Bulletin of Geography. Physical Geography Series, No. 9 (2015): 21–29
http://dx.doi.org/10.1515/bgeo-2015-0012

Simulation and optimization of groundwater exploitation for the water supply of Tarnów agglomeration (southern Poland)

ISSN 2080-7686

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Abstract. This paper presents the application of the simulation-optimization approach to optimize groundwater intake for the water supply of Tarnów agglomeration (southern Poland). Tarnów agglomeration is supplied with water from extensively exploited surface and groundwater intakes located at the confluence of the rivers Dunajec and Biała. Groundwater intakes capture water from the Quaternary aquifer, which is recharged by rainfall and direct infiltration from the rivers and irrigation ditches. Hydrogeological conditions occurring within the area under consideration were mapped by using a single-layer numerical model in Processing Modflow software. After calibrating the simulation model, a simulation-optimization approach was developed with the aim of aiding the process of searching for the best scheme of exploitation of groundwater intake. The unit response matrix method was used to connect the simulation model with the optimization procedure. In the optimization task the objective functions concerning the total volume of groundwater intake discharge and infiltration amount from the River Dunajec or irrigation ditches were applied. Several constraints concerned both the maximum and minimum capacity of individual wells and the entire intake, as well as desirable or undesirable drawdown values in selected control points and control areas. Finally, twelve variants of optimization tasks, for different boundary conditions and different objective functions, were solved and optimal schemes of well discharge distribution within the intake were calculated. The results of optimization show that, depending on the intended objective and the constraints imposed, the best exploitation scenario under the given conditions may be found.

Keywords:
groundwater flow,
simulation,
optimization,
water intake,
exploitation

Introduction

Tarnów agglomeration is supplied with water from extensively exploited intakes located at the confluence of the rivers Dunajec and Biała. In a small area are located three groundwater intakes currently under exploitation (Świerczków, Kępa Bogumiłowicka and Nitrogen Plant groundwater intake), two surface water intakes (Zbylitowska Góra and Mewa) and a newly constructed, currently inactive groundwater intake Zbylitowska Góra. Groundwater intakes capture water from the Quaternary aquifer, which is recharged by rainfall and direct infiltration from the rivers. The aquifer is locally supplemented by water from irrigation ditches (Fig. 1).

In the area of research, there is one useful unconfined aquifer associated with Quaternary formations filling the valleys of the rivers Dunajec and Biała (Fig. 2). The level is made up of sand and gravel deposits with a large addition of pebbles. The Quaternary aquifer lies on an impermeable clay Miocene bed. The most common thickness of aquifers is 5-9 m and the filtration coefficient varies from a few dozen to more than 100 m/d. The highest values of the filtration coefficient, reaching up to several hundred m/d, are in the valley of the River Dunajec.

Hydrogeological conditions occurring within the area under consideration were mapped by using a single-layer numerical model in Processing Modflow software. The model was calibrated for the state of the groundwater level in August 2009. Groundwater level measurements in 51 observation boreholes and dug wells were used. Then, the model was used to simulate several variants of forecasting (Haładus et al. 2011; Haładus et al. 2012). The aim of those studies, in addition to verification of the model, was to analyse several scenarios of exploitation of the intakes, to learn the water circulation pattern, to estimate the volume of the components of the water balance and to verify the resources of the newly constructed intake in Zbylitowska Góra. The results of the analysis of simulated variants may be a reliable basis for the rationalization of water management in the area under consideration.

However, in this paper we propose to use the simulation-optimization approach, which is better suited for searching for the optimum scheme of the exploitation of the groundwater (Treichel, Rodzoch 1997; Treichel et al. 2000). In this approach the simulation model is combined with the optimization procedure by means of the so-called unit response matrix (Gorelick 1983).

