Groundwater Resources and Their Protective Zones

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Abstract

The revision of protective zones of water resources based on recent Czech legislation is intended on the complex and diversified water resources protection according to the character of the water source, natural conditions and the degree of exposure of the water resource.

The mathematical modelling is essential part of hydrogeological studies and groundwater resources protective zones revision and proclamation. Two-dimensional models are frequently applied for the groundwater flow modelling at Quaternary geological formations - namely in highly permeable gravel sands.

In the paper, modelling techniques used at the revision of groundwater resources protective zones are briefly described. Lot of practical applications of the design of groundwater resources protective zones performed during the last decade in the Czech Republic are mentioned in the text.

As the conclusion it can be stated, that the extent of the majority of original - former protective zones was overestimated and could be reasonably reduced. The reduction of the protective zones area is site specific and varies from 20 % to 60 %. The reduction of the extent of protection zones will reduce compensation expenses due to restrictions in the use of protected area and it could influence trends of potable water cost.

Keywords: Groundwater Resources, Mathematical Modelling, Protective Zones

Introduction

Both the old Czech Water Law No. 138/1973 and the new one No. 241/2001 divide the water protection into common and a special one. While common water protection relates to the common surface and subsurface water use, special protection deals with progressive measures serving to the protection of regions with natural water accumulation, protection of water sources, and water supply streams and their catchment. The recent revisions of groundwater resources protective zones are based on the complex groundwater resources protection according to the character of water source, natural conditions and the degree of exposure of the water resource.

Special protection of existing and anticipated water sources is focused on their yield, water quality and health assurance. The measures are proclaimed protection zones with established conditions for activities influencing the yield and quality of water protected.

In the past, the protection of groundwater resources was ensured by protection zones of 1st and 2nd order. The 2nd order zones were divided into the inner and outer sub-zones.

The 1st order zone was designed as the area around the groundwater source (well, collecting gallery, etc.) to the distance 10 to 50 m from the water intake equipment. This zone is equipped by the fence, the land surface is treated and grassed.

The inner part of the 2nd order zone was restricted by the 50 day retention time of groundwater in the aquifer, but at least 50 m distance from the source. Within this zone, all activities potentially endangering water quality are forbidden. All sump tanks has to be removed, wastewater treatment plants, sludge pits, cemeteries, landfills and other pollution sources are forbidden. The area must be protected against flooding and seepage of polluted water, excavation and mining of soil, gravel, sand or peat, establishing of stone quarries, campsites, car washes and parking places are prohibited. Similar restrictions are hold within the outer protection zone of the 2nd order, which comprises entire infiltration region.

The new approaches change these formal regulations into:

- the complex protection of each water resource, which needs special protection;
- the protection diversified according to local conditions and variability of conditions.

The owner of the groundwater resource (water supply company) is obliged to bear all expenses referring to land use restrictions and financial losses. This should result in:

- consistent evaluation of effectiveness of restrictions prescribed;
- reduction of the area with special groundwater protection regime;
- keeping effectively prescribed conditions for activities within protective zones.

At the protection zones design or revision, more individual approach is emphasised based on risk assessment, assembly of GIS maps of hazard, vulnerability and risk. The following text comprises the method of the revision of existing groundwater protection zones using the groundwater flow modelling and risk based techniques.

Principles at the design of groundwater resources protection zones

At present considerable number of groundwater resources protection zones in the Czech Republic are being revised. The majority of groundwater protection zones of the 1st order are satisfactory by their extent and contemporary management.

The objects of the revision are particularly existing protection zones of the 2nd order proclaimed in the past on the basis of older legislation (1979). Resulting revised - improved extent of the protective zone of the 2nd order according to new legislative demands can be discontinuous area including both the groundwater source and the infiltration region. At the same time the design should be based on individual approach, risk assessment and vulnerability analysis. The integral part of the studies are mathematical groundwater flow and pollution models. The boundary of the groundwater sources protective zones of the 2nd order (groundwater withdrawal area) must be completed with regard to boundaries of individual plots and pieces of land with respect to existing and planned land use and ownership.

