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APPLICATION OF HYDRODYNAMICAL MODELS IN REDUCING THE INDETERMINACY OF THE INPUT PARAMETERS FOR UNDERGROUND STREAMS SIMULATION

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Abstract. *The key issue which arises during the preparation of the input data at modeling of all the hydraulic systems is the one of the sufficient and optimal number of input data. Here, the answer to the question has been found by using the existing research in this field, with the application of GROW software package which simulates the two-dimensional streaming of ground water in the aquifer strata. Thus, the subject of this paper is:*

ℕ Analysis of the required number of measuring points in order to reduce the indeterminacy down to the level where the further increase of the number of measuring points would not result in the higher quality.

ℕ Analysis of the input data indeterminacy propagation through the simulation models.

The sample used for the analyses is a part of the water resource system in the aquifer of Semberija, Bosnia and Herzegovina, in the surrounding area of the town of Bijeljina. Apart from the separate analysis of aquifer as a source of groundwater, the paper specially addresses the analysis of the dominant influence of individual indeterminacies and potential for their reduction

Initially, the existing data were used, and then the additional existing and input data were collected, and afterwards the results were compared. Since each new quality piece of input data contribute to the reduction of the model and system indeterminacy, for the purpose of this study, the additional observations and field research were organized. On the basis of the additional measuring and observation, groundwater flow analysis model was calibrated.

Key words: *indeterminacy of input data, ground water flow, numerical model, software package, groundwater, urban water.*

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1. MODEL DESCRIPTION AND PREVIOUS INPUT PARAMETERS

A water-bearing layer, with the roof layer of lower permeability, [literature 8 and 9], for which the basic equation for the constant planar flow of groundwater is given in figure 1. The figure displays the hypothetical regime of groundwater which can be simulated by the modern software.

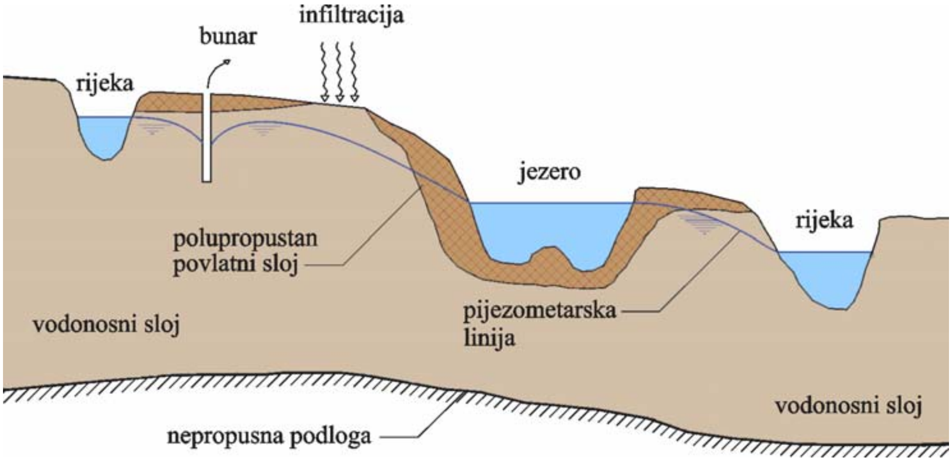

Fig. 1. Physical model of groundwater flow in the aquifer

The fundamental equation of the constant planar flow of groundwater in the aquifer is:

$$L(H) = \frac{\partial}{\partial x}\left(K_x M \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_y M \frac{\partial H}{\partial y} \right) + q_v = 0$$

According to the Dipi* hypothesis, which refers to the groundwater flow, the vertical component of the velocity is neglected, since the piezometric height along the vertical Z axis is constant in every point.

In the previous equation, the members have the following meaning:

q_v – water inflow in the vertical direction per surface area unit (atmospheric water or filtration)
K_x – filtration coefficient in the direction of x axis
K_y – filtration coefficient in the direction of y axis
M – Height (thickness) of an aquifer
H – piezometric height of groundwater

In order to solve the equation of constant planar flow of groundwater it is necessary to know the input data q_v, K_x, K_y, M and H. Determination of these data is performed by the standard hydrologic, hydrogeologic and geologic research and measuring. The spatial and temporal distribution of these data is very important. In order to have a high degree of reliability in determining these data, a certain time period and finances are required, but they are insignificant in comparison to the profit obtained during the system exploitation. Preparation of the input data with a lower degree of indeterminacy has its price. For the purposes of this paper, the observation (measurements) of the groundwater level within a year was performed, so that the filtration coefficient could be gauged and in this way increase the determinacy of this very important piece of input data.

The fundamental parameter that characterizes the filtration properties of the aquifer is the filtration coefficient, that is, the transmission coefficient. The research up to date, in the area of Semberija, is relatively substantial, and a series of test derivation from the wells, granulometric analyses, geophysical research, on whose basis only the local values of the filtration coefficient can be determined. On the basis of these works, it may be concluded that the alluvial layer in the lower course of the Drina river is a powerful collector of groundwater, and that the filtration coefficient in this layer ranges between 10^{-4} m/s to 10^{-2} m/s.

For mapping the streamline of the underground course in the aquifer of Semberija, the GROW hydrodynamic model which successfully simulates the groundwater courses streaming has been used. This model has been developed at the Faculty of Civil Engineering of Belgrade, literature [8 and 9]. As the problem of urban waters in the area of Semberija is very complex, and especially the interaction of groundwater with surface water, here the influence of the input parameters for the mentioned model of groundwater streaming will be analyzed.