In the formulation of the optimization task there is an objective function, which is subject to minimization or maximization, and a set of constraints that allows the analysis only of the so-called feasible solutions. Constraints may concern both the maximum and minimum capacity of individual wells or intakes, as well as desirable or undesirable drawdown values in selected control points and control areas. Other restrictions may be imposed on the direction and values of groundwater flow gradient and/or changes in the water balance components. Consideration of the hydrodynamics of water flow is possible through the unit response coefficients (unit response functions). These coefficients result from the reaction of the system to the unit stress (which is abstraction or recharge of water), located in areas potentially foreseen as the possible location of the wells.

In this paper we apply this approach to find the optimal scheme of the exploitation of the groundwater intake "Świerczków" used to supply Tarnów agglomeration with water.

Simulation Model

Hydrogeological conditions in the Quaternary aquifer, located at the confluence of the River Dunajec and its right tributary Biała (Fig. 1), were mapped by means of a single-layer model using the Processing Modflow software (Chiang, Kinzelbach 2001; Kulma, Zdechlik 2009). A filtration area of 20.03 km^2 was divided into 32,050 data blocks of a size $\Delta x = \Delta y = 25$ m.

The natural limitation of the study area from the west and east were the rivers, i.e. respectively the Dunajec and Biała, which were simulated on the model using constant head boundary conditions. The south artificial model limit was mapped using a third type boundary condition – general head boundary (Zdechlik, Kulma 2009).

Inside the simulated area the surface watercourse (which is the left tributary of the River Biała) and the irrigation ditches were modelled using the mixed, general head boundary conditions. In contrast, the groundwater intakes were mapped using the second type (Neumann) boundary condition.

Model calibration was performed for the groundwater level of August 2009. Groundwater level measurements in 51 observation boreholes and dug wells were used. The hydrodynamic field of the system obtained using the Modflow model shows a good agreement with the measurements – the differences between the observed values and those obtained from the model ranged from -1.1 to 1.0 m (Fig. 3).

Considered as the calibration criteria, the statistical parameters (Anderson, Woessner 1991) were as follows: mean absolute error was 0.57 m, while the standard deviation was 0.65 m. Referring the calculated values to the difference between the highest and lowest groundwater level (approximately 50 m) identified in the study area, the calibration should be considered as correct (Kulma, Zdechlik 2009).

