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GROUNDWATER EXTRACTION CONTROL FOR PROTECTING THE WATER WORKS IN ŁOBODNO (SW POLAND) AGAINST CONTAMINATION WITH NITRATES

JERZY MIZERA[1], GRZEGORZ MALINA[2]

Abstract. The main goal of this research was to reverse, or at least stop the trend of a constant increase of nitrate ions (NO_3^-) concentrations in the recharge areas and water extracted by the water works in Łobodno using specifically designed water extraction regime. To find an effective extraction regime, fifteen operation variants with diverse overall and specific well discharge rates were designed and tested. They assured the lowest possible concentrations in the delivered water, or the highest amounts (loads) of NO_3^- leached out the aquifer, keeping concentrations in the extracted water below the permissible value. The most effective variants at current water demands were these with the reduced discharge rates of wells nos. 3 and 8 (variants 13 and 14). Groundwater extraction according to other variants would be possible as water demands increase, or after the permanent reduction of NO_3^- concentrations in the water extracted by wells nos. 3 and 8. Effective control of the extraction regime will allow for the reduction of NO_3^- concentrations in the extracted water and loads in the aquifer, and consequently for delaying or eliminating the need for treatment (a NO_3^- removal installation) to be applied at the water works in Łobodno.

Key words: nitrates (NO_3^-), groundwater, extraction regime, water works protection, hydraulic control.

INTRODUCTION

The water works in Łobodno (consisting of 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 Częstochowa and neighbouring communes (SW 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 (Szczepański *et al.*, 1999; Karwowska, 2003; Dąbrowska *et al.*, 2005). 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) (Fig. 1). Already in 2001, these concentrations for both wells 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 extracted water were as high as 61.42 and 60.70 mg NO_3/dm^3, respectively. Keeping up this trend, which is predicted by mathematical modelling, 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 Częstochowa (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 Łobodno 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.

[1] Water Supply and Sewerage Company S.A, Jaskrowska 14/20, 42-200 Częstochowa, Poland; e-mail: jerzy.mizera@pwik.czest.pl

[2] AGH – University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, al. Mickiewicza 30, 30-059 Kraków, Poland; e-mail: gmalina@agh.edu.pl

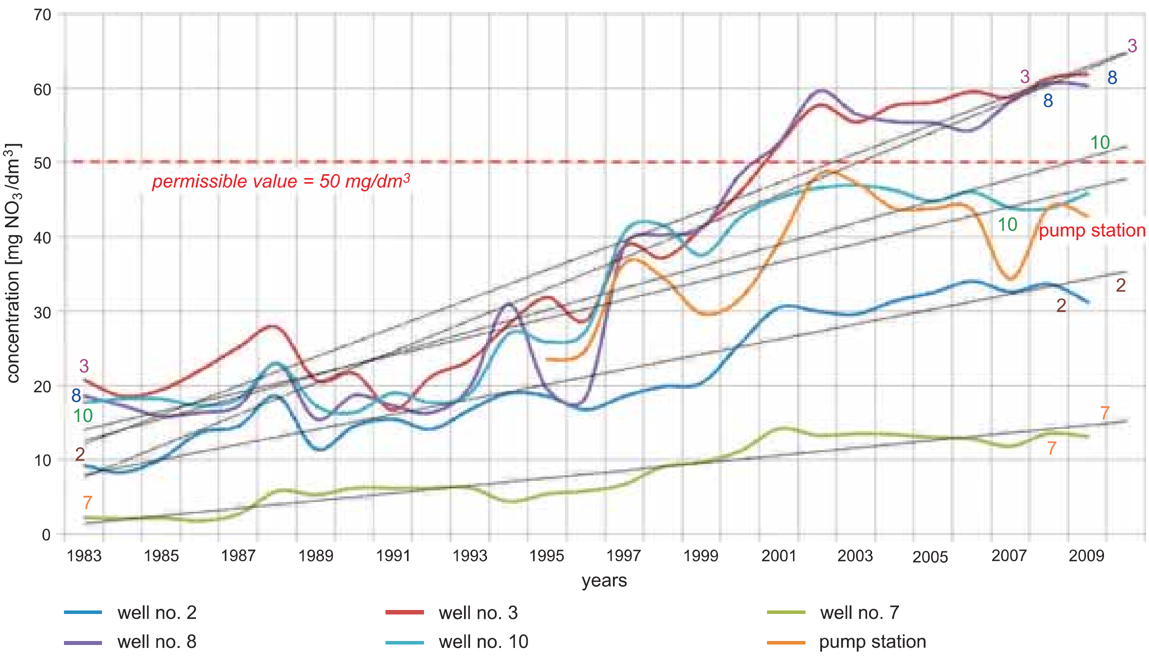

Fig. 1. Changes of mean NO_3^- concentrations in wells of the water works in Łobodno (1983–2008)

SITE CHARACTERIZATION

MORPHOLOGY AND HYDROGRAPHY

The studied area is situated in 2 sub-provinces: the Silesian–Cracow Upland and the Nida Basin. The former includes the Upper Warta and Prosna valleys in under clay dogger built as straight divides with monadnocks of malm limestone. North to the valleys, the Cracow–Wieluń Upland runs that is divided into two units: Wieluń Upland and Częstochowa Plateau.

