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Geologos 30, 3 (2024): 195–208
https://doi.org/10.14746/logos.2024.30.3.18

GEOLOGOS

Groundwater well fields in ice-margin valley aquifers – is it easy to protect them, or not? An overview of hydrogeological and legal aspects of determining wellhead protection zones

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Abstract

This paper discusses principles for delineating wellhead protection zones (WHPZ) of groundwater well fields in ice-margin valleys. A distinctive feature of such well fields is that, apart from the often geogenically contaminated water of ice-margin valleys, they are largely supplied with high-quality water from intertill aquifers of neighbouring uplands. However, much of this inflow can be intercepted by wells for agriculture that are increasingly being constructed in the capture zones of existing municipal well fields, thus posing a threat to the quality of water for the public. This problem has been investigated using the example of a municipal well in Wroniawy (Poland) by analysing changes in the recharge components of this well field with a groundwater flow model. The results indicate that the commissioning of agricultural abstractions in the capture zone of this well field reduces inflow from intertill aquifers (8.5 per cent) and precipitation recharge (3.3 per cent), following a change in the extent of the capture zone. The loss of these qualitative recharge components is substituted by an increase in poor-quality water, i.e., surface water (7.3 per cent) and geogenically contaminated water from the ice-margin valley centre (3.8 per cent). Protecting well fields in such locations from adverse water quality changes requires the implementation of quantitative shielding of best-quality water, calling for WHPZ to cover the entire capture zone regardless of water flow timing, which is not provided for in Polish legislation. Costs and constraints of implementing such a WHPZ can be reduced by dividing it into sectors that differ in the scope of limitations, with the only quantitative protection applied to the outermost, medium- and low-vulnerable parts of the capture zone.

Keywords: Quantitative protection of groundwater, overexploitation, sustainable groundwater management, groundwater flow modelling

1. Introduction

Safeguarding groundwater resources is usually represented by the protection zone concept (Chave et al., 2006), introduced to avoid activities affecting water quality and quantity. It is provided through various prohibitions and restrictions on land use, agricultural practices and water consumption in order to protect public water supplies from contamination and overexploitation. As established by European water law regulations, water conservation is a significant component of an integrated management approach towards public supply safety (Directive 2000/60/EC; Directive 2006/118/EC). Although these directives highlight the importance of sustainable groundwater resource management, they do not provide detailed implementation guidelines. Thus, each EU member state has different regulations in this regard.

Designing wellhead protection zones (WHPZ) is the most effective and widely used prevention measure. A popular solution is to use the reference travel time to determine WHPZ coverage. However, the accepted limits vary considerably worldwide (Doveri et al., 2015). Similarly, guidelines on subzoning of WHPZs are also inconsistent, yet an approach based on three or four subzones differing in the extent of restrictions is the most common practice providing different levels of protection (Brencic et al., 2009; Doveri et al., 2015; Paris et al., 2019; Osmanaj et al., 2021).

In Poland, the obligation to establish protection zones stems from the provisions of the Water Law Act of 20 July 2017 (Water Law, 2017). Implementing this Water Law Act marked a significant change in Poland's approach to establishing WHPZs, as there was no previous obligation to designate these. Currently, operators providing the public with water from highly vulnerable aquifers must establish a WHPZ comprising two subzones: a direct and indirect protection area. The latter covers part of the catchment area delimited by the isochrone of the 25-year water inflow to the operating wells, defined as the sum of the vertical seepage time from the land surface and the horizontal flow time in the aquifer. Polish regulations do not provide for exceptions to these rules. However, in some specific cases, such as the one presented herein, limiting the WHPZ extent to the concept of the 25-year water inflow isochrone may be insufficient to ensure adequate drinking water protection. Therefore, many countries (e.g., Slovenia, Finland, Austria and Kosovo) protect well fields by bringing the entire capture zones of these facilities within the scope of the WHPZ (Brencic et al., 2009; Osmanaj et al., 2021), irrespective of the travel time from its borders.

