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Cost-effective measures to control and contain groundwater contamination

title: **Groundwater extraction control for protecting the water works in Lobodno (SW Poland) against contamination with nitrates**

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INTRODUCTION

The water works in Lobodno (5 deep wells with the total admissible discharge rate of 820 m^3/h) is extracting potable water for the population of the city of Czestochowa and neighbouring communes (S-W Poland) from the fracture-karst upper Jurassic Major Groundwater Basin (MGWB 326). The yield of the MGWB 326 is sufficient to meet all needs, so no licensing conflicts arise on amounts of water available for safe exploitation. However, the recharge areas of deeper and shallow phreatic aquifers are vulnerable to contamination from industrial emissions, point sources (landfills and farms) and the contaminated Warta River. Stationary monitoring of groundwater quality in 1996-1997 showed a constant increase of nitrate ions (NO_3^-) concentrations in the recharge areas of this water works, and their abrupt increase in the extracted groundwater from 28.8 to 38.8 mg NO_3/dm^3 (well no. 3), and from 18.5 to 38.9 mg NO_3/dm^3 (well no. 8). Already in 2001, these concentrations exceeded the permissible value for potable water of 50 mg NO_3/dm^3 (Dz.U.2007.61.417), and in 2008 the mean annual concentrations in the extracted water were as high as 61.42 and 60.7 mg NO_3/dm^3, respectively. Keeping up this trend, which is predicted by mathematical modeling, may lead in the worst case to exclusion of wells from operation and/or the need for applying groundwater treatment, as it is already the case in another water works operated by the Water Supply and Sewerage Company (PWiK) in Czestochowa (Malina - submitted).

The main goal of this research was to reverse, or at least stop this trend in order to protect the water works in Lobodno using a specifically designed water extraction regime. Such a hydraulic control of groundwater flow conditions should not only protect the wells against contamination with NO_3^- but reduce the contamination loads in the aquifer as well.

HYDROGEOLOGY

Groundwater in this area is connected to rock formations varying in age that compose the Quaternary, Jurassic, Cretaceous and Triassic multi-aquifer formations (Malina *et al*. 2007). The Warta River, which cuts outcrops of the upper Jurassic formations, often changes its character from draining to infiltrating. The Jurassic multi-aquifer formation consists of upper, middle and lower Jurassic water-bearing horizons. The upper Jurassic horizon is built of fissured and karst limestone, with preferential groundwater flow paths and good recharge conditions. It is drained by watercourses, with a part of underground runoff crossing Cretaceous outcrops and recharging this formation. Under natural conditions, groundwater quality is high, fully corresponding to drinking water standards, thus the upper Jurassic horizon (MGWB 326) is the main source of potable water. However, considering the zones of hydraulic contacts with surface and watercourses, the water is particularly vulnerable to contamination. The middle Jurassic horizon includes three formations of sandy and sandy-gravel deposits. Silt and clayey rocks isolate the aquifers, and groundwater table is confined except the outcrops. The recharge is via outcrops and groundwater flow is in the northeast direction. The lower Jurassic horizon is built of a number of sandy-sandstone strata, separated by silt-shale deposits. Groundwater table outside outcrops is confined, and preferable hydrogeological parameters are in the bottom passages of the horizon.

The MGWB 326 is symbolically divided (with the Warta River as a natural border) into two sub-basins: MGWB 326 (S) - with the area of 170 km^2 and documented and approved disposable water resources of 4,220 m^3/h (additional 30,000 m^3/d documented for a perspective water intake in Julianka) (Malina *et al*. 2007), and MGWB 326 (N) - with the area of 570 km^2 and documented and approved disposable water resources of 8,900 m^3/h. In the studied area two groundwater bodies (GWB) no. 94 and 95 were distinguished. The former encompasses lower and middle, while the latter – upper Jurassic groundwater horizons (Paczyński, Sadurski, 2007).

METHODS

The operation strategy of the water works in Lobodno was developed in such a way that, by creating appropriate hydrogeological conditions (required groundwater flow directions forced by controlled well discharge rates), water resources could be protected, as well as NO_3^- concentrations in water delivered to clients kept below the permissible level (Mizera, 2010).

The continuous groundwater exploitation with high rates was assumed to decrease the NO_3^- concentrations in the extracted water. To find an effective extraction regime for the water works, 15 operation variants with diverse overall and specific wells discharge rates were designed based on specific water demands. The admissible discharge rates of wells no. 3 and 8 were set within the range of 200-245 m^3/h, with their suggested periodic reduction to ca. 100 m^3/h, due to current low water demands. Moreover, other factors were taken into account, such as: current admissible discharge rates of wells, NO_3^- concentrations in the extracted water and water delivered to clients, NO_3^- loads leached out the aquifer, operation time and technical conditions of wells, location of contamination sources within the recharge areas.