Hydrographically, the area is located on the basins of Odra and Vistula rivers, and the watershed ranges through the Częstochowa Plateau. The principal watercourses run in accordance with morphological units and the strike of monocline. Their tributaries flow in general perpendicularly to the general strike, having their springs in zones of structural ledges, and flowing down to the principal watercourses through depressions between ledges. In the central part of the area, the watercourses change their run crossing the ledges and creating ravines. The river system density is low in areas of fault ledges and well developed in river valleys composed from Quaternary sandy and sandy-gravel sediments. The lowest density is observed within the Częstochowa Plateau, due to rapid drainage and high infiltration into the malm limestone.

The average annual (1985–2004) precipitation and temperature in 2 meteorological stations of 627 and 705 mm/y, and 7°C, classify climate type as low-humid and moderate, respectively. Varying recharge conditions (effective infiltration) from 31.5 to 190 mm/y (i.e. 5–30% of precipitation) are due to lithology, diversity of land use and groundwater extraction regimes.

GEOLOGY AND HYDROGEOLOGY

Groundwater is connected to rock formations varying in age that compose the Quaternary, Jurassic, Cretaceous and Triassic multi-aquifer formations (Fig. 2) (Malina *et al*., 2007). The Warta River, which cuts outcrops of the Upper Jurassic formations, often changes its character from draining to infiltrating.

The Quaternary multi-aquifer formation. It is connected to sands of glacial and river accumulation. The variation in lithology and thickness of sand layers causes changes of storage capacity, continuity and transmissivity of aquifers. Changes in the development of profiles in the case of thicker aquifers (built with the alternating layers of clays and sands) cause the formation of number of water-bearing horizons with various hydraulic connections. The recharge proceeds through direct infiltration and drainage in general by watercourses. This formation is of useful importance only within river valleys filled with sandy and sandy-gravel sediments. In the case of shallow thin aquifers, the water is extracted by dug (farmer) wells.

The Cretaceous multi-aquifer formation. It is divided into Upper Cretaceous and Cretaceous water-bearing horizons. The former is composed from fissured marls and limestone. Fissure intensity in upper parts decreases with depth

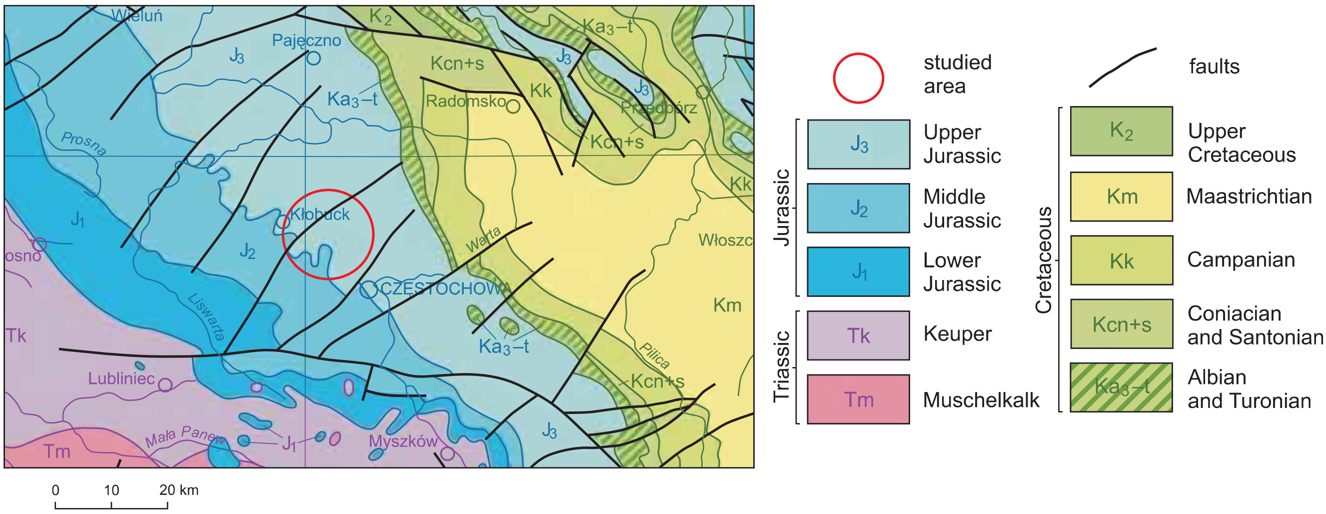

Fig. 2. Study area on the background of Geological map of Poland without Cenozoic deposits, scale 1:1,000,000 (Dadlez *et al.*, 2000)

