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Numerical modelling as a tool for optimisation of ground water exploitation in urban and industrial areas

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Abstract

The paper presents an approach to flow and transport modelling, which has been an important tool for the development of protection options for the important groundwater resource of the City of Ostrava in the Czech Republic. The resource is threatened by the impacts of long-term contaminant releases from a number of industrial enterprises in its neighbourhood. Due to the complex hydrogeological settings and man-made impacts, effective protection of the Nova Ves groundwater resource requires careful co-ordination of mitigation measures at individual sites.

It was proved that long-term pumping intensity (140 l/s) does not guarantee protection of the water quality. A reduction in the pumped discharge to 120 l/s was recommended. To ensure the long-term water quality in the water withdrawal area without any restriction on pumping discharge, a reduction in ammonium in the vadose zone by the 50 % would be required. However, so far, no remediation activities have been started.

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1. Introduction – numerical modelling as a tool for groundwater protection

Numerical models are means for simulating complex processes, which undoubtedly is the case of groundwater and surface water flow as well as the transport of substances dissolved in the water.

Most of numerical modelling applications within hydrogeology fall into one of the following spheres:
- Regional hydrogeological studies – calculation of the groundwater reserves, exploitable resources and their quality,
- Dealing with environmental loads – risk analyses and groundwater remediation,
- Specific applications – underground storage of spent nuclear fuel, settlement of mining hydrogeological issues, civil engineering, etc.

Numerical models are most frequently used in a predictive way. Models can predict the behaviour of the geohydrodynamic system in reaction to anticipated anthropogenic impacts (groundwater exploitation) or changes in natural conditions (the effect of droughts, floods, etc.). However, the importance of numerical modelling for hydrogeological synthesis of the area of interest is also indisputable as it allows 3D visualisation of the flow field, calculation of areal water budgets – prognosis of exploitable groundwater reserves, etc. Numerical models help us to evaluate the feasibility of our conceptual ideas and together with sensitivity analyses of models they can be used when drafting concepts of further hydrogeological prospections.

Considerable continuous groundwater withdrawals affect hydraulic conditions, groundwater reserves and sometimes also water quality within the hydrogeological structure. A characteristic feature of a regional hydrogeological structure influenced by water pumping is a gradual decrease in the groundwater level and the amount of groundwater draining to surface waters over a period of years up to tens of years. Numerical modelling has become a standard evaluation tool of all the above-mentioned impacts.

Implementation of groundwater flow models allows us to:
- Simulate groundwater flow in natural (unaffected) conditions for different variants of groundwater withdrawal. The rate of hydraulic effects on the hydrogeological structure (caused by the pumping) can be determined upon the difference between the simulated unaffected natural situation and the situation with simulated pumping. It can contribute to the prevention of conflicts of interests with other consumers or to environmental protection,
- Define the groundwater reserves in the hydrogeological structure,
- Define groundwater flow directions and velocities from infiltration zones to discharge points,
- Evaluate long-term discharge development of each groundwater resource, including evaluation of the seasonal fluctuation effect due to groundwater recharge unevenly distributed in time.

From the point of view of groundwater withdrawal operators and groundwater "regulators", a calibrated model can provide information on:
- Optimal groundwater withdrawal control in each water resource,
- Decreed pumping rate reduction (including determination of the impact of such reduction),
- The need to increase groundwater exploitation (e.g., for substitute supplies for households),
- A proposal or adjustment of the water quantity and quality monitoring in view of water resource protection,
- A proposal of groundwater protection zones,
- Dealing with emergency situations concerning groundwater quantity and quality.

