Anthropological impacts on groundwater systems: GIS-based groundwater modelling

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Abstract The area of interest, the Volma catchment, is 20 km from Minsk, the capital of Belarus. With a growing population and economic development, the demand for groundwater was increased. Human interference in the hydrological equilibrium in the area has created undesirable side effects. To mitigate conflicts of interest and to avoid severe, and sometimes irreversible environmental effects, it is thus essential to be able to predict the reaction of aquifers, and the resources they contain, to development and exploitation. The best available tool for such an assessment is a numerical groundwater model. The principal objective of this research is to comprehensively evaluate and quantify the groundwater resources of the River Volma catchment. In addition, it is critically important to realistically determine the various options related to future development, in order to optimize utilization of the resources, whilst at the same time minimizing any detrimental environmental effects of such development. In the groundwater model solution of the Volma catchment, two approaches were applied: (a) manual trial-and-error adjustment of parameters; and (b) automated parameter estimation (PEST). The distributed finite-difference flow code (MODFLOW) selected for this study has proved to be a useful tool for creating a groundwater flow model for the study area. Such a cell-based flow code has an advantage when integration with raster-based GIS operations is required.

Keywords groundwater; MODFLOW; PEST; trial-and-error calibration; Volma, Belarus

INTRODUCTION

The groundwater resource potential of the catchment of the River Volma is very high due to the high storage capacity and good water quality. In order to meet the increasing demand for water supply, groundwater has been over-pumped by three well fields. A large part of the area was wetland. During the last 20 years, the drainage of swamps has been carried out very enthusiastically. The aim of this activity was to turn the swamps into agriculture fields. Numerous canals now cut through the region.

These activities infringed on the natural equilibrium of the region and the upper part of the River Volma became completely dry. The abstraction of groundwater from the wells and drainage lowers the water table, allows the natural recharge to increase, and causes the natural discharge to decrease. It has affected agriculture and the ecosystem in the area. Now the agriculture needs irrigation and this in turn uses water resources. Groundwater contour maps (Fig. 1 (a),(b) of the area were created from groundwater level measurements.



Fig. 1 Groundwater heads of: (a) aquifer I; (b) aquifer II.

METHODOLOGY

To mitigate conflict of interests and to avoid severe, and sometimes irreversible environmental effects, it is thus essential to be able to predict the reaction of aquifers, and the resources they contain, to development and exploitation. The best available tool for such an assessment is a numerical groundwater model. A three-layer groundwater model of the Volma catchment was created and used in combination with remote sensing/Geo-Information Systems for this purpose.

The purpose of building a conceptual model is to simplify the field problem and to organize the associated field data so that the system can be analysed more readily. Accordingly, the aquifer is assumed to be homogeneous and isotopic. Except for the groundwater recharge, all the spatially distributed data, e.g. the initial groundwater level, the top and bottom surface of the layers, the bottom of the riverbed, etc., were first mapped using GIS by digitizing point data or contour lines. Conductivity, transmissivity and vertical conductivity were mapped with GIS using the Quaternary deposits map and geological and lithological cross sections.

The conceptual model of the groundwater flow of the catchment of the River Volma consists of three units:

- the unconfined phreatic aquifer (aquifer I), which consists mainly of peat and sand,
- the (semi) confining layer, which consists of mainly loam and clay,
- the (semi) confined aquifer (aquifer II), which consists of sand with gravel.

RESULTS

In the groundwater model solution of the Volma catchment, two approaches were applied:

- manual trial-and-error adjustment of parameters;
- automated parameter estimation (PEST).

Simulated groundwater heads are presented in Fig. 2(a) and (b).

Manual trial-and-error adjustment of parameters

A priori calibration targets and criteria have been adopted based on the discrepancies between the measured and the simulated groundwater heads at the 58 groundwater observation wells.

The initial value of conductivity of the unconfined aquifer and transmissivity of each zone of the (semi) confined aquifer were adjusted. The parameters were increased when the measured heads were higher than the calculated head and decreased when the measured head was lower than the calculated heads. When the error was not decreased any further, adjustment of the parameters was paused and vertical conductivity was tried.

The results of each model execution are compared to the calibrated targets; adjustments are made to all or selected parameters, and another trial calibration is initiated. Hundreds of model runs were needed to achieve a calibration. The objective of the calibration is to minimize the difference between the measured and simulated values, sometimes called the calibration criterion.

A scatterplot of measured against simulated heads is one way of showing the calibrated fit. Deviation of points from the straight line should be as low as possible. A scatterplot may be helpful in detecting trends (e.g. heads in a portion of the model are too high). Figure 3 demonstrates that all the points lie along the regression line





(b)



Fig. 2 Simulated groundwater heads of: (a) aquifer I; (b) aquifer II, steady state conditions.