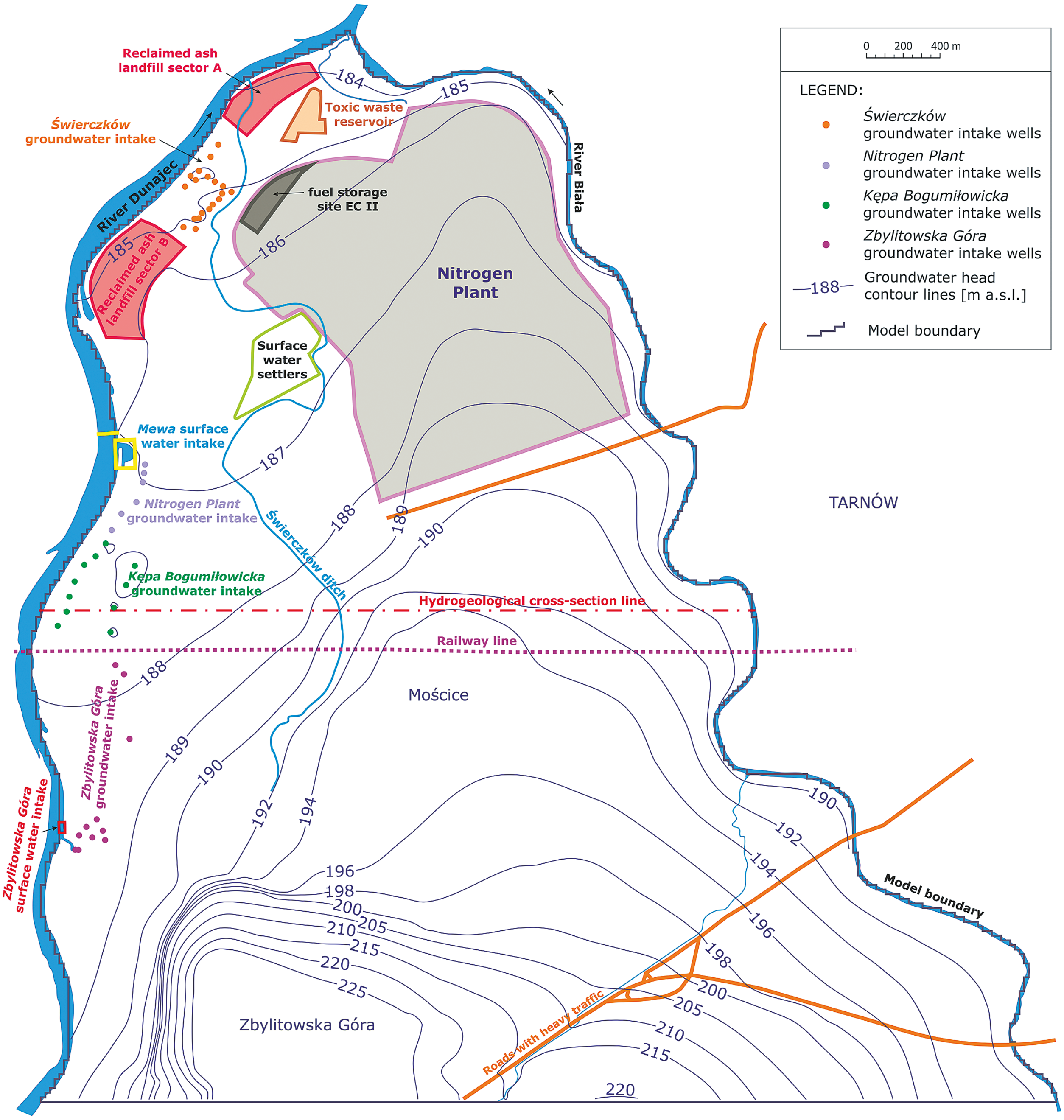

Fig. 1. Location of the study area with groundwater head distribution (state in August 2009)