and creates preferential groundwater flow paths. The hydrogeological parameters are various and considerably dependant on the degree of fissuring. The recharge proceeds through outcrops or, indirectly through Quaternary deposits, whereas discharge is via watercourses. Groundwater table is either confined or unconfined, depending on the presence of confining low permeable layers. This formation is hydraulically connected with Quaternary aquifers. The contact with water of deeper strata may occur in zones of large tectonic dislocations. The Lower Cretaceous horizon is built of sands and sandstone. Groundwater table is confined, except the outcrops, where a joint Cretaceous–Quaternary horizon is often observed. It has a considerable thickness of 50–60 m, and the area determines its storage capacity.

The Jurassic multi-aquifer formation. It 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 it is the main source of potable water (MGWB 326). 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.

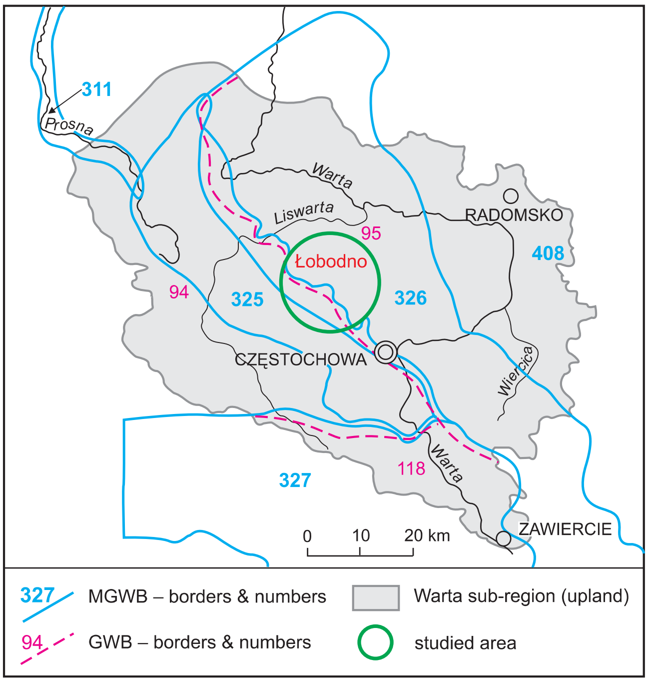

Fig. 3. Location of studied area in relation to MGWB and GWB, distinguished in the sub-region of the Warta River (after Paczyński, Sadurski, eds., 2007)

The MGWB 326. It is symbolically divided (with the Warta River as a natural border) into two sub-basins: MGWB 326S – 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 works in Julianka; Mizera *et al*., 2000b), and MGWB 326N – with the area of 570 km^2 and documented and approved disposable water resources of 8,900 m^3/h (Mizera *et al*., 2000a). In the studied area two groundwater bodies (GWB) nos. 94 and 95 were distinguished (Fig. 3): the first encompasses Lower and Middle, while the second covers Upper Jurassic groundwater horizons (Paczyński, Sadurski, eds., 2007).

METHODS

Operation of wells is the main factor determining changes of hydrogeological conditions in the recharge area of any water works. Depending on wells' discharge rates the flow directions can be changed significantly, and by appropriately selected discharge distribution (within the frame of required water demands), the water works operation can be controlled in terms of their areas of influence (a drainage area), and the contamination loads leached out the adjacent aquifers. Therefore, it is possible to develop an operation strategy of wells in such a way that, by creating appropriate hydrogeological conditions (required groundwater flow directions forced by controlled well discharge rates), water resources of the water works can be protected, as well as NO_3^- concentrations in water delivered to clients kept below the permissible level.