Fig. 3 Plot of simulated vs measured heads.

y = 0.9481x + 9.9439. This case would be judged a good usable relationship between h_m and h_s . The closer R^2 (the coefficient of determination) is to one, the better the regression equation "fits" the data.

Three way of expressing the average difference between simulated and measured heads are commonly used.

1. The mean error (*ME*) is the mean difference between measured heads (h_m) and simulated heads (h_s) and n is the number of calibration values:

$$ME = 1/n \sum_{i=1}^{n} (h_m - h_s)_i$$

2. The mean absolute error (*MAE*) is the mean of the absolute value of the differences in measured and simulated heads:

$$MAE = 1/n \sum_{i=1}^{n} \left| (h_m - h_s)_i \right|$$
(2)

3. The root mean squared (*RMS*) error or the standard deviation is the average of the squared differences in measured and simulated heads.

$$RMS = \left[1/n\sum_{i=1}^{n} (h_m - h_s)^2_i\right]^{0.5}$$
(3)

The three measures of error discussed above quantify the average error in the calibration: ME = -0.57; MAE = 1.36; RMS = 1.94

In the new parameter estimation, PEST, the measure of calibration error is the sum of the weighted squared residuals and is represented by (*PHI*):

$$PHI = \sum_{i=1}^{n} (h_m - h_s)^2$$
(4)

Based on the result of the manual trial-and error-calibration, the calculated sum of the squared residuals (PHI) is 217.44.

The trial-and-error procedures are time consuming, especially when the number of unknown parameters are large. The process is influenced by the modeller's expertise and biases. The modeller uses all the information about the system to evaluate its response to changes to its parameters and boundary conditions and then make decisions that eventually lead to a calibration. Moreover, accurate solution of the inverse problems cannot be found in this procedure, and different results may be obtained by different users. Therefore, it is necessary to try a more sophisticated method, hence, the author used another method of calibration, automated calibration using the new program PEST (Parameter ESTimation).

Automated parameter estimation (PEST)

In this second approach (automated parameter estimation, PEST), for the first initial parameter values for the first PEST run, the results of the manual calibration were used. A model is used to relate system properties (by optimizing leakance, conductiveity and transmissivity) to quantities (groundwater heads) that have been measured.

The certainty and reliability of the parameters' estimated values are analysed based on the resulting 95% confidence limits of each parameter, their variances and covariances from the covariance matrix, their correlation from the correlation coefficient matrix. PEST adjusts the model parameters until the fit between model outputs and field observations is optimized in the weighted least squared sense (PHI) (Fig. 4.).

The measures of the average error in the PEST calibration were:

ME = 0.14; MAE = 0.92; RMS = 1.23; PHI = 87.69.

In many respects, the automated inverse modelling method has a number of very important advantages:

- it is much faster and less frustrating than the trial and error method;
- it is objective, and information on uncertainty levels is continually available in the calibration procedure;
- the most accurate data set—the measured heads—is treated as an independent variable, and thus has the greatest influence on the accuracy of the model solution.



Fig. 4 PHI vs calibration/runs.

A trial-and error calibration may produce non-unique solutions when different combinations of parameters yield essentially the same head distribution. In PEST we avoid it by omitting highly correlated values. Solving the problem by manual trial-anderror adjustment of parameters does not give information on the degree of uncertainty in the final parameter selection, nor does it guarantee the statistically best solution.

An automated statistically based solution of the inverse problem quantifies the uncertainty in parameter estimates and gives statistically the most appropriate solutions for the given input parameters provided it is based on an appropriate statistical model of errors.

Proponents of trial-and-error calibration argue that this method uses information that is "unquantifiable", i.e. the subjective good judgement of the modeller. Detractors stress that modeller bias should be minimized by using automated methods. The truth, as usual, lies in between these two extreme viewpoints.

CONCLUSION

Three-dimensional model seems to give sufficiently accurate results to represent the real groundwater system in the study area. It can be concluded, that groundwater modelling is the key to the quantitative description of the hydrological system. Hydrological analyses were made using GIS technological support for groundwater modelling.

The groundwater model is used to understand the behaviour of groundwater systems and to predict the response of an aquifer to any external changes, or to select the best of several alternative management plans for a groundwater basin. Although groundwater models are time consuming to design and therefore expensive in terms of labour time, use of a groundwater model is the best way to make an informed analysis or prediction of the consequences of a proposed action, the aquifer response under a range of hydraulic stresses.

The harmful influence of man on the environment cannot and will not be eliminated for many decades in the future. Many activities regarded as necessary to sustain our way of life contribute to the deterioration of the environment. It is obvious that this conflict cannot be solved by forbidding all activities. Therefore, it is necessary to develop attitudes and tools reducing the adverse impact of our activities on the environment. We must hand down to future generation a better planned and a more beautiful land, and, at the same time, we must preserve the natural environment: even marshes have a charm of their own.

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