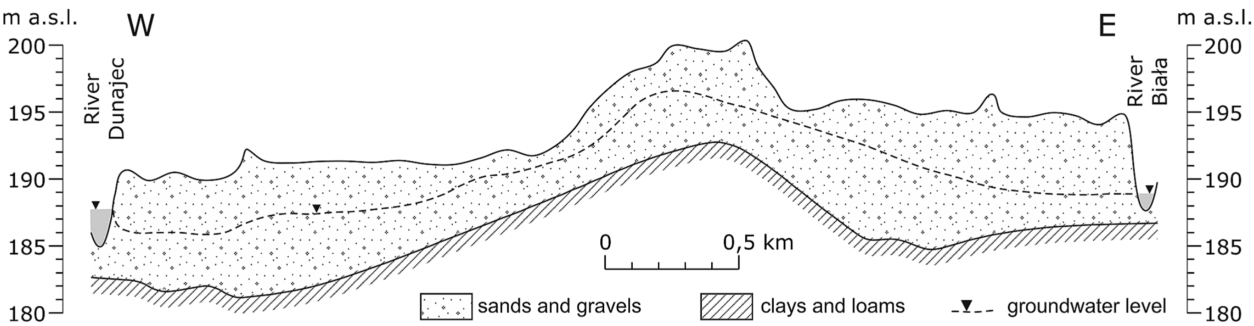

Fig. 2. Schematic hydrogeological cross-section

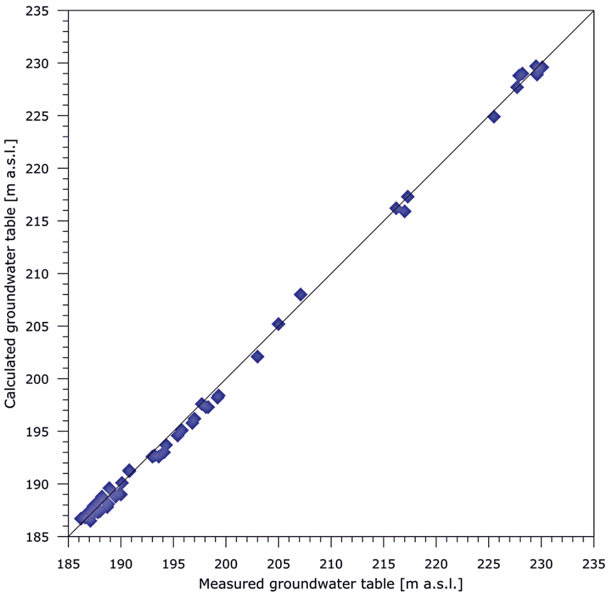

Fig. 3. Comparison of calculated and observed groundwater table at calibration points

The calibrated model was used to carry out a number of predictive simulations. In the first variant the hydrogeological conditions of August 2009 were restored. The groundwater table was strongly influenced by the exploitation of groundwater intakes and the level of water in the rivers (Fig. 1). The average surface water levels in both the rivers Dunajec and Biała were assumed for this variant. Also the boundary conditions included the irrigation ditches, which supply the aquifer with water from the River Dunajec, in order to increase the operational capability of the Świerczków intake.

Prognostic model calculations were performed in two other variants applying low water levels in surface water courses as the boundary conditions. In option 2 the natural hydrogeological conditions were simulated, i.e. lack of water abstraction in the intakes. In this option the existing water threshold in the River Dunajec was included in the boundary conditions to allow the work of the surface water intake "Mewa".

Prognostic option 3 concerned the situation in which the abstractions of groundwater intakes of Nitrogen Plant and Kępa Bogumiłowicka are, respectively, 93.2% and 97.2% of the approved operational resources. Only at the Świerczków intake was the abstraction mapped on the level of just about 63.8% of the approved resources, simulating the work of active wells. In contrast, for a newly constructed groundwater intake, located in Zbylitowska Góra (Fig. 1), the amount of abstraction was adapted to the possibilities of its recharge.

The results obtained from the simulation allow the water circulation pattern to be discovered and the balance of the groundwater within the area covered by the study to be calculated. The total amount of groundwater included in the balance of the Quaternary aquifer in the area covered by hydrogeological model is about 15,180 m^3/d in the natural conditions (option 2) and increases to about 45,790 m^3/d in the prognostic option 3. The main factor influencing the water resources in the Quaternary aquifer is the recharge from the River Dunajec at the rate of about 11,870 m^3/d (option 1) to 26,710 m^3/d (option 3). This represents approximately 39.3% and 58.3% of total water volume of the modelled aquifer system, respectively. Considering the fact that the recharge of the irrigation ditches also comes from the River Dunajec, the part of surface water supplying the Quaternary aquifer rises up to about 68.6%. Under the natural conditions (option 2) the magnitude of this factor plays a minor role and is about 2,470 m^3/d (approximately 16.3% of total water volume). Most of the recharge from the river occurs in the vicinity of the water threshold on the River Dunajec and is local.

In addition to water balance considerations, on the basis of the simulation results it is possible to determine the size of the decrease in the groundwater level in the observed areas. The results of the simulation can also be used to determine the disposable and operational resources, and therefore provide a reliable basis for the rationalization of water management in the area.

However, the search for the optimum scheme of the exploitation of groundwater must be based not only on the classical method of "successive trial and error", limiting the analysis to pre-announced variants of recharge/abstraction, but may use a more systematic approach, combining the hydrodynamic model with optimization methods. The two most common methods to combine the mathematical model of the groundwater system with the formulation of the optimization task corresponding to a given management problem are the unit response matrix method and the method of embedding (Gorelick 1983; El Magnouni, Treichel 1994; Treichel, Rodzoch 1997).