The revision issues from the experience gained at previous hydrogeological prospecting of groundwater withdrawal areas. The objects of the revision are also gravel pits donated by groundwater.

The content and composition of documentation for protective zones design

At the revision and design of groundwater source protective zones it is necessary to comprehend all important facts influencing groundwater quantity and quality at the catchment area. Therefore the design of protective zones of groundwater sources includes following activities:

- Summary and analysis of hydrogeological data.
- Groundwater flow and pollution modelling.
- Final design of the borders of protective zones considering land owner rights and all activities within the protective zone (urbanisation, sewerage, industry, agriculture, transport, etc.).

The summary of hydrogeological data consists of:

- *the report* containing basic data about the water captation structure, area of interest including potential pollution sources, physical-geographical and geomorphologic conditions, precipitation and hydrological, geological and hydrogeological conditions, present extent of protective zone, etc.
- *the graphical and tabular appendices*, which should contain basic water management map, hydrogeological map, map of thickness and type of impervious topsoil layers, basic map with boreholes and wells and interpreted piezometric contours and potential groundwater pollution sources, geological profiles, geological and technical documentation of wells and other hydrologic and hydrogeologic boreholes, technical documentation of public and private wells, etc.

The part of hydrogeological basic data are long-term groundwater table and surface water level and quality observations at corresponding catchment area. Hydrogeological data serve as a basis for mathematical model and its calibration.

Mathematical modelling of groundwater flow at Quaternary formations

The purpose of the modelling

At the design of groundwater sources protection zone of the 2nd order it is necessary to analyse following factors influencing the extent and location of the protective zone:

a) area exploitation and possible sources of risk (urbanisation, industrial and agricultural production);
b) terrain geomorphology, especially trajectories of surface runoff;
c) land surface, type of plots and vegetation influencing surface water infiltration;
d) thickness and type of impervious topsoil layers - aquifer isolator;
e) groundwater flow direction and inflow of water to the aquifer (infiltration, bank infiltration) with respect to water draw-off;
f) groundwater retention time at the aquifer.

Mathematical model

Mathematical model of groundwater flow at extensive Quaternary aquifers issues from two dimensional approximation of the saturated groundwater flow in almost horizontal aquifer (Dupuit theory). The governing equation of unsteady 2D flow at *x-y* plane issues from the mass conservation law completed with Darcy equation:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial H}{\partial y}\right)-S\frac{\partial H}{\partial t}=Q\,, \tag{1}$$

where S is aquifer storage coefficient, Q is the source (sink) representing pumping from wells and T_x and T_y are transmissivity coefficients defined as follows:

$$T_x(x,y,t) = k_x(x,y)\ .\ h(x,y,t), \tag{2a}$$

$$T_y(x,y,t) = k_y(x,y)\ .\ h(x,y,t), \tag{2b}$$

h is thickness of aquifer. *Initial condition* prescribes known initial piezometric head H_0 at the entire flow domain Ω:

$$H(x,y,0) = H_0(x,y). \tag{3}$$

Boundary conditions are as follows:

- Dirichlet condition prescribed along the boundary Γ_1 with known piezometric head:

$$H(x,y,t)/\Gamma_1=\overline{H}(x,y,t)\,; \tag{4}$$

- Neumann condition prescribed along the boundary Γ_2:

$$T_x\frac{\partial H}{\partial x}n_x+T_y\frac{\partial H}{\partial y}n_y=q_n\,, \tag{5}$$

where $\overline{H}$ is known piezometric head, n_x and n_y are direction cosines of outer normal to the boundary Γ_2 and $q_n(x,y,t)$ is known value of specific discharge through the boundary Γ_2.

For the numerical solution of the problem the finite elements method is frequently used.

Model calibration and verification

Calibration and verification plays an important role at the application of mathematical models. In case of approximately horizontal aquifer, the measured variables are piezometric head (water table). Calibrated model parameters are hydraulic conductivity (transmissivity), storage coefficients and location and values of boundary conditions (piezometric head H, groundwater flow q_n across the boundary), sometimes the calibrated phenomena is also accurate pumping from individual wells. The method of calibration can be carried out by both trial-and-error method and method of inversion optimisation. The calibration, which in case of large flow domain in natural conditions is usually very complex, is based on knowledge and experience of the staff and is carried out by the trial-and-error method.