Observations of the operation of water works in Łobodno within 1985–2008 showed a gradual increase of NO_3^- concentrations in the extracted groundwater with decreasing wells' discharge rates. Therefore, it was assumed that at the continuous groundwater extraction with high rates the NO_3^- concentrations will tend to decrease. To find an effective extraction regime for the water works, fifteen operation variants with diverse overall and specific wells discharge rates were designed based on specific water demands (Mizera, 2010). Admissible discharges of wells nos. 3 and 8 were assumed 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: (i) current admissible discharge rates of wells, (ii) NO_3^- concentrations in the extracted water and water delivered to clients, (iii) NO_3^- loads leached out the aquifer, (iv) operation time and technical conditions of wells, (v) 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 (Szczepański *et al*., 2000; Kaczorowski, 2005). This model and chemical analyses of water from the water works allowed for calculations of NO_3^- transport using MT3D software. Numerical modelling allowed for calculating NO_3^- concentrations in MGWB 326N, in the vicinity of the water works in Łobodno at diverse water extraction regimes. The NO_3^- transport model was validated for selected solutions of groundwater flow and prognoses of NO_3^- migration (Kaczorowski *et al*., 2006). The validated model was then used for prognoses of NO_3^- distributions at diverse groundwater extraction regimes.

The NO_3^- migration in 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 modelling, while loads of NO_3^- discharged to groundwater – based on empirical studies. It was assumed that the NO_3^- concentration in water in mg NO_3/dm^3 is numerically equal to 1/10 of nitrogen fertilizers expressed in kg N/ha, and the use of nitrogen fertilizers in Poland was of 60–70 kg N/ha (Kleczkowski, 1984; Witczak, Adamczyk, 1994). The same NO_3^- loads discharged to the groundwater from surface and constant quantities of the water extracted by the water works (which reflects current water demands) were used in all variants. The NO_3^- loads leached out the aquifer as a result of the extraction of contaminated groundwater 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 was determined as nitrate nitrogen (NNO_3) in the licensed laboratory of the PWiK using the spectrofotometric method (UV-VIS CINTRA) according the Polish standards (PN-82/C-04576/08) with the detection limit of >0.1 mg NO_3/dm^3, and the accuracy of ±5% (Witczak, Adamczyk, 1994, 1995).

RESULTS AND DISCUSSION

The results presented in Table 1 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 nos. 3 and 8 to ca. 100 m^3/h allowed for their more frequent operation (significantly limited due to reduced water extraction resulting from current 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 loads (from 1,677 to 70,564 tons NO_3/a) leached out the aquifer, 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

Table 1

Results of groundwater extractions variants of the water works in Łobodno including simulated NO_3^- concentrations and loads

Variant no.	Discharge rate [m^3/h]	Continuous discharge		Periodic discharge		NO_3^- concentrations [mg/dm^3]	NO_3^- loads leached out [tons/a]
		well no.	rate [m^3/h]	well no.	rate [m^3/h]		
1	100	7	75	10	25	22.11	1,677
2	200	7 10	75 95	2	30	31.92	6,323
3	300	7 10	75 95	2	130	33.30	12,664
4	400	7 10 2	75 95 205	3	25	35.29	20,108
5	500	7 10 2	75 95 205	3	125	40.50	30,862
6	600	7 10 2 3	75 95 205 200	8	25	43.94	42,155
7	700	7 10 2 3	75 95 205 200	8	125	46.25	55,068
8	820	7 10 2 3 8	75 95 205 200 245	–	–	48.29	70,564
9	275	7 3	75 200	–	–	48.40	22,204
10	320	7 8	75 245	–	–	49.30	32,334
11	370	7 3 10	75 200 95	–	–	48.06	25,928
12	415	7 8 10	75 245 95	–	–	48.80	36,058
13	175	7 8	75 100	–	–	40.29	5,968
14	175	7 3	75 100	–	–	40.98	6,074
15	275	7 8 3	75 100 100	–	–	47.96	11,345

water at discharge rates of 100–500 m^3/h, were in variants (1–5), in which wells nos. 3 and 8 were not operated. On the other hand, operation of wells nos. 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 extracted water were in variants 6–12, in which wells nos. 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 nos. 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 Łobodno 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 nos. 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 nos. 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

1. The permissible NO_3^- concentration for potable water (50 mg NO_3/dm^3) was not exceeded in the water extracted by the water works in Łobodno at any of the studied variants.

2. Under actual conditions of low water demands, operation of the water works in Łobodno at variants 13 and 14 is the most effective 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.

3. Effective control of the extraction regime of each well should allow for reduction of groundwater contamination with NO_3^- within its recharge area, and consequently for delaying or eliminating the need for treatment (a NO_3^- removal installation) to be applied at the water works in Łobodno.

4. The most attractive extraction regime of the water works in Łobodno 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 nos. 3 and 8 with higher discharge rates should be favored.

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