The previous gauging of the model was done, according to the literature [5], in 1995. For the previous model, the data of piezometric observation from 1985 were used. In the area of Semberija, a total of 38 piezometers and dug wells were installed, where the groundwater table was monitored. In the zone close to the Grmis spring (to a distance of 5 km from it) there were 30 observation posts, and the remaining 8 were dispersed in the wider area of groundwater streaming. Monitoring of the groundwater table was performed in the period from the mid of July 1985 till the end of July of 1986. On the basis of the obtained monitoring data, the isolines maps of the groundwater table in the minimum level season were made, and, as well, the diagrams of groundwater oscillations. Analyzing the observation diagrams of the aquifer water level, it may be concluded that the amplitudes of the aquifer surface oscillations are very small and they amount to 1-2 m. The least depth to the level of groundwater is 2,10 m and the greatest is 6,25 m . In the area of the Grmis spring, the depths to the groundwater level are 5,0 to 5,5 m. Unfortunately, the quantities of water pumped out at the Grmis spring were not measured simultaneously with the observation of the groundwater table, so in gauging it was the catalogue value of the pump exploitation yield value that was adopted, and for the wells of the Obarska sugar refinery, the assumed capacity is 2 x 50 l/s. This piece of input data is very unreliable and its actual value can have a significant departure from this value.

The representative values of the filtration coefficient can be obtained only by gauging the hydrodynamic model. For model gauging, the usual status of groundwater level in the first half of November 1985 was chosen, along with the correspondent low water of the rivers Sava and Drina, acting as the contour conditions to the north and the east. The southeast border of the model is the change of the plain into the foothill of Majevica Mountain. At this time, the Sremska Raca water flow measurement station on the Sava River, was not in operation. So the levels measured in Sremska Mitrovica and Zupanja were used, and on the basis of the decrease of the water table i=0,003%, the level of the Sava in the area of Semberija was determined. In the lower course of the Drina river, on the basis of the measured data, the decrease of the water table was determined and it was

0.066%. The precision in the determination of the water table decrease is fairly unreliable, but in this case, regarding that the decreases are relatively small, it does not significantly affect the calculation results.

During the gauging the filtration coefficients ranging from 10^{-4} m/s to 10^{-2} m/s were assumed and varied until the piezometric levels matched with the measured ones. The precision evaluation was done through the statistic methods, absolute mean departure, absolute maximum departure, standard departure and the visual review of the data. The absolute mean departure of the calculated level from the measured one is 0.21 m and the maximum departure is 0.69 m. The height difference between the maximum and minimum observed level is 16.75m, so regarding the ratio, they can be considered satisfactory.

Thus, the previous gauging of the model was done in the simulation N85V1 for the exploitation quantities of 280 l/s at the Grmis spring in 1995. The verification of the gauging was done in the simulation N94V2 for the exploitation quantities of 230 l/s, where the situation in November 1994 was simulated. For this period a very small number of data were available, but the departure of the measured and the calculated groundwater table with the gauged filtration coefficients was acceptable. The maximum departure of the calculated water levels from the measured ones was 0.49 m and the average absolute departure was 0.35 m. It was noticed that the previous simulations of groundwater in the zone of the spring Grmis which were done in the beginning of the 1995, were done on the basis of the sparse input parameters, so it was attempted to enrich these parameters. Out of the existing geotechnical boreholes (a total of 32 boreholes) the ground level and roof level (upper limit of water permeable layer) were defined while the underlying stratum level (floor) was defined only by two boreholes. Therefore it was decided to use the existing hydrogeologic map to define the level of the floor, which is rather unreliable and falls into the category of improvised and estimated data. In this way, additional 28 floor levels were obtained, which are highly unreliable.

On the basis of the data on the existing boreholes, data on the existing piezometers and the data on the existing wells, the upper aquifer levels were determined. 78 levels were positively ascertained, and around 60 other were improvised, that is, estimated. The data for the levels determined in this way can lead to the errors in results and reasoning, so the consequence is the expensive and unreliable structures.

The input data on the characteristic water level of the rivers Drina and Save were also inadequate, and only one water level situation both for the rivers Drina and the Sava were taken into account.

2. COMPLETION OF THE MODEL WITH NEW INPUT DATA

In order to increase the reliability of the input data and the models, in this paper were used the new data which were assembled from the different, but fairly reliable sources, and the data of the observation of the groundwater table in a one-year period.

The first step in the preparation and systematizing of the input data for the hydrodynamic model, is the exclusion of all the unreliable input data. Since the determination of the thickness of the water bearing bed requires the level of the floor and the roof, around 30 levels of the floor and 60 levels of the roof (top of the aquifer stratum), determined through the extrapolation of the geological maps were excluded. Instead of that, in the meantime, the new data were collected (around 20 levels of the floor and as many of the roof) which are very reliable because they were in the most part obtained by the real boreholes. In the table 1, there is a review of the old and new data and the input data improvement percentage.

Table no. 1.

Data title	NUMBER OF DATA		Increase of the number of data (%)
	Old - unreliable (pcs)	New - reliable (pcs)	
Floor levels	2	22	1100,0
Aquifer top levels(roof)	78	100	128,2
Terrain level	4	52	1300,0
Water level of the Drina	1	6	600,0
Water level of the Sava	1	3	300,0
Water level of the Dasnica canal	0	2	-

Since the model was produced and gauged, for a long period of time no observation of the existing piezometers were performed, nor was the filtration coefficient determined, at least in the zone of the groundwater spring. Therefore, for these purposes, 12 new piezometers, around 12 m long were installed. The observation of the new and the existing piezometers in the wider area of the spring began in November 1997 with the observation of the levels (figure 2) whose aim was the new gauging of the model and determination of the more reliable filtration coefficient. The repeated gauging of the hydrodynamic model employed the observation data performed within one hydrologic year, so that the model could be used with an increased degree of reliability.

The new data on the water levels [3], were collected for the rivers Sava and Drina which are simultaneously the borders of the analyzed area to the north and the east, and for the Dasnica canal which is a main recipient of the Bijeljina sewage system.

Apart from this, it is necessary to organize the tracing tests in order to define the actual velocities and flow directions of the groundwater streams, and produce the data basis with the existing and the new input data and simulations.

