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METHODOLOGY FOR DETERMINATION OF THE APPLICABILITY OF THE ARTIFICIAL ENRICHMENT OF AQUIFERS

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Abstract. *The methodological approach for the design of the artificial enrichment and protection of the ground water source is given through the clear algorithm. The proposed methodology is the sequence of steps enabling the designer to define the possibility of the artificial enrichment, based on the realistic engineering probability and realistically accessible database of the research work. The methodology may be applied in the number of existing ground water sources which are located in the alluvia of the rivers, where the application of the artificial enrichment is necessary. The methodology comprises a combination of the modern computer programs for production of the mathematical models of the ground water dynamics and the empirical formulae which are the consequence of the observation of the existing, already constructed systems.*

1. INTRODUCTION

In order to provide the invariable conditions of exploitation on the ground waters sources which are located in the alluvium of a river, it is necessary to define the aspect of the invariable quantities and the appropriate quality provision. The provision of the invariable quantities on the ground water source is possible either by building the new wells or by recreating the contact between the ground and the surface waters that got blocked in due course. When these activities do not yield the desired results, the construction of the facilities for the artificial enrichment of the aquifers is undertaken.

The procedure for defining the facilities for the artificial enrichment of the aquifers, according to the enclosed methodology, comprises the collection of all the available data (geomorphological, hydrological, hydrogeological, hydrotechnical etc.) on the source of the ground waters for which we desire to provide the invariable conditions of exploitation, including the analysis and adaptation of the hydrodynamical models of those sources.

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Having in mind the need for complex consideration of the problem, the methodology representing the guidelines to the manager during solving the problems of providing the invariable conditions of exploitation of the ground water sources, was defined.

2. Presentation of the Methodology

Regarding the present status of this issue at the national end global level, and on the basis of the local experience in design and exploitation of the artificial enrichment of the aquifers, it seems that there is the need to precisely define the sequence of the procedures that ought to be done in order to define the applicability of the artificial enrichment of the aquifers method in order to sustain the invariable conditions of exploitation.

The procedures are defined and presented in the form of an algorithm which is displayed in a logic scheme (Fig. 1) titled: "**Methodology for determination of the applicability of the artificial enrichment of the aquifers aimed at sustaining the invariable conditions of exploitation**". The algorithm has nine steps in total:

1. Requirement for provision of the invariable conditions of the source exploitation with the application of the artificial enrichment of the aquifers method.
2. Collection of the available data.
3. Defining of the required water quality at the source
4. Hydrodynamics of the source
5. Defining of the hydrotechnical characteristics of the artificial ground water enrichment from the aspect of quantity.
6. Defining of the hydrotechnical characteristics of the artificial ground water enrichment from the aspect of quality.
7. Recapitulation off all the facilities within the system for the artificial enrichment of the aquifers (basis for the bill of quantities)
8. Evaluation of the expected value of the investment aimed at the sustaining of the invariable conditions of exploitation of the aquifers at the ground waters source.
9. Economic evaluation.

Acting upon the defined procedure with the available record of the existing hydrogeological data, the sufficiently accurate answer on the applicability of the aquifer artificial enrichment method aimed at the sustaining of the invariable conditions of exploitation is obtained. The available records of the existing hydrogeological data mean that there is at least the minimum design of the existing source, designs of the well and the lithological profile of the wells on the source. The algorithm is primarily intended for the design at the level of general, that is preliminary design. With a sufficient amount of research work resulting from the application of the preliminary design, the algorithm can be applied again when making the main project. The algorithm is an instruction on what needs to be considered in order to determine the applicability of the artificial enrichment of the aquifers aimed at the sustaining of the constant conditions of exploitation. The design of the artificial infiltration systems, as a rule, is a combination of:

1. The work with the hydrogeological data records
2. The work with the software package for hydrodynamical modeling (PMWIN, MODFLOW, Groundwater Vistas, etc) where the regional input infiltration and tapping of aquifer wells is simulated.

3. The work and the usage of the experience data from the local and foreign practice about the way and character of the infiltration (defining of the hydrotechnical characteristics of the infiltration facilities and defining of the degree of the treatment of water which is let into the infiltration facilities in order to realize the planned quantity of water for the artificial ground water enrichment, so that the spreading basin working cycle would be as long as possible).
4. Construction of a pilot spreading basin and observation of the infiltration effects (it is recommended that the basin is not smaller than 50 × 50 m and that the observation lasts from a few months to a year and more, if possible.)
5. Summing up of the experiences and their implementation in the project.