The unit response matrix method (also called the impact factor method) uses the principle of superposition and linear systems theory to describe the behaviour of the groundwater system considering the stress carried out by abstraction in the wells. The method consists in determining at the initial stage, using a simulation model, the distribution of output variables (state variables) such as piezometric height, the concentration of pollutants, etc. resulting from the individual stress (abstraction of water or recharge) located in the places potentially provided for the possible location of the well. Then, the calculation is repeated as many times as the number of potential locations, which allows the construction of a matrix, called the unit response matrix, that combines outputs observed at checkpoints with unit changes of decision variables. It should be emphasized that the unit response matrix includes the full hydrogeological information we have about the system that was used to construct a reliable simulation model of the groundwater system. This matrix is part of a set of constraints in the optimization task. In this way, the mathematical model of the groundwater system is associated with the formulation of the optimization task. Additional constraints may then be formulated in order to reduce drawdown in some selected points, or impose restrictions on the values of the decision variables.

In this paper we use the unit response matrix method, which is well suited for modelling the regional aquifer systems (Kholghi et al. 1996; Larroque et al. 2008), despite the requirement of linearity assumptions regarding the model.

Decision Variables, Constraints and Criteria of Optimization

The optimization problem was formulated for the water intake "Świerczków". Decision variables were related to the abstraction of water in the wells of the intake. Świerczków water intake consists of 19 wells, of which 11 to 14 are currently operated. Some wells are excluded from use, due to the limited performance or bad quality of the water. For the purpose of optimization it was assumed that all wells of Świerczków intake which were considered in the simulation will be treated as decision variables. The names of these wells are as follows: W-1, W-2, W-3, W-4, W-5, W-7, W-8, W-2a, W-3a, W-4a, W-20 and W-21 (Fig. 4). In total, there were 12 decision variables.

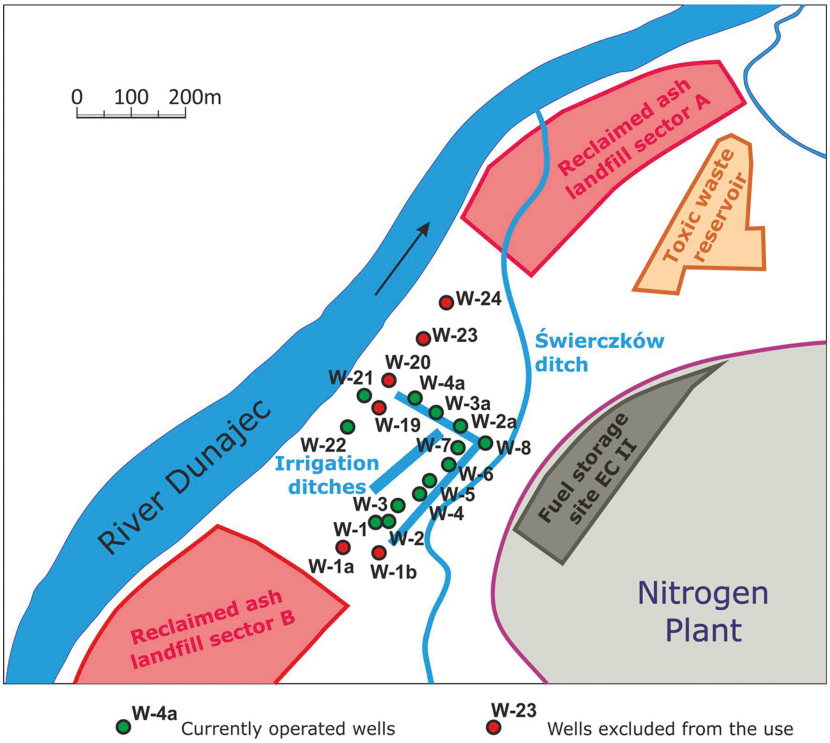

Fig. 4. Location of wells under optimization in the Świerczków water intake

The following constraints were adopted in the optimization task: controlling the water level at selected checkpoints, abstraction of water from the wells in a volume not exceeding the determined water resources and the amount of the recharge/drainage from the River Dunajec and from the infiltration ditches.