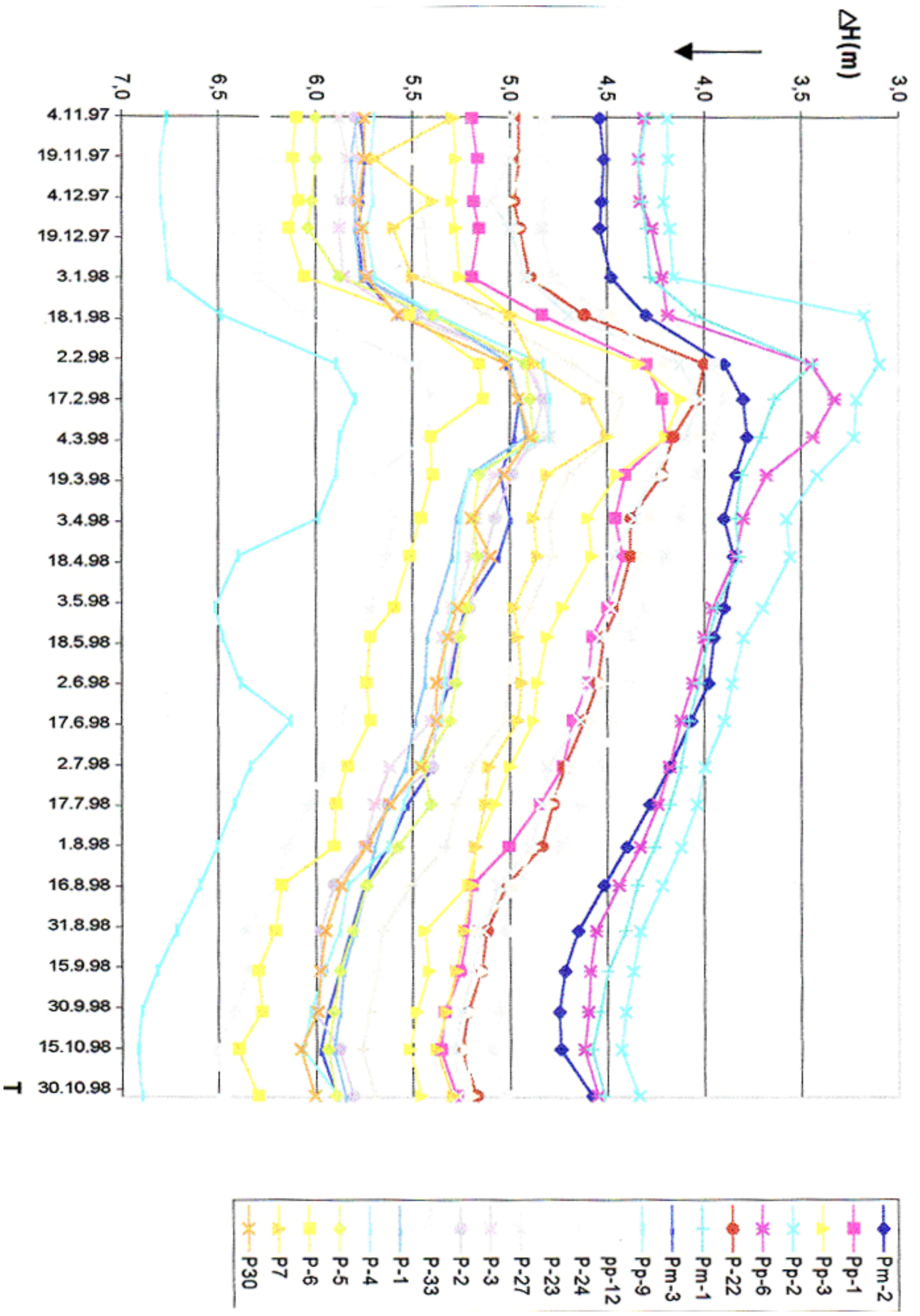

Fig. 2. Diagram of the groundwater table observation

3. GROUNDWATER STREAM SIMULATION

The existing software package was applied again for the simulations of the groundwater streams of Semberija (Pokrajac, 1997; Djuric, 1999), and the graphical representation of a simulation for the exploitation quantities of 330 l/s at the Grmis spring (DIS3 simulation), was given in the figure 3. In the beginning, the model with the insufficient number of input data was used, without the appropriate observations (measurement) of the groundwater table. When the additional input data were collected, that is when the model was enriched, a significant discrepancy in the output results was perceived. Then the appropriate measuring of the groundwater table was performed at the existing and the newly organized piezometers (two times a month within one year) for the purpose of gauging (calibration) of the model. In some points which are of a particular interest in the wider spring area, the old model with the sparse input data and the new model with the enriched input data in the wider area of the spring (figure 4) were used and the histogram with the results was produced, for the four characteristic simulations, and the levels according to which the new model was calibrated were measured.

- simulation S94V3 – the old model with the sparse input data,
- simulation DIS3 – the old model with the enriched input data,
- simulation DISK5 – new (calibrated) model with the enriched input data,
- simulation DISK3 – new calibrated model with the enriched input data for the same contour conditions as for the simulations S94V3 and DIS3, that is for the case when the quantity pumped from the well was Q=330 l/s,
- measured level at the old and the new piezometers..

From the histogram, it is obvious that the difference of the level in some points of the aquifer reach a significant value for the same contour conditions. The new model which was gauged on the basis of multiple piezometers within a year, certainly has the highest precision and reliability.

The results of the S94V3 simulation with the existing input data (groundwater table expressed in the absolute levels meters above sea level) were presented in the figure 5, and the results of the DIS3 simulation with the new input data in the figure 6, were obtained using the geographical information system GIS. In the figure 7. the results of the simulation with the new calibrated model were presented.

