): Hydraulic Calculation of Horizontal Open Drainages. In E3S Web of Conferences, EDP Sciences, 5039.

Arnold, J. G., Allen, P. M., Bernhardt, G. (1993): A Comprehensive Surface-Groundwater Flow Model. Journal of hydrology 142(1–4): 47–69.

Averyanov, S. F. (2015): Management of the water regime of reclaimed agricultural lands / Monograph / – Moscow: Russian State Agrarian University – Moscow Agricultural Academy named after K. A. Timiryazev. 542 p.

Barlow, P. M., Moench, A. M. (1998): 98 Analytical Solutions and Computer Programs for Hydraulic Interaction of Stream-Aquifer Systems. US Department of the Interior, US Geological Survey.

Bredehoeft, J. (2011): Hydrologic Trade-offs in Conjunctive Use Management. Groundwater 49(4): 468–75.

Erkinjonovich, A. Z., Mamadaliyevich, M. M., O’G’Li, S. M. A., Egamberdiyevich, T. N. (2021): Farg’ona Shahar Yer Osti Sizot Suvlarining Ko’tarilish Muammosi Va Yechimlari. Oriental renaissance: Innovative, educational, natural and social sciences, 1(3), 138–144.

Gosses, M., Nowak, W., Wöhling, T. (2018): Explicit Treatment for Dirichlet, Neumann and Cauchy Boundary Conditions in POD-Based Reduction of Groundwater Models. Advances in water resources 115: 160–71.

Haitjema, H. (2006): The Role of Hand Calculations in Ground Water Flow Modeling. Groundwater 44(6): 786–91.

Haitjema, H. M. (1995): Analytic Element Modeling of Groundwater Flow. Bloomington: Academic Press.

Hunt, R. J. (2006): Ground Water Modeling Applications Using the Analytic Element Method. Groundwater 44(1): 5–15.

Istok, J. (1989): Groundwater Modeling by the Finite Element Method. Washington, DC (USA) American Geophysical Union.

Maxwell, R. M., Putti, M., Meyerhoff, S., Delfs, J-O., Ferguson, I. M., Ivanov, V., Kim, J., Kolbitz, O., Kollet, S. J., Kumar, M., Lopez, S., Niu, J., Paniconi, C., Park. Y-J., Phanikumar, M. S., Shen, C., Sudicky, E. A., Sulis, M. (2014): Surface-subsurface Model Intercomparison: A First Set of Benchmark Results to Diagnose Integrated Hydrology and Feedbacks. Water resources research 50(2): 1531–1549. https://doi.org/10.1002/2013 WR013725

Mulligan, K. B., Ahlfeld, D. P. (2016): Model Reduction for Combined Surface Water/Groundwater Management Formulations. Environmental Modelling & Software 81: 102–10.

Rossman, N. R., Zlotnik, V. A. (2013): Regional Groundwater Flow Modeling in Heavily Irrigated Basins of Selected States in the Western United States. Hydrogeology Journal 21(6): 1173–1192.

Sophocleous, M. A., Koelliker, J. K., Govindaraju, R. S., Birdie, T., Ramireddygari, S. R., Perkins, S. P. (1999): Integrated Numerical Modeling for Basin-Wide Water Management: The Case of the Rattlesnake Creek Basin in South-Central Kansas. Journal of Hydrology 214(1–4): 179–196. https://doi.org/10.1016/S0022-1694(98)00289-3

Strack, O. D. L. (1989): Groundwater Mechanics. Prentice Hall.

Tang, Y., Zhou, J., Yang, P., Yan, J., Zhou, N. (2017): Groundwater Engineering. 2nd ed. Shanghai: Springer. 423 p.

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