For model calibration both historical and present records of corresponding pumping scenarios and observed levels in trial boreholes should be used. In some cases, results of observation of natural state and of pumping tests are available (Figure 1).

Model verification should be performed using different sets of measured data than that used for the model calibration.

The important fact is that in practice no time series of pumped amount, observed piezometric heads and other variables (e.g. boundary conditions) are normally available. Therefore, when there is no chance to calibrate transient flow models, steady flow models are usually applied. The modelling scenarios are selected with the aim to ensure the safety and minimum risk of groundwater source contamination. Regarding the critical time delay of groundwater in aquifer, dry periods with drawdowned water table in combination with maximum permitted groundwater pumped amounts seem to be the most unfavourable conditions.

Scenarios solved

At the solution variable pumping from individual wells is necessary to be assessed together with the fluctuation of boundary conditions. Scenarios modelled therefore deal with existing pumping, pumping permitted by local authorities respectively future presumed groundwater pumping. The solution usually comprises following scenarios:

- Assessment of natural state without pumping.
- Pumping at existing conditions, i.e. known pumped discharges and observed water table in boreholes. These scenarios serve for model calibration and verification.
- Solution of variants dealing with average and maximum permitted yields from individual wells.

Evaluation of survey and modelling results

The land use and potential risk sources

During the protective zone design, the site investigation of historical, present and future groundwater pollution sources is necessary. Pollution sources are identified according to their location, type of pollutant, and magnitude. They are interpreted in the separate thematic GIS layer (Fig. 2).

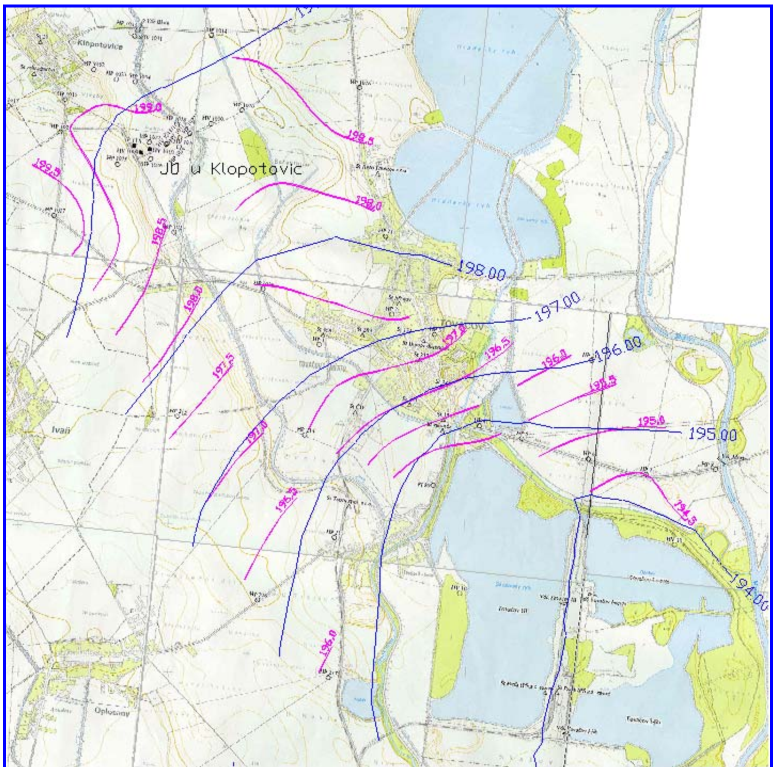

Fig.1 Model calibration for the protection zone of 2nd order at Tovacov

Terrain geomorphology, surface runoff, thickness of impervious topsoil layer

The influence of the terrain relief and paths of surface runoff (local water courses and melioration ditches) should be assessed in the context with the thickness of impervious topsoil layers and its permeability. The assessment is based on the definition of aquifer vulnerability. The topsoil permeability and thickness are classified using scores, lower permeability has lower score and lower thickness is classified by higher values (see Tables 1 and 2).