In order to control the decrease in the water level resulting from the increased water abstraction, eight checkpoints have been placed along the River Dunajec around the Świerczków intake. Another nine checkpoints have been located in the immediate vicinity of the rehabilitated ash landfill, located in the south-west of the analysed intake. This landfill is separated from the water intake by an engineering protective barrier. In all the checkpoints, the height of the water table, calculated in the simulation model for the boundary condition variant with the average water levels in the River Dunajec, was adopted as a limiting constraint.

The list of constraints relating to the control of the water table in selected checkpoints was supplemented by 12 wells of the intake, in which the acceptable drawdown was controlled. The limiting condition for these constraints was assumed to be the maximum value of the drawdown calculated for each well for the conditions of maximum allowed exploitation discharge. These values varied from 1.5 m for well W-21, to a maximum of 2.54 m for well W-2.

Another constraint was related to the amount of water abstraction from individual wells and from the entire intake. The volume of the total exploitation resources of Świerczków intake was approved in 2003 and is equal to 13,380 m^3/d, with a maximum value of drawdown equal to 2.54 m.

The third group of constraints concerned the restrictions in balance components. Two balance zones (in which the volume of the recharge/drainage was controlled) were defined in the research area. The first zone (zone 1) included a section of the River Dunajec in the neighbourhood of Świerczków intake. In this balance area, the constraints concerning infiltration from the first type of head boundary condition were included in the optimization task (the head boundary condition was used to model the impact of the River Dunajec on the aquifer). The second balance zone (zone 2) included the irrigation ditches in the neighbourhood of Świerczków intake that were simulated in the model using the mixed (third type) boundary condition. Irrigation ditches are supplied with the surface water from the River Dunajec, which then infiltrates into groundwater in order to increase the production capacity of the intake.

Optimization criteria were the total volume of the discharge of Świerczków intake (the sum of discharges of the wells in the intake) and the amount of the groundwater recharge within the designated balance zones.

Optimization Tasks

We analysed four variants of optimization tasks: two for the so-called average and low water levels on the River Dunajec, and two for the normal and amplified clogging of the irrigation ditches which is observed in reality. In each of the variants of optimization tasks an appropriate unit response matrix was calculated, which was an important part of a set of constraints in optimization. The calibrated hydrodynamic model (built in the Processing Modflow software) was used to determine the unit response matrix. A new matrix has to be calculated at each change of boundary conditions.

In each variant of optimization tasks the following objective functions were successively maximized:

(1) the total volume of the discharge of Świerczków intake,

(2) the amount of the infiltration from the River Dunajec within the first balance zone,

(3) the amount of infiltration from the irrigation ditches within the second balance zone.

Constraints in each version of optimization task were the same and were related to drawdowns at selected checkpoints and the limited resources of groundwater intake. Optimization tasks were solved in MATLAB, using specially written script. The obtained optimal solutions in different versions of the optimization tasks differ from each other, but the differences were relatively small. This is due to the fact that the modelled system is strongly dependent on the boundary conditions (mainly the constant head boundary condition introduced on the River Dunajec) and has a few degrees of freedom.

The obtained solutions were then verified by the simulation model. We observed consistency of the drawdown values at control points calculated by the simulation model with the values calculated in the optimization task. In addition, we evaluated the acceptability of the solutions from the point of view of other restrictions, not taken into account in the optimization task (e.g. the components of the water balance).

Table 1 shows the results of the optimization for one variant of boundary conditions: the average water states on the River Dunajec and the amplified value of the clogging of irrigation ditches. The summarized results of other variants, i.e. the comparison of the values of objective functions for different variants, are presented in Figure 5. The detailed results for the other variants of optimization tasks are presented in a report from the grant.