When applying hydrogeological models, we encounter several model domains. The so-called holistic approach, which deals with the water system within the whole hydrological cycle, has so far only been applied for research purposes and on a relatively local scale. Such approaches are demanding both in terms of calculation time and with respect to the complexity of the input parameters. That is why most applications concentrate on dealing either with merely subsurface water (saturated flow, unsaturated or variably saturated flow) or surface water. It implies the necessity to determine the boundaries of the so-called model domain and the boundary conditions (often not within the natural boundaries) defining the exchange of mass and energy with the surrounding systems. The model domain should optimally cover the whole hydrogeological structure and therefore make the description of the hydrogeological boundary conditions realistic. Complex simulation of the system's behaviour then still requires a combination of various types of hydrological and hydrogeological models. A problem can lie in the fact that hydrogeological structures usually differ from watercourse catchment areas in terms of their area.

Groundwater flow models are based on a synthesis of information on geology, hydrogeology, hydrology, climatology and geography. The requirements for the input data and the skills of the "modellers" to critically assess and process the model inputs are the key limits to the successful application of numerical models.

The inputs of numerical models for groundwater flow and mass transport are the following data types:

- Hydrogeological and geometric information – thickness, area and limits of aquifers, aquicludes, aquitards, delineation of boundary conditions,
- Hydrological information – especially information on total runoff, baseflow and long-term precipitation average,
- Hydraulic characteristics – resistance and capacity parameters characterising the model domain (coefficients of hydraulic conductivity, storativity) including their spatial variability,
- Spatial distribution (horizontal and vertical) of pressure conditions in the model domain derived upon the measuring of groundwater levels,
- Data on the spatial distribution of selected substance concentrations and data on the potential sources of these substances (contamination sources),
- Parameters of transport processes [1] –dispersivity, distribution coefficients (sorption), reaction rates etc.

The quality and amount of the input data significantly affect the reliability of the simulation's results. When simulating natural systems; the most common goal is to create a model which is sufficiently capable of predicting future situations caused by natural changes in hydrological and climatic conditions or by anthropogenic intervention. In the optimal case, the model inputs should be measured directly in situ (including their variability). However, in actual situations, it is rather the outputs of the model solution (groundwater levels, substance concentration in groundwater) than the inputs that can be measured. The fitting of model outputs and measured values is achieved by model calibration [2] where the set of input parameters is found in order to produce model outputs complying with reality (measurements) at the required level. Only a calibrated model can be used for a qualified prediction of the system response in conditions which have not occurred yet but which can potentially appear (substantial increase in groundwater withdrawal, distribution of pumping wells, decreased supply of groundwater as a result of extreme droughts, etc.).

2. Case study – optimization of the protection of the Nova Ves water withdrawal area using numerical groundwater flow and mass transport modelling

The Nova Ves wellfield, with a capacity of up to 240 l/s, is the only significant groundwater resource available to the city of Ostrava, with a population of 300,000. This drinking water resource is endangered by the impacts of long-term groundwater pollution from a number of industrial enterprises located within its recharge area. Apart from that, there is contamination by sulphates released from the mine waste rock that has been widely used for terrain levelling.

Forced by environmental authorities, all industrial enterprises have implemented measures to stop further contaminant releases. Nevertheless, existing soil and groundwater pollution originating from past long-term activities remains a threat for the groundwater extraction wellfield. The protection zone that has been declared around the Nova Ves resource does not cover the whole water resource capture zone. The zone was delimited more with respect to preventing the origin of new pollution sources within the drawdown cone than with respect to existing industrial enterprises that had been established before groundwater extraction began.

The problem was investigated for years within various national projects financed by the Ministry of the Environment – risk assessments, feasibility studies, and an international DANCE project paid for by the Danish Ministry of the Environment [3 to 8]. A substantial budget would be needed to remediate the pollution but so far that has not been available. Therefore, protection of the well field is mainly based on passive protection measure sand by means of optimised groundwater management using numerical models.

The Nova Ves wellfield is located in the Odra River plain, in an area where a deep and narrow subglacial erosion channel with permeable sedimentary fill runs below the alluvial gravel aquifer, forming one hydrogeological unit. The Odra River is the natural drainage base of a larger territory. Fig. 1 facilitates a basic understanding of the geological settings.