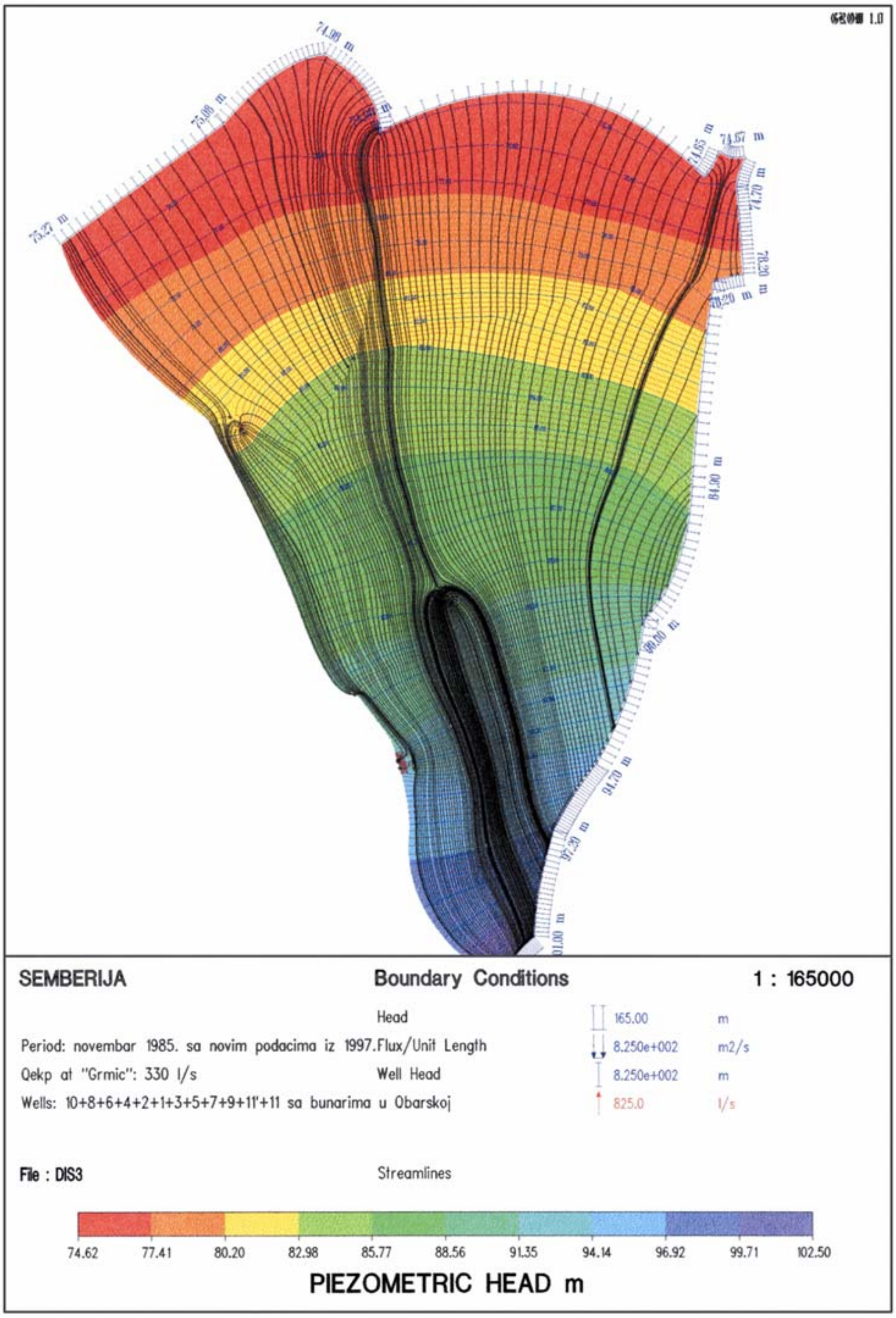

Fig. 3. Graphical representation of one simulation of the groundwater streams in Semberija aquifer