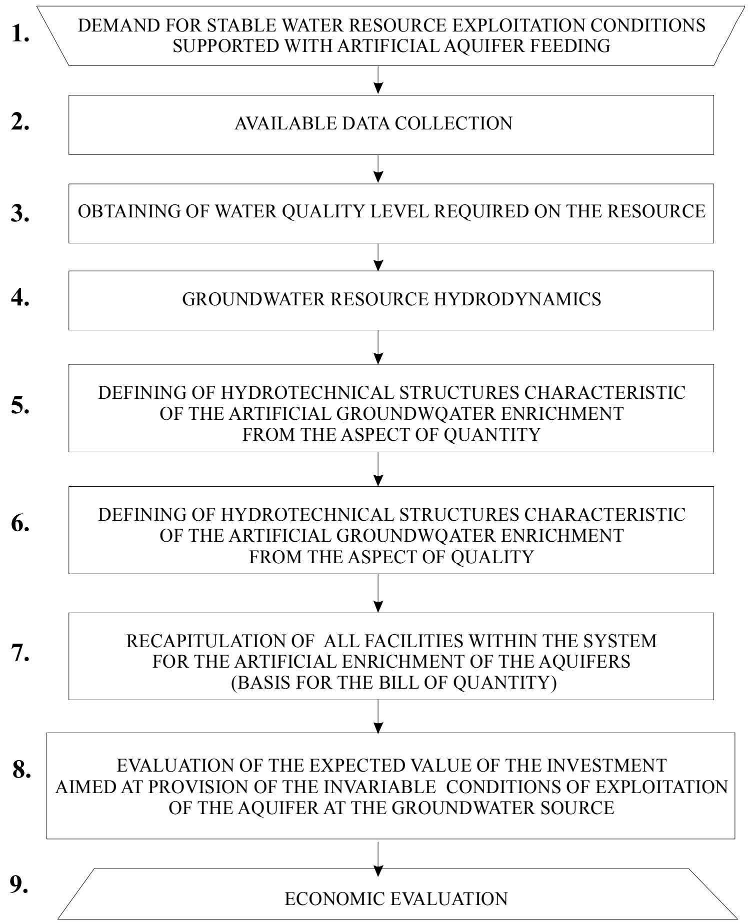

Fig. 1. Logic scheme of the methodology for determination of the applicability of the artificial enrichment of the aquifers

In the context of making the technical documentation, the better the items 1 through 3 are done, the higher is the possibility that the results of the observation of the pilot spreading basin will be within the designed and expected limits.

3. Detailed Explanation of the Methodology Presented in the Logical Scheme

The defined methodology for determination of the applicability of the artificial enrichment of the aquifers method, given from the aspect of sustainability of the invariable conditions of exploitation through nine steps, gives an answer resulting in the evaluation of the expected value of investment on the source of the ground waters, intended to sustain the invariable exploitation conditions.

In the first step of the methodology presented in the logic scheme, figure 1, the requirement for providing the invariable conditions of exploitation of the ground water source with the application of the artificial enrichment of the aquifers is defined. The requirement may be initiated by an enterprise, social-political organization, or by the scientific and research organization. It is necessary to formulate the requirement in the form of a design task which has to be signed and verified by the investor. The design task is formulated by the professional person.

In the second step of the methodology presented in the logic scheme, figure 1, the required quality of water of the source is defined. This step is necessary because there are sources of ground waters where the concentrations of some matters dissolved in water, that is tapped by the facilities, depart from the maximum allowed concentrations sanctioned on the basis of the national standard. The ground waters tapped from such source undergo the purification process (removal of ferrous and manganese elements, etc). In order to make clear what is wanted and achieved, it is necessary what quality of ground water is expected to be extracted from the aquifer.