Table 1 Classification of topsoil permeability

Soil classification	Score
Clay	0.2
Clayey loam	0.5
Loam	1.0
Sandy loam	1.8
Loamy sand	4.5
Sand	9.5

Table 2 Classification of topsoil thickness

Topsoil thickness [m]	Score
0.10 - 0.29	12
0.30 - 0.59	6
0.60 - 1.19	3
1.20 and more	1

The aquifer vulnerability ratio can be defined as the product of both scores. The verbal valuation of vulnerability with measures recommended are shown in Table 3.

Firstly the vulnerability map is developed using GIS techniques. Thereafter the vulnerability is compared with the hazard factors at the area like the pollution sources, surface water courses, petrol station locations and other factors.

Table 3 Classification of vulnerability and recommended measures

Product of scores	Vulnerability	Vulnerability class	Measures
0.00 - 0.99	very low	1	common land management practices
1.00 - 2.99	low	2	
3.00 - 5.99	medium	3	organizational, economical and agrotechnical measures
6.00 - 11.99	high	4	
12.00 - 23.99	very high	5	grassing or forestation
24.00 and more	extremely high	6	

Flow direction and groundwater inflow to the aquifer

Basic idea about flow directions, groundwater table gradient and inflow to the aquifer is obtained by hydrogeological prospecting. Additional more accurate information is provided by the model calibration and simulation of scenarios chosen. Within this step, it is necessary to specify possible infiltration regions and their probable influence on groundwater withdrawal facilities and groundwater quality.

Groundwater retention time in the aquifer

One of the basic information at the design of an extent of protective zone is the groundwater retention time in the aquifer. The part of the modelling is the construction of groundwater retention time isochrones characterizing time delay of groundwater before its captation from the aquifer (see Fig. 2). The isochrones are evaluated for individual modelling scenarios. In Table 4, the requirements for the extent of groundwater protective zones from various countries are shown.

Data mentioned in Table 4 show that the methods of design and requirements for the extent of groundwater protective zones are not unified and significantly differ at individual countries. With respect to slowly degradable contaminants, it is usually recommended to ensure time delay corresponding to 300 to 500 days.

Risk maps

Risk maps should make possible interpretation of:

- aquifer vulnerability - thickness of impervious topsoil layers - aquifer isolator (Fig. 2);
- hazard factors - potential pollution sources, isochrones of time delay (Fig. 2),
- land use;
- hydrodynamics of an aquifer at various withdrawal scenarios;
- groundwater retention time in an aquifer.

Based on the risk map, the design of the groundwater protection zone boundary is carried out. In practice, the use of GIS is strongly recommended.