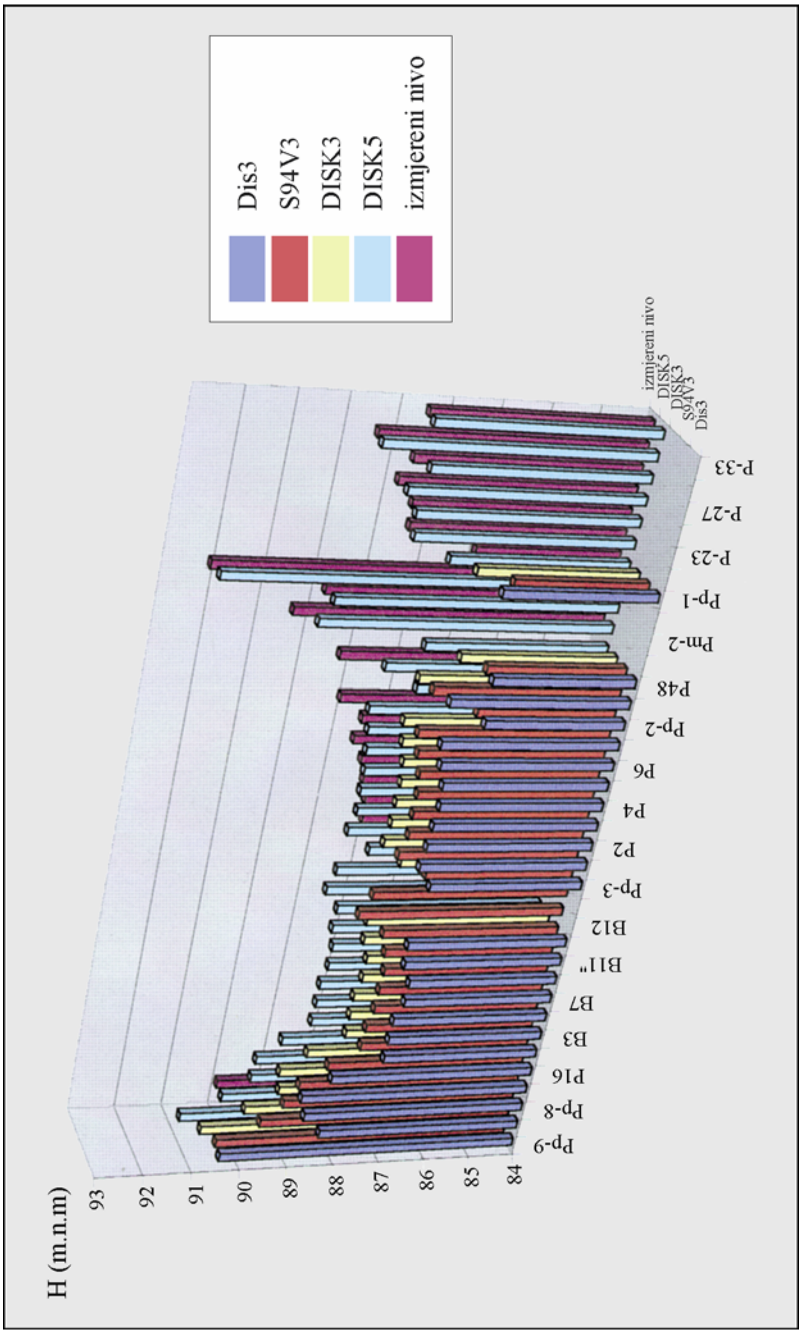

Fig. 4. Histogram of groundwater table for the simulations with new and old models and measured levels

By comparing the simulations results, one may observe the difference and conclude that the results obtained by the new (calibrated) model have the highest determinacy, that is, that the results obtained with the smaller number of input data and the non-calibrated model must be used with reserve.

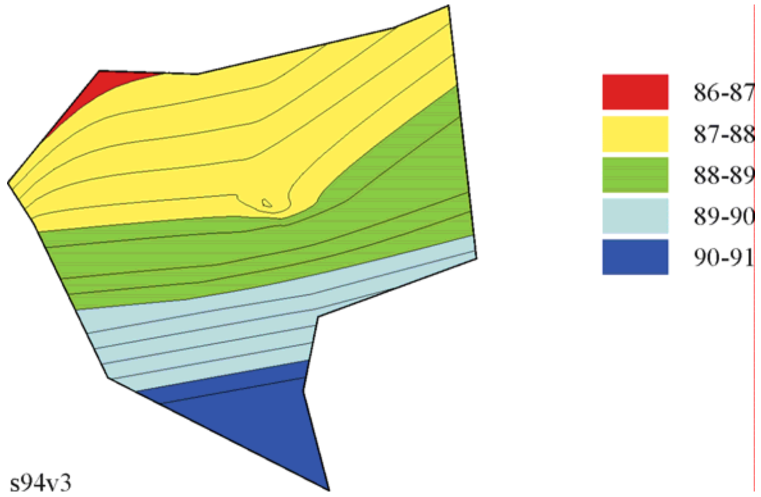

Fig. 5. Groundwater level determine on the basis of the existing input data (simulation S94V3)

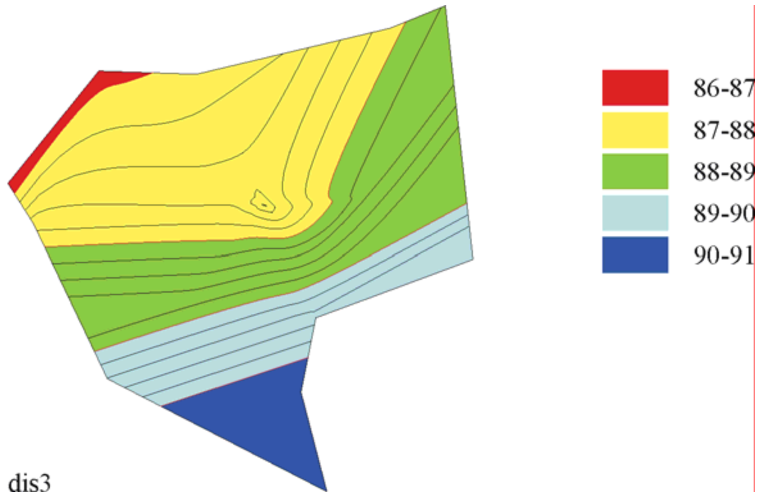

Fig. 6. Groundwater level determined on the basis of the new input data (simulation DIS 3)

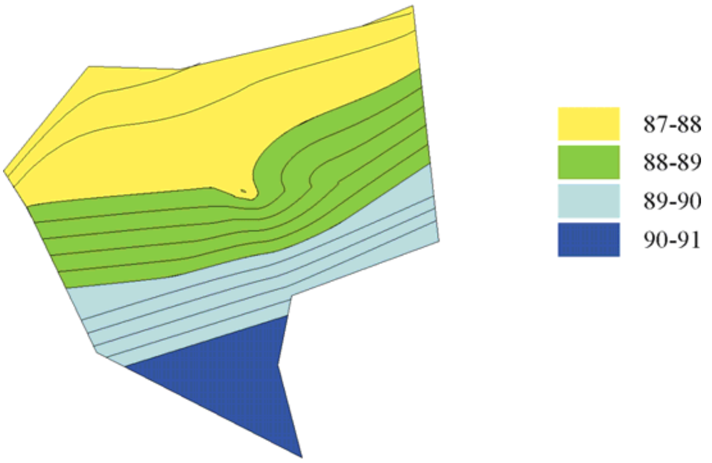

Fig. 7. Groundwater level determined with the new (calibrated) model for the contour conditions from the simulations S94V3andi DIS3 (simulation DISK3)

The difference in the levels of the groundwater table obtained with the new calibrated model in which the additional input data have been included, and also with the old model (difference of the simulations DISK5 and DIS3 results) is presented in the figure 8 using GIS – geographical information system.