Drawdown from the wellfield spreads preferentially along a paleochannel course causing the descent of groundwater from the overlying alluvial river plain into it. A substantial portion of the resource withdrawal rate comes from induced river recharge A smaller contribution is represented by groundwater infiltrating to the river plain from the adjacent upper terrace, and recharge from precipitation.

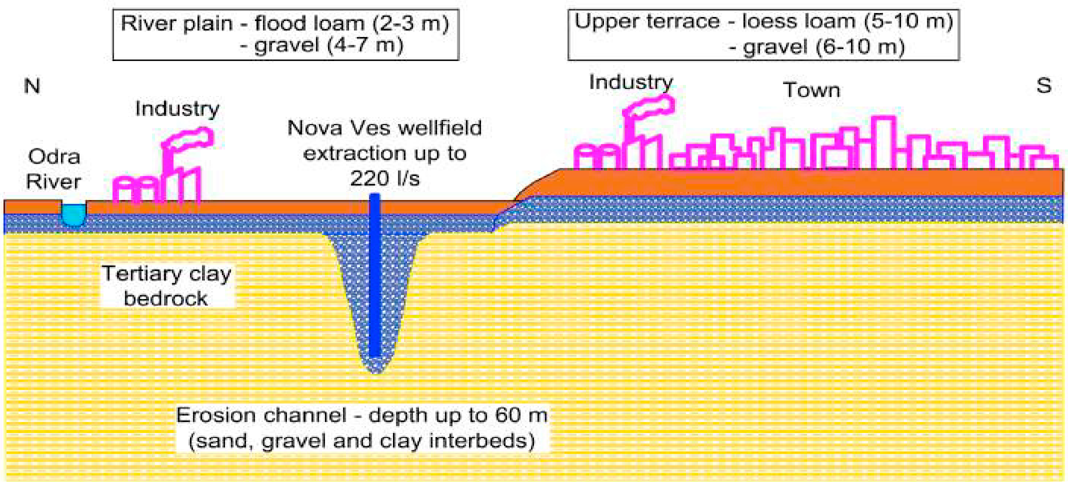


Fig. 1. Ostrava-Nova Ves groundwater resource – idealized cross-section

Unconfined conditions are developed in the river plain aquifer within wellfield depression cone. The upper terrace aquifer is naturally unconfined in its whole extent. There are also mine waste rock dumps and widespread terrain levelling covers formed by the same material. Shallow (often periodical) groundwater bodies have developed in them.

The Nova Ves groundwater resource is endangered by contamination flux from pollution sources located both on the alluvial river plain and the adjacent upper terrace. Figure 1b presents a scheme of the domain with the location and character of pollution sources.

From the area of the Odra River plain, the Nova Ves drinking water resource is threatened by the migration of ammonia and sulphate ions. They migrate from pollution sources from the North towards the wellfield preferentially through the erosion channel with permeable sedimentary fill below the river plain aquifer. The ammonia ions pollution is caused by two industrial enterprises – by the chemical plant BC-MCHZ and the KJS Cokery plant – which are located north of the wellfield, just above the erosion channel. Groundwater pollution from both neighbouring plants forms one merged plume where local hot spot concentrations of NH_4^+ reach hundreds to thousands of mg/l.