As shown in Table 1, the obtained optimal solution is different for different types of the objective function. Although the values of the objective function are close to each other for different types of the function, the distributions of the discharges of the wells are different in each case. It should also be noted that in the case of clogged ditches, the maximum total discharge of the intake drops to 5,515 m^3/d, which represents about 66% of the maximum expected total discharge of Świerczków intake.

Table 1. Results of optimization for the variant of the average water states in the River Dunajec and the amplified value of clogging of irrigation ditches.

Objective function	Maximization		
	Total intake discharge [m^3/d]	Infiltration from the River Dunajec [m^3/d]	Infiltration from irrigation ditches [m^3/d]
Maximum value of the objective function	5515.1	4626.5	115.2
Total discharge of *Świerczków* intake	5515.1	5512.2	5511.2
Infiltration from Dunajec river (zone 1)	4626.1	4626.4	4618.1
Infiltration from irrigation ditches (zone 2)	111.8	114.1	115.2
		Optimal discharges of the wells [m^3/d]	
W-1	652.3	650.7	650.9
W-2	241.7	240.1	239.4
W-3	211.9	206.1	208.0
W-4	49.3	36.8	37.5
W-5	0	54.1	59.2
W-7	0	0	0
W-8	101.8	67.9	141.1
W-2a	0	0	0
W-3a	420.3	420.7	247.4
W-4a	796.8	796.8	871.8
W-20	1622.9	1622.6	1633.7
W-21	1418.1	1416.4	1422.2

The results of optimization do not indicate explicitly a unique best solution. The solutions are different for different types of objective function which was maximized. This means that practically each of them can be implemented. These solutions meet imposed constraints such as the maximum approved volume of groundwater resources of the intake or acceptable lowering of the water table in the selected checkpoints.

Figure 5 summarizes the results of optimization for all 12 variants of optimization tasks: 3 for the average water level in the River Dunajec and normal clogging conditions in the irrigation ditches, 3 for a low water level in the River Dunajec and normal clogging conditions in the irrigation ditches, 3 for the average water level in the River Dunajec and amplified clogging conditions in the irrigation ditches, and finally 3 for a low water level in the River Dunajec and amplified clogging conditions in the irrigation ditches. The three variants of optimization tasks in different boundary conditions correspond to maximization of three different objective functions: (1) total discharge of the intake, (2) infiltration from the River Dunajec, zone 1, (3) infiltration from the irrigation ditches, zone 2.