In the fourth step of the methodology presented in the logic scheme, figure 1, the hydrodynamic analysis is made. If there is a hydrodynamic analysis of the source, that is a previously made mathematical model, it will facilitate the making of the new, that is reformed mathematical model. After the verification of the mathematical model, the infiltration and tapping of water from the wells in the water-bearing layer, with different exploitation scenarios is simulated. In this way the macro location of the infiltration facilities is defined. The mathematical model should be made using the existing database of the hydrogeological data with the software facilitating both the simulation of the hydrodynamics in the ground and the simulation of the pollution transport, so that, as early as in the model, the indicators of the time of water flow from the spreading basin to the tapping can be obtained. The model provides the flow net before and after the application of the artificial enrichment of aquifer method, that is the macro location of the artificial enrichment structures where the best effects are expected. During the simulation of the various aquifer exploitation scenarios, the aspect of control or the total isolation of the model tapping from the direction (zone) from where the pollution comes (threatening to pollute the entire source area and whose penetration the intergranular porous environment is unable to purify), should be considered. This is also a part of the various scenarios that should be studied on the hydrodynamic model.

In the fifth step of the methodology presented on the logic scheme, figure 1, there is the hydrotechnical definition of the structures for the artificial aquifer enrichment of the ground waters, from the aspect of quantity.

On the basis of the regularities which are empirically defined in respect to the scope of their applicability (the researchers defined the applicability area of the spotted regularities for their hydrogeological conditions) the following hydrotechnical characteristics of the spreading basins should be defined, as follows: defining of the surface of the spreading basins depending on the probable rate of infiltration, defining of the cleaning dynamics, defining of the additional surface because of the periodical cleaning requirement, defining of the volume of the spreading basin from the aspect of continuous replenishment of ground waters in the conditions of a temporary deterioration of the surface water used for this purpose.

In the previous chapters, the world and national experiences regarding the infiltration rate are considered in detail, and the most important criteria for the choice of the infiltration systems elements are defined. For the methodology, the diagram 1 and 2 are especially important, for the expected rate of infiltration is defined on their basis. Diagram 1 is the apparent infiltration rate in meter per a second, depending on the permeability of the soil. The formula $V_{inf}(m/s) = 10^{(0.76 \log k)-2.44}$, is published in the Association Internationale D'Hidrologie Scientifique 1970 no 87 where K – filtration coefficient (m/s).

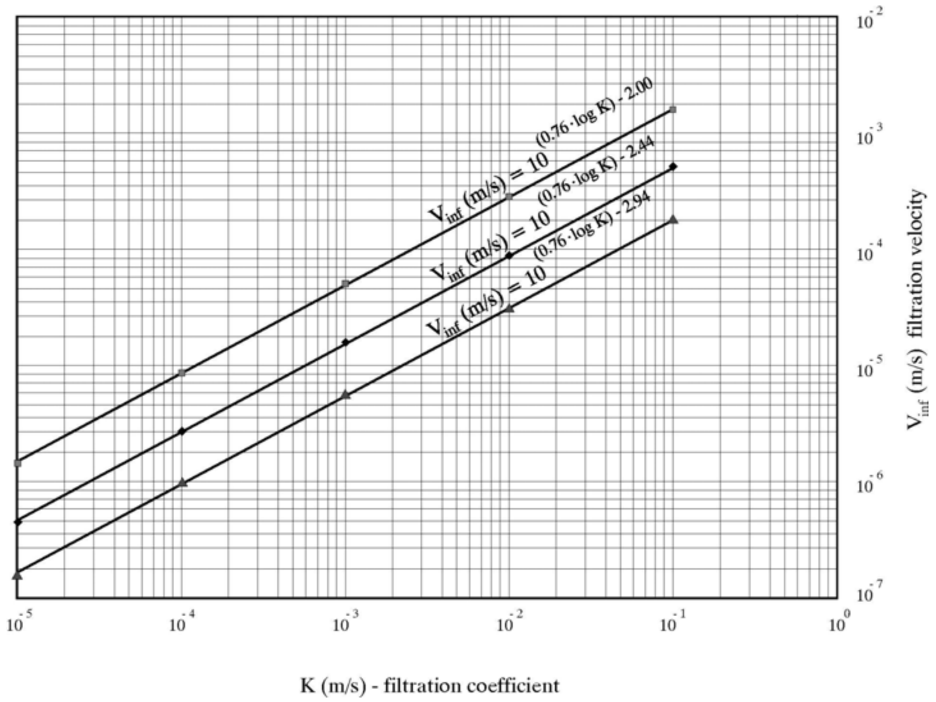

Diagram 1. Dependence of the filtration rate on the filtration coefficient

In this step, the civil engineering and hydrotechnical characteristics of the infiltration systems are defined, thus creating the conditions for realistic consideration of the investment cost.