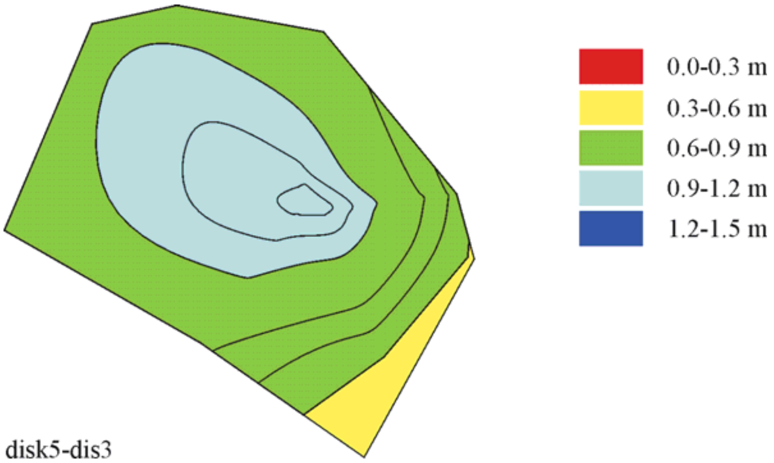

Fig. 8. Difference of the groundwater table obtained with the new and the old model

4. REDUCTION OF THE INDETERMINACY OF THE HYDRODYNAMIC MODEL DEPENDING ON THE NUMBER OF INPUT DATA

When it comes to the research and formation of the new groundwater springs, or to the extension of the existing ones, it may very often be concluded in advance that the benefit of such problems is enormous, having in mind the significance and demand of potable water. Therefore, the motive and price of the research and preparatory works should not be an issue. It is though, justifiable, to pose a question of the sufficient number of input parameters for the hydrodynamic model, which will be analyzed using the GROW model. In practice, often in preparing the input data a certain number of research works is anticipated, for instance number of drillholes which will be used to define the thickness of an aquifer, which plays a significant role in the basic equation of the groundwater streaming. The anticipated number of research works is slightly higher than the required one, and thus the cost of the preparation is higher. In this way the designers wish to ensure safety, giving the reliability the priority, and not observing the cost or time. In order to avoid such approach in practice, here, with the aid of the GROW software package, the sufficient number of prospecting drillholes will be analyzed. These simulations can be performed simultaneously with the prospecting works. For the purpose of this paper, the existing input data were primarily used, so each existing piece of data (for example data on the drillholes), is treated as if the works were performed in situ, that is, as if the new prospecting works – drilling, were carried out. The existing, but old data, are as valid as the new data obtained by drilling. If such old data are discovered, there is no need for a new drilling operation, so the saving is considerable.

In the initial phase of forming any hydrodynamic model, the degree of indeterminacy of the input parameters, and so of the model indeterminacy, is the highest, that is, the model indeterminacy is the highest. The goal of any model is to keep the indeterminacy at the lowest level possible, that is, that it tends to zero, which is, in the majority of cases, impossible. In order to reduce the degree of indeterminacy, it is necessary to collect and study the existing prospecting works and design documentation, and then to organize additional prospecting works, gauging, verification of the model.

The fundamental input data for the hydrodynamic groundwater streaming model in the intergranular porous environment are:

- hydrological data
- geological and hydrogeological data
- topographic data.

The indeterminacy of each stated input data as well as the indeterminacy of the model can be expressed in percentage. Further on, the stated data can be broken down into several elements (for example, geological and hydrogeological data) with the special indeterminacy of these elements, that is indeterminacy of the stratigraphic data (slope and roof levels which define the thickness of the aquifer), and the indeterminacy of the filtration characteristics which are defined by the filtration coefficient. The detailed analysis of the indeterminacy of all the input data is a very complex process, so here only one element of the geological and hydrogeological data will be analyzed – *thickness of the aquifer*.

So, the question could be formulated in the following way: “How many drillholes in an aquifer of the known surface should be made, in order to find out the thickness of the aquifer, which is one of the basic elements in the groundwater streaming equation, provided that the output results (groundwater table levels) are within the required range”?

The solution of this problem depends on the topographic, geological, hydrogeologic and other conditions, and varies from case to case. In the example of the Semberija aquifer, it was a two-direction consideration.

a) That the first simulation is performed with the prospecting works in the close proximity of the spring (figure 9), and that every following simulations is done with the drillholes radially arranged in the space, progressively increasing the radius until the whole area has been covered..
b) That the first simulation is performed with the lowest thickness of the aquifer present in the entire are, and each following simulation with greater thickness and with the successive increase of the number of input data. In this simulation the total surface area of the aquifer is included (figure 10). Each following simulation includes the data from the previous simulation.