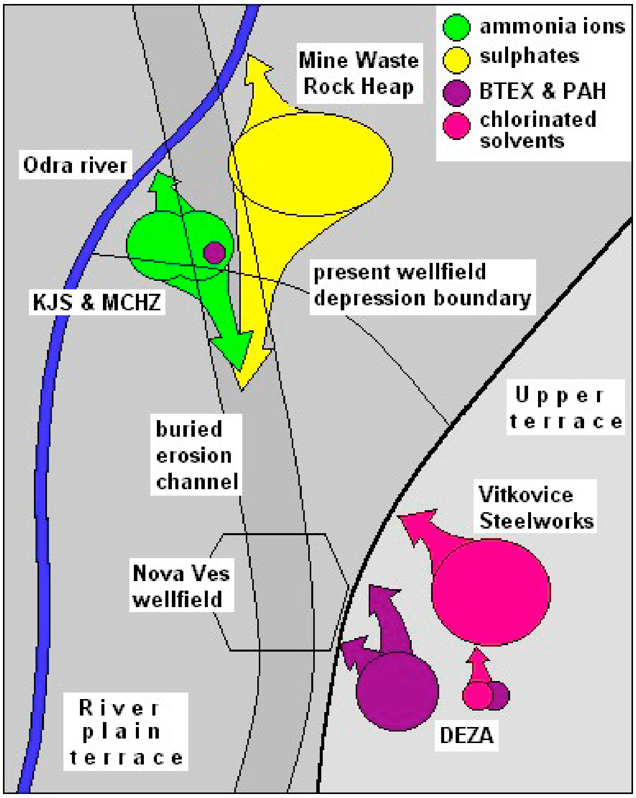


Fig. 2 Ostrava-Nova Ves groundwater resource – situation scheme

Sulphate pollution has also been traditionally attributed to the BC-MCHZ and KJS Cokery plants. Newer findings have revealed that these plants are only contributors to this type of pollution. Carboniferous waste rock forming huge mine tailings heaps and extensive terrain levelling covers was addressed as the principal source of sulphate pollution in the Odra River plain north of the Nova Ves wellfield. Sulphates are released by weathering of the pyrite contained in that material. There are locations where concentrations of sulphates in groundwater reach thousands of mg/l. In some exploitation wells of the Nova Ves wellfield, sulphate concentrations are well over drinking water limits (DWL 250 mg/l). According to records from the beginning of the 20th century, the average SO_4^{-2} content was about 70 mg/l at that time.

Waste rock has been present here for more than one hundred years. It is a crucial question whether the sulphate releasing potential of waste rock is past its maximum or not. A special study including column leaching tests and some field groundwater sampling was carried out to assess – at least qualitatively – this problem.

In practice, the sulphate leaching process is mainly governed by the availability of oxygen and percolating water and by the presence of other rock minerals with buffering capabilities. It has been confirmed that the sulphate producing potential of the waste rock is enormous and far from being exhausted. Sulphate concentrations in groundwater beneath the waste rock heaps are lower than theoretical level of saturation which could be about 240 g/l. Evidently, the leaching process is running well below its potential maximum intensity, and the transfer of sulphates to the groundwater must be steady-state for a long time already. It can continue for many tens of years under these conditions.

The two industrial plants are also sources of organic pollution (benzene at BC-MCHZ and BTEX, phenols and PAHs at KJS Cokery). It has been quite well documented by long-term monitoring that organic pollution at the MCHZ & KJS sites remains stabilised within the source areas and only a very limited descent down to greater depths of the paleochannel can be observed. Regarding the age of the pollution sources (certainly many tens, maybe one hundred years old), it can be explained by intensive attenuation processes with an important contribution of natural biodegradation.

The principal threat to the Nova Ves groundwater resource from the upper terrace is represented by the DEZA site (Fig. 2), where heavy pollution exists both within the vadose zone and groundwater saturated zone. This pollution has been caused by long-term operation of a coal tar distillation plant which was active in the past. The outflow concentrations of pollutants from the upper terrace were taken as inflow data for the river plain model. This is a worst-case approach – in reality, only part of the groundwater descending from the upper terrace directly enters the alluvial plain aquifer while some of it discharges as springs at the foot of the upper terrace, where as volatile pollutants can escape into the atmosphere.

Organic pollutants – namely BTEX and PAHs – including free phases from the DEZA site, are presently the primary threat to the Nova Ves groundwater resource. The pollution outflow from the DEZA site is controlled mainly by the relief of the impermeable pre-quaternary bedrock.