In the sixth step of the methodology presented on the logic scheme, figure 1, the characteristics of the artificial aquifer enrichment system are defined, from the aspect of quality. It is most important to answer whether the preceding purification is required, generally, because of the presence of certain matters which cannot be removed by the purification action of the porous environment.

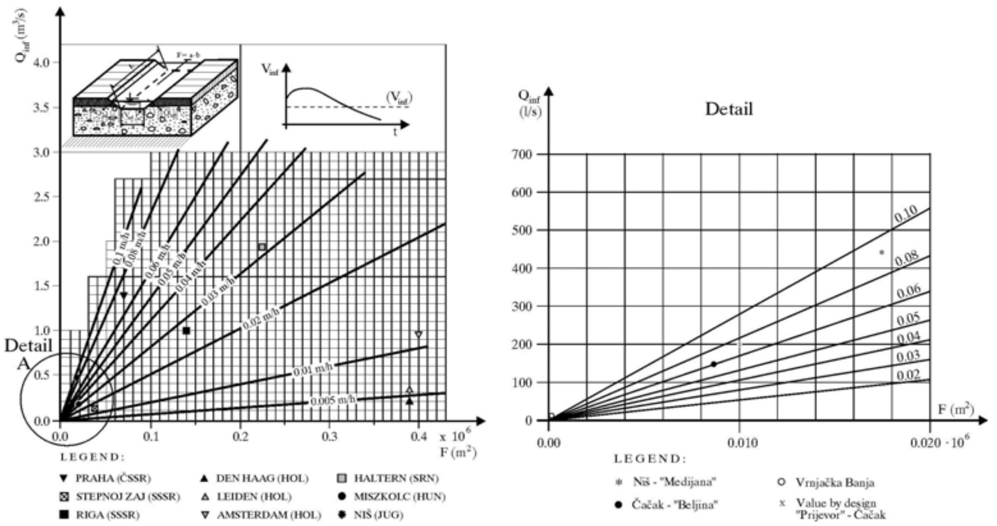

Diagram 2. dependence of the quantity of infiltrated water from the size of the surface, all in respect to the mean filtration rate according to the national and foreign experience.

Table 1. Filtration rate according to the national and foreign experience

Location	Infiltration thru soil	Filtration coefficient (m/s)
Praha	Sand and gravel	$3–4\times10^{-4}$
Riga	Sand and gravel	3.5×10^{-4}
Stepnojzaj	Sand and gravel	10.4×10^{-4}
Den Haag	Fine sand	–
Leiden	Fine sand	–
Amsterdam	Fine sand	1.2×10^{-4}
Haltern	Fine sand	1.2×10^{-4}
Miszkolc	Fine sand	–
Niš	Gravel and sand	3.0×10^{-4}

If there are data (results of the physical, chemical analyses) related to the quality of water in a river and the data on the water quality at the source, that is in the wells along the river, one should try to define the empiric regularity in respect to the transformation of the significant parameters. The regularity defined in such way presents the mathematical model of the water quality transformation at the concrete source, which can be used for the consideration, i.e. evaluation of the efficiency of the purifying action of the porous environment in case of the accident situations, or change of the river water quality in time. If there are no data – results of the chemical analysis, one should see whether the correlation can be established with some analysis of the similar source for which there is data and that has the water quality transformation model. In case the analogy with the known source cannot be established, then an observation spreading basin ought to be built, and the results of the physical and chemical analyses of a river, i.e. water in the spreading basin and the water taken in by the wells should be observed.

Following, as examples, are the formulae for the transformation of quality for the individual parameters for the source "Prijevor" in Cacak. These formulae empirically define the mathematical model of the transformation of quality. Through the empirical formulae, the expected degree of reduction of the chemical parameters is calculated, that is the purifying action effect of the porous environment on the correction of the pH (formula 1), reduction of the usage of $KMnO_4$ (formula 2) and the content of CO_2 (formula 3) and Fe (formula 4) is predicted.