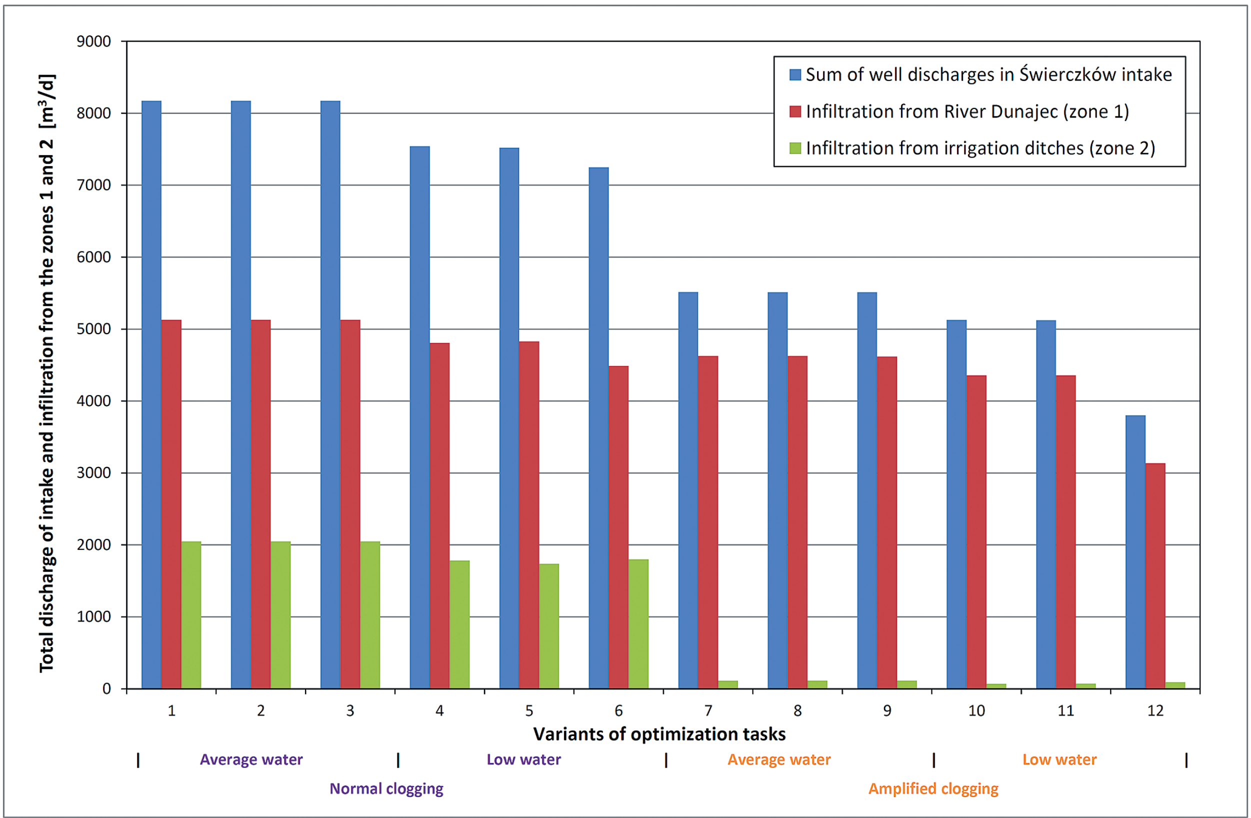

Fig. 5. Values of objective functions in variants of optimization tasks (1-12 – variant numbers)

It is worth noting that in the case of amplified clogging of irrigation ditches (variants from 7 to 12) the amount of water infiltrating from the ditches into the aquifer is strongly limited. Because of this limited recharge of the aquifer the total discharge of the intake has decreased. It proves that the irrigation ditches play an important role in supporting the working conditions of Świerczków intake.

Summary and Conclusions

A simulation-optimization approach was developed in this study with the purpose of aiding the process of searching for the best scheme of exploitation of groundwater intake. A reliable and well calibrated numerical model mapping the system of water circulation in the areas of intakes under consideration allows one to simulate the behaviour of the exploited groundwater system. To find the optimal scheme of well discharge distribution the optimization methods may be applied. The unit response matrix method was used to connect the simulation model with the optimization procedure. In the optimization task the objective functions concerning the total volume of groundwater intake discharge and the infiltration amount from the River Dunajec or irrigation ditches were applied. Several constraints concerned both the maximum and minimum capacity of individual wells and the entire intake, as well as desirable or undesirable drawdown values in selected control points and control areas. Finally, twelve variants of optimization tasks, for different boundary conditions and different objective functions, were solved and optimal schemes of well discharge distribution within the intake were calculated. The results of optimization for Świerczków intake show that, depending on the intended objective and the constraints imposed, it is possible to find the best exploitation scenario under the given conditions. This scenario allows water abstraction in sufficient quantity without having a negative effect on the flow conditions in the aquifer. The results define the safe working conditions of water intakes without the risk and without the transformation of the aquatic environment at regional and local scale.

Acknowledgments. This study was conducted as a part of a research project of the Ministry of Science and Higher Education No. N N525 410535. Financing from the grant of statutory research in the Department of Hydrogeology and Engineering Geology at AGH University of Science and Technology in Krakow (11.11.140.026) is also acknowledged.

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Manuscript received 3 March 2015, revised 6 October 2015 and accepted 24 October 2015.