Based on existing geological and hydrogeological documentation, numerical groundwater and contaminant transport models for MGWB 326N were developed using the Visual Modflow package. Calculations of groundwater transport were done and verified with the Modflow software (Malina *et al.,* 2007). Numerical modeling using MT3D software allowed for calculating NO_3^- concentrations in MGWB 326N, in the vicinity of the water works in Lobodno at diverse water extraction regimes. The NO_3^- transport model was validated for selected solutions of groundwater flow and prognoses of NO_3^- migration. The validated model was then used for prognoses of NO_3^- distributions at diverse groundwater extraction regimes.

The NO_3^- migration in the unsaturated zone was evaluated based on infiltration rates and average values of soil volumetric humidity. The lateral migration time was obtained from analytical calculations and modeling, while loads of NO_3^- discharged to groundwater – based on empirical studies. The same NO_3^- loads discharged to groundwater and constant quantities of water extracted by the water works (which reflects current water demands) were used in all variants. The NO_3^- loads leached out the aquifer were calculated as a sum of products of a NO_3^- concentration in a block with a well and a discharge rate of a well. The average NO_3^- concentration in the extracted water was calculated as a quotient of the total NO_3^- load leached out and the total discharge of the water works.

Water for analysis (ca. 1 dm^3) was sampled from the wells and piezometers using the Kemmerer sampler that allows to sample water at discrete depths within a body of water, and transported to the laboratory according to the standards (PN-88/C-04632/04, ISO 5667/3). Concentrations of NO_3^- in groundwater as nitrate nitrogen (NNO_3) were analyzed in the licensed laboratory of PWiK using the spectrofotometric method (UV-VIS CINTRA) according to the Polish standards (PN-82/C-04576/08).

RESULTS AND DISCUSSION

The results show that the permissible NO_3^- concentration for potable water (50 mg NO_3/dm^3) was not exceeded in any of studied variants. The water works operation assured the lowest possible concentrations in the delivered water, or the highest loads of NO_3^- leached out the aquifer, keeping concentrations in the extracted water below the permissible value. The periodic reduction of the admissible discharge rates of wells no. 3 and 8 to ca. 100 m^3/h allowed for their more frequent operation (significantly limited due to reduced water extraction resulting from low water demands) and, consequently for more flexible operations of the water works.

An increase of NO_3^- concentrations (from 22.11 to 48.29 mg/dm^3) was observed in variants 1-8, along with an increase of leached loads from the aquifer (from 1,677 to 70,564 tons NO_3/a), with increasing total discharge rates of the water works from 100 to 820 m^3/h, respectively. The lowest NO_3^- concentrations (22.11-40.50 mg/dm^3) in the extracted water at discharge rates of 100-500 m^3/h, were in variants (1-5), in which wells no. 3 and 8 were not operated. On the other hand, operation of wells no. 3 and 8 led to increased loads of NO_3^- leached out the aquifer (variants 6-8). The highest NO_3^- concentrations (43.94-49.30 mg/dm^3) in the extracted water were in variants 6-12, in which wells no. 3 and 8 were in operation. The highest loads (70,564 tons NO_3/a) were leached out the aquifer in variant 8, in which wells no 3 and 8 operated with the admissible discharge rates.

Under actual conditions of low water demands, variants 13 and 14 are the most effective operation mode for the waterworks in Lobodno as they allow for fulfilling the requirements regarding permissible concentrations of NO_3^- in water provided to clients (40.29 and 40.98 mg/dm^3, respectively). They also lead to the reduction of NO_3^- accumulation in the adjacent zones of wells no. 3 (variant 13) and 8 (variant 14) screens.

The selection of efficient extraction variants has to be, however, determined not only by actual water demands, but also by operation conditions of each well and their effects on groundwater dynamics and the chemical status. From this point of view, continuous operation of well no. 7 may assure water supply with NO_3^- concentration at a safe level, i.e. far below the standards. On the other hand, continuous operations of wells no. 3 and/or 8 at the admissible discharge rates may lead to significant reduction of NO_3^- contamination, and consequently to groundwater remediation due to high NO_3^- loads leached out the aquifer.

CONCLUSIONS

- The permissible NO_3^- concentration for potable water (50 mg/dm^3) was not exceeded in any of studied variants.
- Under actual conditions of low water demands, variants 13 and 14 are the most effective operation modes of the water works in Lobodno to protect the extracted water against contamination. These operation modes, along with the substantial reduction of current NO_3^- loads discharged from the surface to the aquifer, should result in a gradual decrease of NO_3^- concentrations in the groundwater.
- Effective control of the extraction regime of each well should allow for reduction of groundwater contamination with NO_3^- within the recharge areas, and consequently for delaying or eliminating the need for treatment (a NO_3^- removal installation) to be applied at the water works in Lobodno.

- The most attractive extraction regime of the water works in Lobodno should lead to fulfilling demands in terms of water quality and quantity on one hand, and to enhanced removal of NO_3^- loads from the aquifer (i.e. to fasten aquifer remediation), on the other. In such a case more frequent operation of wells no. 3 and 8 with higher discharge rates should be favored.

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