The formulae for the transformation of quality of the individual parameters at the source "Prijevor" are:

$$pH_{(well)}=0.43\cdot pH_{(lake)}+4.42 \quad (7 \le pH_{(lake)} \le 8.6) \tag{1}$$

$$KMnO_{4(well)}=0.05\cdot KMnO_{4\,(lake)}+2.3 \quad (7 \le KMnO_{4(lake)} \le 8.6) \tag{2}$$

$$NO_2(well) = 0.002686 - (\frac{1}{75000})\sqrt[2]{-1000 + 60000 \cdot NO_3(lake)} \quad (0.017 \le NO_{2(lake)} \le 0.1) \tag{3}$$

$$Fe(well) = 0.035 - \sqrt[2]{3.6\cdot 10^{-4} - 4.5\cdot 10^{-4}\cdot Fe(lake)} \quad (0 \le Fe_{(lake)} \le 0.8) \tag{4}$$

These formulae are obtained by the analysis of the series of data on the quality of water in the wells at the source and the quality of water from the reservoir from which the infiltration is executed. Processing of the series of data is done by using the standard capacity of the Microsoft Excel program. By the simple selection of the displayed series of data on the diagram (chart) the adding option is selected (trendline). The approximation of the series of data may be done by the linear, logarithm, polynomial (of any degree), exponential approximations etc. After obtaining the curve which defines the best the series of registered values, the second series of values ought to be done (input and output). The obtained equations of input (river water) y1 = f(t) and output (well water) y2 = f(t) should be reduced by the common value "t" and obtain the function of change y2 = f(y1). The obtained formula should be graphically confirmed and see how the values calculated by the formula y2 = f(y1) fit in the measured values.

In the seventh step of the methodology presented in the logic scheme, figure 1, the recapitulation of all the works and facilities is done, thus creating the data base for the creation of the bill of quantities.

In the eighth step of the methodology presented in the logic scheme, figure 1, the evaluation on the expected value of the investment aimed at sustaining the invariable conditions of exploitation.

The arguments affecting the evaluation of the expected value of the investments are primarily economic (resulting from the natural – technical factors), then the spatial – planning ones and finally social. The evaluation is the function which is different for each concrete case and where the importance of the individual arguments changes in different cases.

In the ninth step of the methodology presented in the logic scheme, figure 1, the economic evaluation of the works defined in the step eighth is done.

It is clear that the prices in the preliminary and main design should be defined according to the conditions of the market in question, according to the working costs, material cost, equipment cost, and occupied space cost. It is recommended to form the priced bill of quantity in the form of the Microsoft Excel file is. In this way, the time used in making the priced bill of quantities for some variant solution is significantly reduced, and the accuracy of the calculation might seldom be questioned.

Such evaluation of the value of the investment aimed at sustaining the invariable conditions of exploitation at the source using the artificial aquifer enrichment method can be compared to the evaluation of the investment value of construction of the classical river water purification facility.

4. Conclusion

The methodological approach for the design of the artificial enrichment and protection of the ground water source is given through the clear algorithm. The proposed methodology is the sequence of steps enabling the designer to define the possibility of the artificial enrichment, based on the realistic engineering probability and realistically accessible database of the research work. The evaluation is based on the consideration of the possibilities of the artificial replenishment of the required quantity of water into the aquifer, defining of the technical characteristics of the facilities that would execute the replenishment, and the evaluation of the values of the finances that must be invested in the realization of the previously defined facilities for the provision of the invariable conditions of exploitation at the source. The methodology may be applied in the number of existing ground water sources which are located in the alluvia of the rivers, where the application of the artificial enrichment is necessary.

The methodology comprises a combination of the modern computer programs for production of the mathematical models of the ground water dynamics and the empirical formulae which are the consequence of the observation of the existing, already constructed systems.

Yet, all these should serve as a beginning in the process of defining the characteristics of the infiltration systems which are intended for the provision of the invariable conditions of exploitation.

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METODOLOGIJA ZA ODREĐIVANJE MOGUĆNOSTI PRIMENE VEŠTAČKOG OBOGAĆENJA IZDANI PODZEMNIH VODA

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Kroz jasan algoritam, u radu je dat metodološki pristup za pojektovanje veštačkog obogaćenja izvorišta podzemnih voda i njihove zaštite. Predložena metodologija predstavlja redosled koraka koji omogućava da se inžinjerski realno definiše ocena o mogućnosti veštačkog prihranjivanja izvorišta podzemnih voda. Metodologija se može primeniti na niz postojećih izvorišta podzemnih voda koja se nalaze u aluvijonu reka a kod kojih je nužna primena veštačkog obogaćenja. U metodologiji je izvršen spreg savremenih softverskih paketa za izradu matematičkih modela dinamike podzemnih voda i empirijskih formula nastalih praćenjem postojećih sistema.