3. Proposed protection measures based on the application of numerical modelling

Groundwater transport modelling was an important tool for the development of the proposal for protection measures. They were based on an evaluation of the present groundwater pollution on its migration pathways to the wellfield and on the prediction of its future fate and impacts.

The application of numerical modelling (MODFLOW [10], MODPATH [11], MT3D [12]) was performed in several stages.

Stage 1/ Introductory flow and transport modelling focussing on the Odra River fluvial plain terrace, including:

- Identification and quantification of pollution sources, prediction of the level of threat to the groundwater resource, testing of protection alternatives (with the emphasis on possible passive protection measures),
- Identification of information gaps, uncertainties,
- Specification of tasks and problems to be resolved during the following stages of modelling.

Stage 2/ Validation of the fluvial plain hydraulic model on the second measured data set.

Stage 3/ Further development of the transport model based on the results of a new sampling and drilling campaign, including:

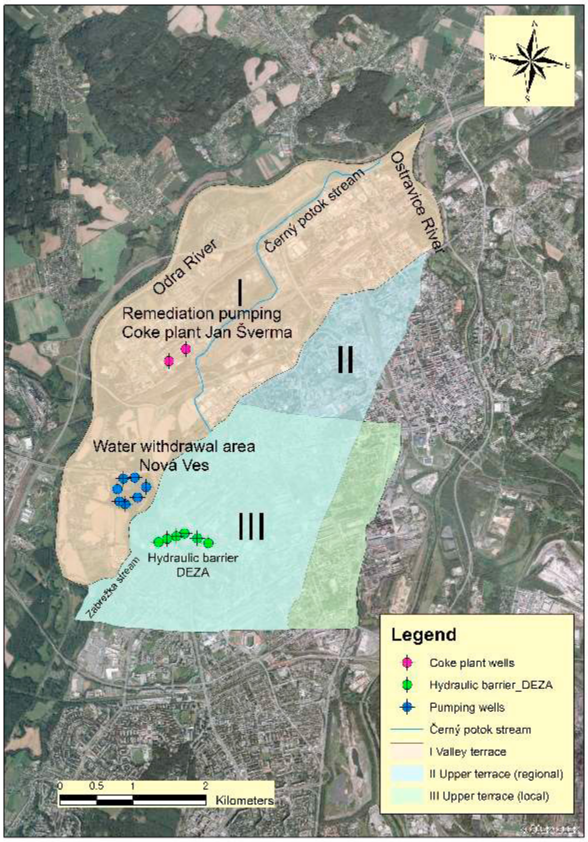
- Development of the fluvial plain terrace transport model (inclusion of a reaction package),
- Setting up a model of the upper terrace connected with the fluvial plain terrace model by the common boundary condition,
- Testing of the pollution input from the upper terrace (DEZA chemical plant), remediation alternatives.

Stage 4/ Development of criteria for a co-ordinated approach to protecting the Nova Ves groundwater resource, including:

- Proposal and testing of mitigation alternatives,
- Alternative proposal fora monitoring system.

The location of the model domains is presented in Figure 3a.

The project was based on the consistent exploitation of existing data. Gathering of a large amount of materials and information about the geological and hydrogeological conditions of the area concerned, including hydrodynamic tests carried out, preceded the setting up of the numerical models. A geological database containing information on1898 boreholes was setup. The database also contains information on results from soil and groundwater sampling that have been carried out within various projects assessing soil and groundwater pollution sources.