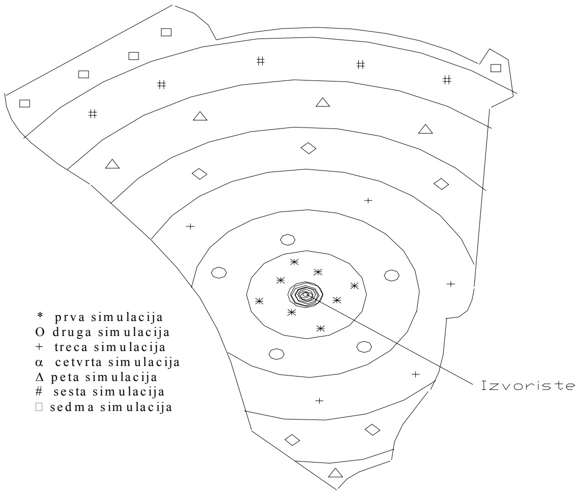

Fig. 9. Radial arrangement of prospecting works

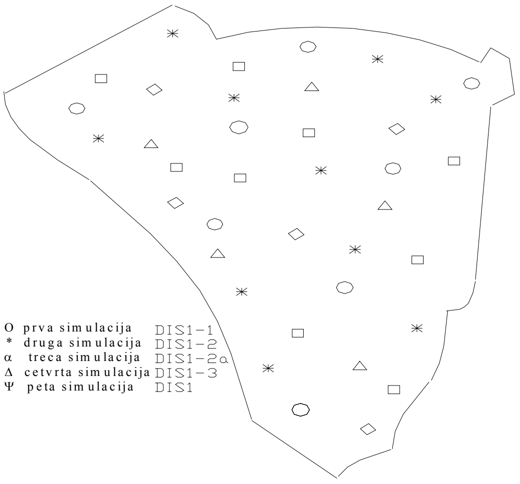

Fig. 10. Arrangement of the prospecting works and simulations depending on the thickness of the aquifer

Both approaches are correct, but the second one has a certain advantage as it takes into consideration the influence of the change of the aquifer thickness on the output results. For the Semberija aquifer in the first simulation DIS1-1 (table 2.), a certain number of input data with the least thickness of the aquifer was chosen, and in the every succeeding simulation, the input data with the greater thickness of the aquifer are added. This procedure is generally recommended for the analysis of other water bearing strata.

Seven simulations of groundwater streaming were done, with the different number of data defining the thickness of the aquifer. The indeterminacy of the thickness of the aquifer was defined according to the literature. The number of the input data was increased until any indeterminacy became equal to zero, which represents a very rigorous criterion. Each high indeterminacy (where low precision is required) will result in the small scope of the prospecting works, and thus in the less cost. The first simulation included the aquifers with the least thickness, and each succeeding simulation had added the data from the deeper drillholes, that is, the data with the greater thickness of the aquifer up to the actual thickness obtained on the basis of the available and the new data.

Table 2.

Simulation	Number of input data	Calculated water level m.a.s.l. (well no. 5)	Difference in elevation ΔH(m)	Absolute indeterminacy $\delta\,\Delta H$ (m)	Relative indeterminacy $\delta\,\Delta H/\Delta H$ stv. (%)		
					(pp1)	(p16)	(pp2)
DIS 1-1	8	-	-	-	-	-	-
DIS 1-2	18	85,09	0	2,03	94,4	60,4	≈100
DIS 1- 2a	23	87,12	2,03	0,22	10,2	6,5	11,4
DIS 1- 3	28	87,34	2,25	0,17	7,9	5,1	8,8
DIS 1	37	87,53	2,44	0	0	0	0
DIS 1 - a	42	87,49	-	-		-	
DIS 1 - b	51	87,52	-	-		-	

The referential plane (datum) is the standard water level in piezometers Pp1, P16 and Pp2 which are beyond influence of the exploitation wells of the spring area. The representative levels are those water table levels in the well B5 which is approximately in the central part of the groundwater intake and which had been included in all the existing and new simulations. According to this:

ΔH stv Pp1 = 87,24 – 85,09 = 2,15 m
ΔH stv P16 = 88,48 – 85,09 = 3,39 m
ΔH stv Pp2 = 87,02 – 85,09 = 1,93 m

Simulation DS1-1 with eight input data was not successful, because such low number of data is not sufficient for simulating the wider spring area. The first successful simulation is DIS1-2 with 18 input parameters, so the rest of the simulations were carried out with the increased number of input data. It may be observed that up to the simulation DIS1 containing 37 input data, the calculation level of the well water table had been increasing significantly, and that after that, with the increase of the number of input data of the levels, the water table in the well remained almost unchanged. Also the relative indeterminacy (fig. 11) drops steeply with 25 input data, only to reach zero with 37 input data.

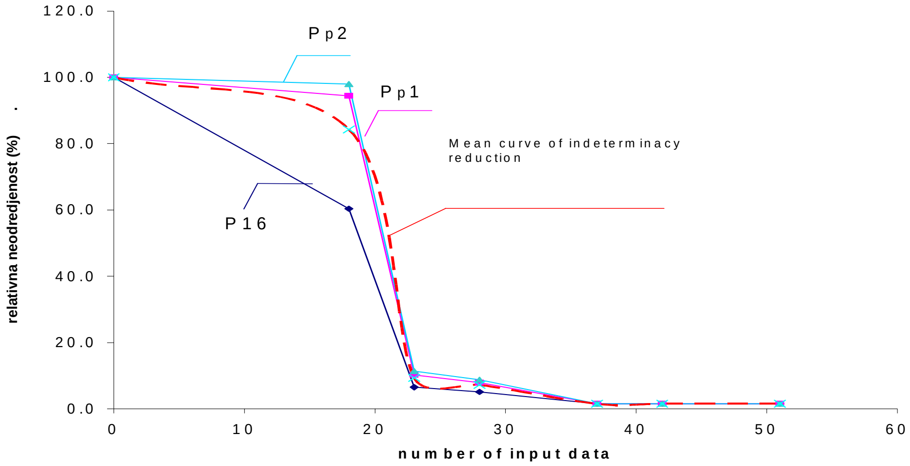

Fig. 11. Reduction of input data indeterminacy.

As it may be observed in the figure 11, for the hydrodynamic groundwater streaming model in Semberija, 37 input data defining the thickness of the aquifer are sufficient, so this number of input data will be taken as the final in the new, future simulations.

The number of input parameters varies from case to case and primarily depends on the geological composition, hydrogeological, climate and topographic characteristics of the considered area. The quantification of these parameters must, according to this, be performed for each case separately, but the methodology, in principle, remains the same for all the models. The point is that the increase of the number of input data (whose preparation costs a lot) is carried out to a limit of the optimum number of input data, from where no change of the number of input data will result in the change of the output data of the model (streamline image, piezometric height etc.). The excess number of input data incurs great expenses, and the precision of the calculation is increased either to a minimum extent or not at all, so the modeling becomes unprofitable with a large number of input parameters.