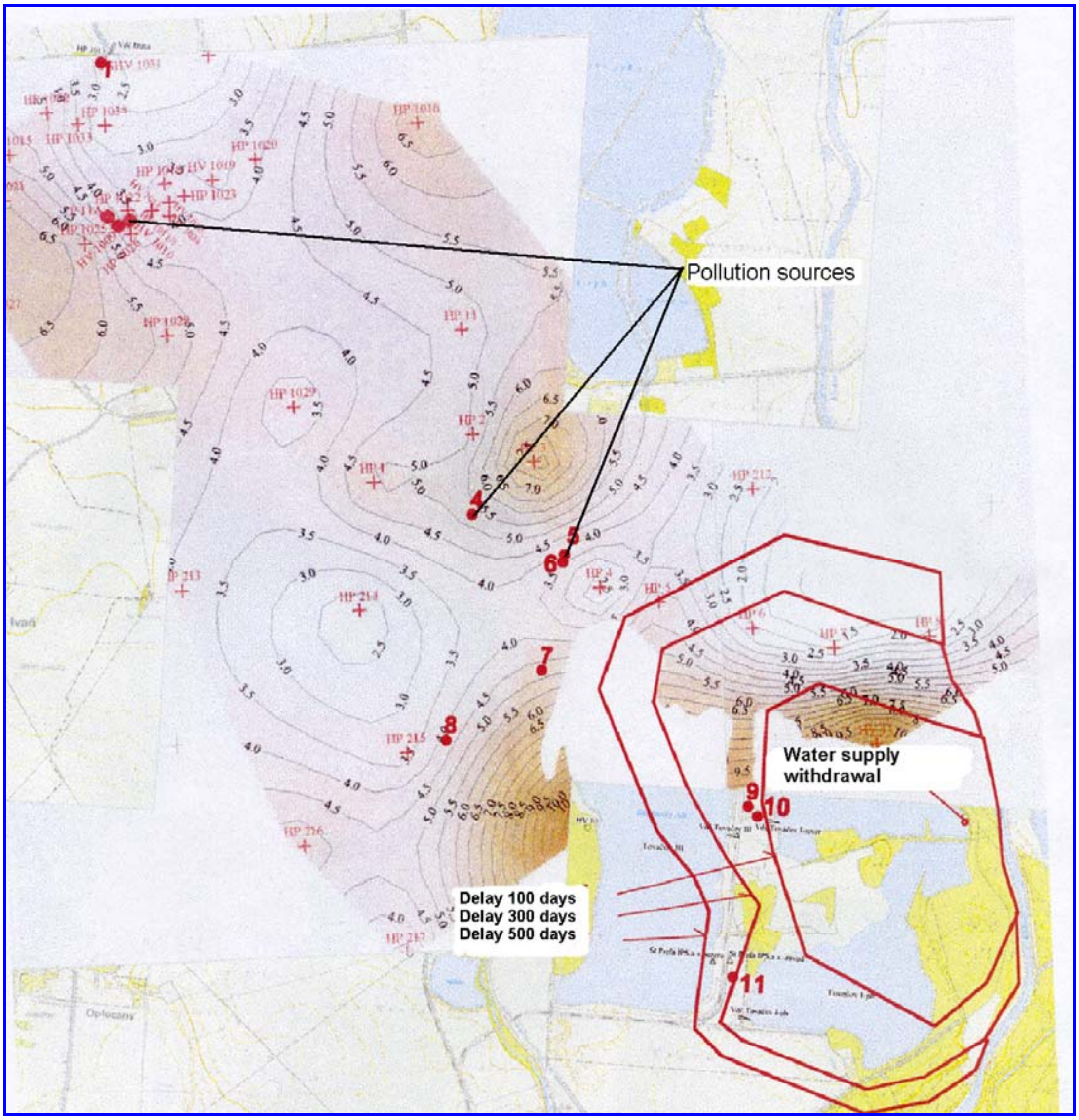

Fig. 2 Example of the hazard and vulnerability map

Tab. 4 - Basic requirements for groundwater protective zones

Country	Protective zone of the 1st order	Protective zone of the 2nd order
the Netherlands	retention time from 60 days to 1 year	retention time 10 years
Germany	10 m from well, 20 m up the stream	retention time 50 days, resp. distance 300 m from wells
Switzerland	retention time 10 days	min. 2 times distance of 1st zone
England, Wales	retention time 50 days, min. distance 50 m	retention time 400 days
Ireland	min. distance 10 m	retention time 100 days, min. distance 1,000 m when insufficient amount of data
Spain	retention time min. 24 hours, min. area from 100 to 400 m^2	retention time 50 - 60 days
USA (Wash.)	retention time 1 year	retention time 5 years

Practical applications

The method described was practically applied at the revision and setting of protective zones of the 2nd order of about 30 groundwater withdrawal areas located at the floodplain Quaternary sediments in the Czech Republic. These areas represent important sources of potable water for almost half of million inhabitants, corresponding to maximum yield bigger than 1 000 l/s.