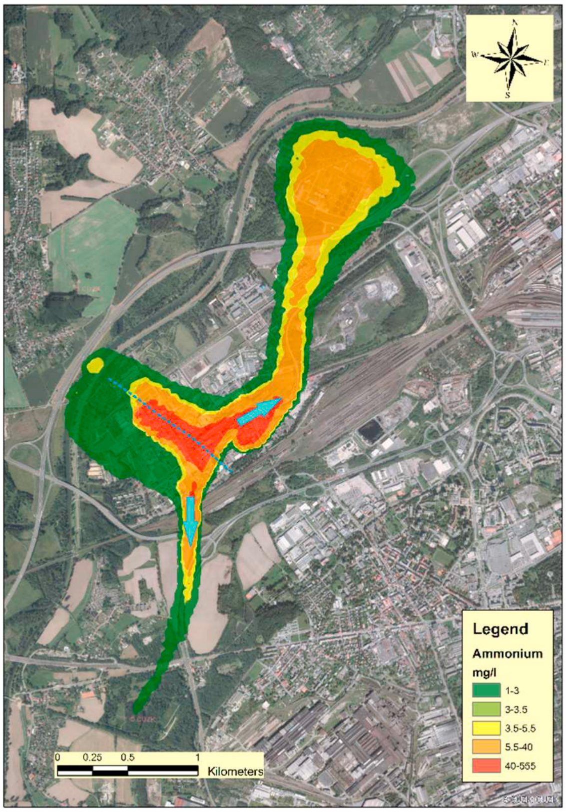


Fig. 3. (a) Numerical model domains; (b) simulated plume of ammonia in groundwater (arrows - groundwater flow direction, dashed line – position of groundwater divide), background aerial image CUZAK

All performed simulations fall within one of the following three groups:

- Simulations of passive protection of the Ostrava-Nova Ves drinking water withdrawal area in the form of controlled pumping. This method causes a restriction in the possible capacity of the water resource. It was proved that long-term pumping intensity (140 l/s) does not guarantee protection of the water quality (Fig. 3b). A reduction in the pumped discharge to 120 l/s was recommended and this solution would potentially affect remediation activities of point sources of pollution.
- Simulations of a reduction in pollution sources in the vadose zone with regard to the maximum possible pumping intensity in the water withdrawal area (240 l/s). To ensure the long-term water quality in the water withdrawal area without any restriction on pumping discharge, a reduction in ammonium in the vadose zone by the 50 % would be required. However, so far, no remediation activities have been started.
- Simulation of the option of ceasing pumping in the wellfield. There are worries regarding the impacts of a rise in the groundwater level to the original level, which is unknown and had to be simulated. Residential areas and industrial enterprises have been built without respect to the original natural groundwater level. The situation is complicated by terrain subsidence caused by former mining activities. A combination of methods of numerical modelling and spatial analyses in ArcGIS based on a digital terrain model, cadastral maps and field recognition brought concrete solutions – a design of preventive hydraulic measures to prevent flooding of the terrain [5].

Great attention was paid to validation of the model with respect to uncertainties connected with the fate of contaminants. Principally, high-end and low-end solutions were developed to provide margins of risk issuing from pollution migration. The project results are a solid foundation for the implementation of measures to protect the only groundwater resource for this town of300,000 inhabitants.

4. Conclusions

Numerical modelling of hydrogeological processes is a demanding interdisciplinary task. Though the irreplaceability of numerical models when dealing with complex issues in difficult hydrogeological conditions is indisputable, their successful application is conditioned by several factors on the side of the "modellers" hydrogeologists and hydrologists, as well as the clients (managers). Modellers shall pay attention to the formulation of the correct conceptual model (with good knowledge of the location), the choice of suitable software (or the governing equation describing physical and chemical processes) and to the definition of the simplifying presumptions on which the model solution is based. Attention shall be paid to model calibration (water level and budget criterion) and uncertainty analysis. This way, clients' disillusionment can be prevented as in some cases they can feel that their expectations are not being met.

On the side of the clients, knowledge of the requirements of hydrogeological models and of input data is beneficial as it can be reflected as early as in the survey phase. It is also beneficial for mutual communication between the two groups when the professional community is familiar with the possibilities (but also restrictions) of numerical modelling, which results in the realistic assignment of the modelling goals.

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