The previous analysis was carried out for the system in exploitation, where certain comparison on the existing structures is possible (wells, piezometers etc). In the case of prospecting and forming of the new spring of groundwater, an analogy can be applied, provided that the observation of the water table, test pumping and comparison are carried out on the wells and the piezometers built for the purposes of simulations and model calibration.

Apart from the difference in the numerical values which refer to the levels of groundwater table in the points of special interest, the difference of the spring area feed zone width (figure 12) is significant. For the exploitation quantities on the springs of 230, 280 and 330 l/s, according to the old simulations, which had only the scarce input data available, the widths of the feed zones were 1320, 1400 and 1480 m. According to the new simulations the corresponding feed zones are 1810, 2060 and 2450 m wide.

It is clear that with the increased pumping at the spring Grmis, the feed zone of the spring is significantly increased. So, at exploitation of around 600 l/s from the existing wells. The feed zone stretches directly into the populated area of Bijeljina, which is very unfavorable from the aspect of groundwater pollution by the town waste waters. From this aspect, it is necessary to construct new wells east of the existing ones, when exploiting the greater quantities from them (advancing east, toward the river Drina), in order to avoid the populated area. At exploitation quantities below 600 l/s, the feed zone of the existing wells stretches below smaller settlements. These places are the constant polluters and the urgent construction of the sewage system network is necessary in order to protect the spring.

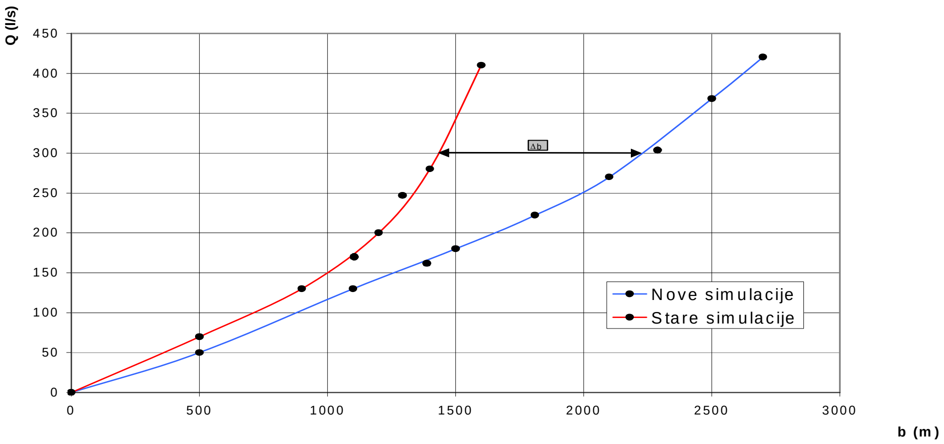

Fig. 12. Dependence of the spring feed width from the exploitation quantities.

5. CONCLUSION

Employing the facilitation effected by the GROW software package, when analyzing the thickness of the aquifer, a procedure of gradual increase of the number of input data until the output data (results) become constant was applied, until the degree of indeterminacy becomes the lowest one. In this way, the modern technology helped determine the sufficient number of input data defining the thickness of the water bearing stratum for the Semberija aquifer. With a further increase of input data, that is, of drillholes, the reliability of the model is not increased, that is, the indeterminacy of the model is not reduced, so the additional prospecting works are unnecessary. This methodology and the research result are the main contribution of this paper.

In order to reduce the indeterminacy of the filtration coefficient and the model, the prior gauging of the model on the basis of the existing observation of the groundwater table had been conducted. The repeated gauging and indeterminacy reduction required organizing the additional field prospecting works – installing the new piezometers and observation of the groundwater table in the span of one year. Also, the comparison of the simulation results after the additional observation, with the model which was simulated on the basis of the existing results, was done.

In cases where the input parameters for the model have not been obtained by measuring, and where the model has not been calibrated, the output results are unreliable.

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PRIMENA HIDRODINAMIČKIH MODELA U SMANJENJU NEODREĐENOSTI ULAZNIH PARAMETARA ZA SIMULACIJU PODZEMNIH TOKOVA

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Ključno pitanje koje se nameće tokom pripreme ulaznih podataka kod modeliranja svih hidrotehničkih sistema je pitanje dovoljnog i optimalnog broja ulaznih podataka. Ovde je odgovor na postavljeno pitanje pronađen korišćenjem dosadašnjih rezultata istraživanja iz te oblasti uz primenu softverskog paketa GROW kojim se simulira dvodimenzionalno strujanje podzemne vode u vodonosnim slojevima – izdanima. Dakle, predmet ovog rada je:

ℕ analiza potrebnog broja mernih mesta kako bi se neodređenost modela smanjila do nivoa kada se daljim povećanjem broja mernih mesta ne dobija veći kvalitet,

ℕ analiza propagacije neodređenosti ulaznih podataka kroz simulacione modele.

Kao primer na kome su obavljene analize korišćen je deo složenog vodoprivrednog sistema u akviferu Semberije, u širem gradskom području Bijeljine. Pored klasične zasebne analize akvifera za zahvatanje podzemne vode, u radu se posebna pažnja obraća na analizu dominantnih uticaja pojedinih neodređenosti i mogućnosti njihovih smanjivanja.

U startu su iskorišćeni postojeći ulazni podaci, a zatim su prikupljeni dodatni postojeći ulazni podaci, da bi se potom izvršilo poređenje rezultata. Kako svaki novi kvalitetan ulazni podatak doprinosi određenom smanjenju neodređenosti modela i sistema, za potrebe ovog rada organizovana su dodatna osmatranja i terenski istražni radovi. Na bazi dodatnih merenja i osmatranja izvrešena je kalibracija modela za analizu strujanja podzemne vode.