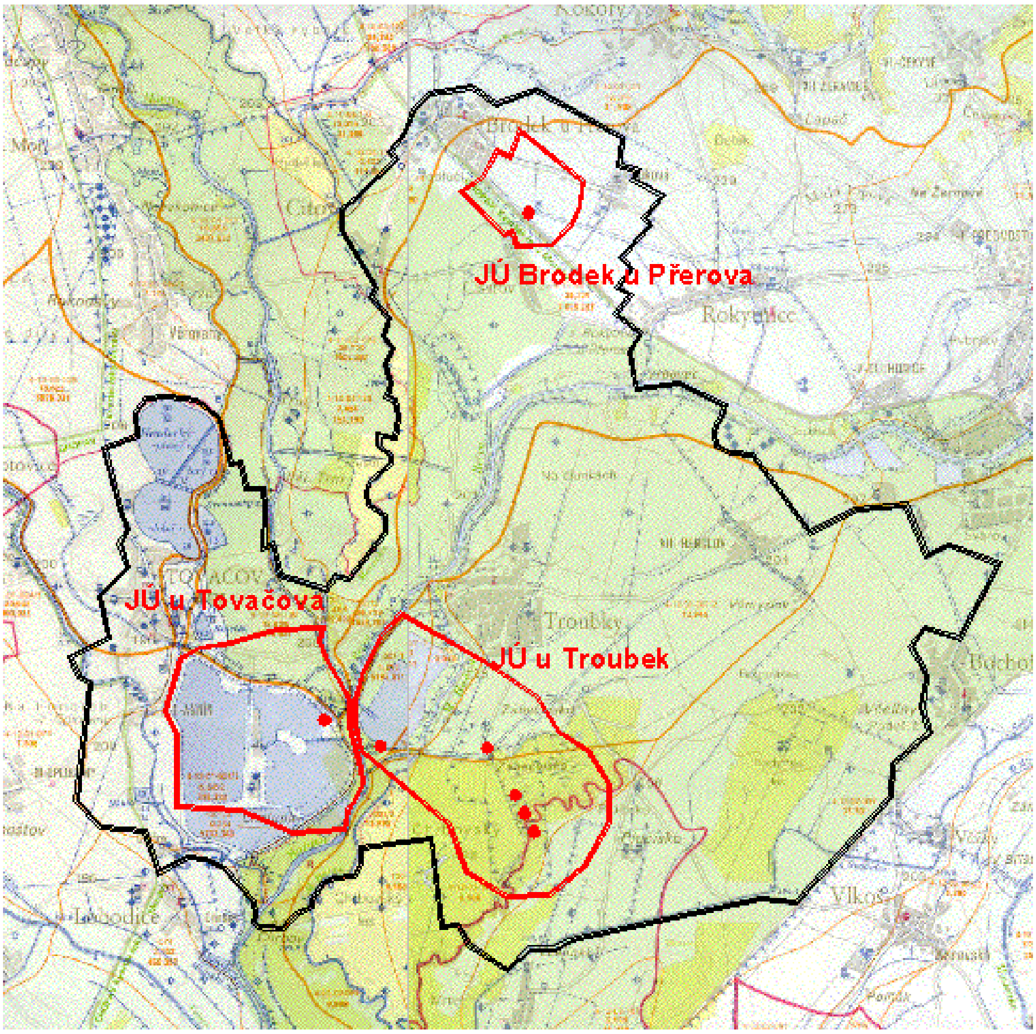

Fig. 3 Example of the revision of protective zones of 2nd order – comparison of original extent (outer thick line) of the zone with newly designed ones (three sub-zones inside the original zone)

Conclusions

The results of the mathematical modelling and GIS risk based techniques were used at the design and revision of protective zones of 2nd order of groundwater withdrawal areas. The revision of the extent of protective zones mentioned, was carried out in context with legislative changes in the Czech Republic. It can be stated that practically in all cases the surface area of protective zones was reduced by 20% to 60% (see example Fig. 3) according to local conditions. After the final completion and the design of the location of the protective zone boundary with respect to the land-owner property rights, restriction of activities within the protective zone etc., the measures can cause the decrease of financial expenses of water works companies for potable water production. Finally it can significantly influence the cost of potable water for public use.

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