The extents of WHPZs are delineated using various methods worldwide. Analytical solutions are acceptable for small wells in uncomplicated hydrogeological conditions, with Wyssling's method being the most popular (Wyssling, 1979). This approach allows the extent of the WHPZ to be determined by quick calculations, but the results obtained are generally simplified (Paris et al., 2019). Groundwater flow modelling is preferred for larger and interacting well fields (Liu et al., 2019; Ozdemir, 2021; Zeferino et al., 2022).

Model-based methods, particularly those supported by the MODFLOW algorithm, are prevalent in designing WHPZs, as they enable recharge balance to be performed. These methods require a wide range of input data and measurements. Thus, although more time-consuming, they are considered more reliable for the delineation of areas contributing to well recharge, especially in combination with the MODPATH code (Pollock, 1989, 2016), which supports tracing of groundwater pathlines (Moutsopoulos et al., 2008). In addition, options for calculating horizontal and vertical groundwater flow time facilitate groundwater protection zoning (Gurwin, 2015; Živanović et al., 2016). Consequently, well-calibrated models are valuable tools for determining the WHPZs, which are essential in water resource management (Goodarzi & Eslamian, 2019).

Most research on WHPZs addresses water quality protection issues (Ahmadi et al., 2023). The world literature dealing with WHPZs has paid much attention to well fields recharged from vulnerable, unconfined aquifers that are susceptible to contamination (Liu et al., 2019; Corson-Dosch et al., 2022; Friesz et al., 2022; Steiakakis et al., 2023), espetially those in fractured rocks (Živanović et al., 2021). Against this background, there is a noticeable lack of publications dedicated to protecting well fields in ice-margin valleys.

A characteristic feature of the well fields located in these aquifers is that they are typically recharged by high quality groundwater from adjacent inter-till aquifers and the inflow from low terraces of ice-margin valleys, often characterised by unfavourable features in the hydrogeochemical environment (Górski, 2001, 2017). Maintaining a supply balance between these two sources requires a reasonable control of water distribution. Therefore, the groundwater facilities in ice-margin valleys require a dedicated approach to WHPZ designation and should receive more attention.

The available publications on ice-margin valleys provide information on the varied and locally adverse chemical water composition (Dąbrowski et al., 2005; Górski, 2010b) or the complex relationship between recharge sources (Dąbrowski et al., 2018), but do not explain how these factors influence the principles of determining WHPZs. Meanwhile, proper management of water recharging well fields in these aquifers is becoming more difficult due to growing pressure from agriculture, prompted by climate change and subsequent high demand for water during increasingly frequent droughts.

The expanding number of wells for agriculture constructed in the capture zones of existing municipal well fields poses a challenge to protecting the quality and quantity of water for public use. Therefore, the present paper addresses the problem of effective quantitative protection of groundwater resources, with quality not directly threatened by contamination from the land surface. A scheme for protecting a well field located in an ice-margin valley is presented from a hydrological perspective, using the example of the Wroniawy municipal well field (Poland). The present paper aims (1) to investigate the impact of groundwater abstraction for agricultural purposes on the municipal well field recharge components and (2) to determine a suitable WHPZ. The problem was studied by using groundwater flow modelling through water balance and travel time analysis.

2. Material and methods

2.1. Study site

2.1.1. Location and land use

The study site covers the capture zone of the municipal water supply, which provides water to the residents of town of Wolsztyn and adjacent villages in the western part of Wielkopolska district (Poland). The system consists of the Wroniawy and Wroniawy-bis well fields which abstract Quaternary aquifers (Fig. 1).

The well fields are located within the Warsaw-Berlin ice-margin valley (WBIMV), but their capture zone includes both the WBIMV and the adjacent Poznań upland. The area is heavily drained by the River Obra, which is channelised and splits into the North, Central and South Obra canals. A further drainage component is the Tłocki Ditch, flowing into the North Obra Canal from the upland side.

Land use is dominated by arable land, meadows and scattered villages, accompanied by intensive livestock-farming development. The central parts of the WBIMV are sparsely populated, while its edges and moraine upland are settled, with the village of Wroniawy being the most significant residential centre in the well fields capture zone.

2.1.2. Geology and hydrogeology

The geological structure of the Quaternary sediments provides for the occurrence of the two aquifers (i.e., upper and lower) with a hydrogeological duality observed (Fig. 2).

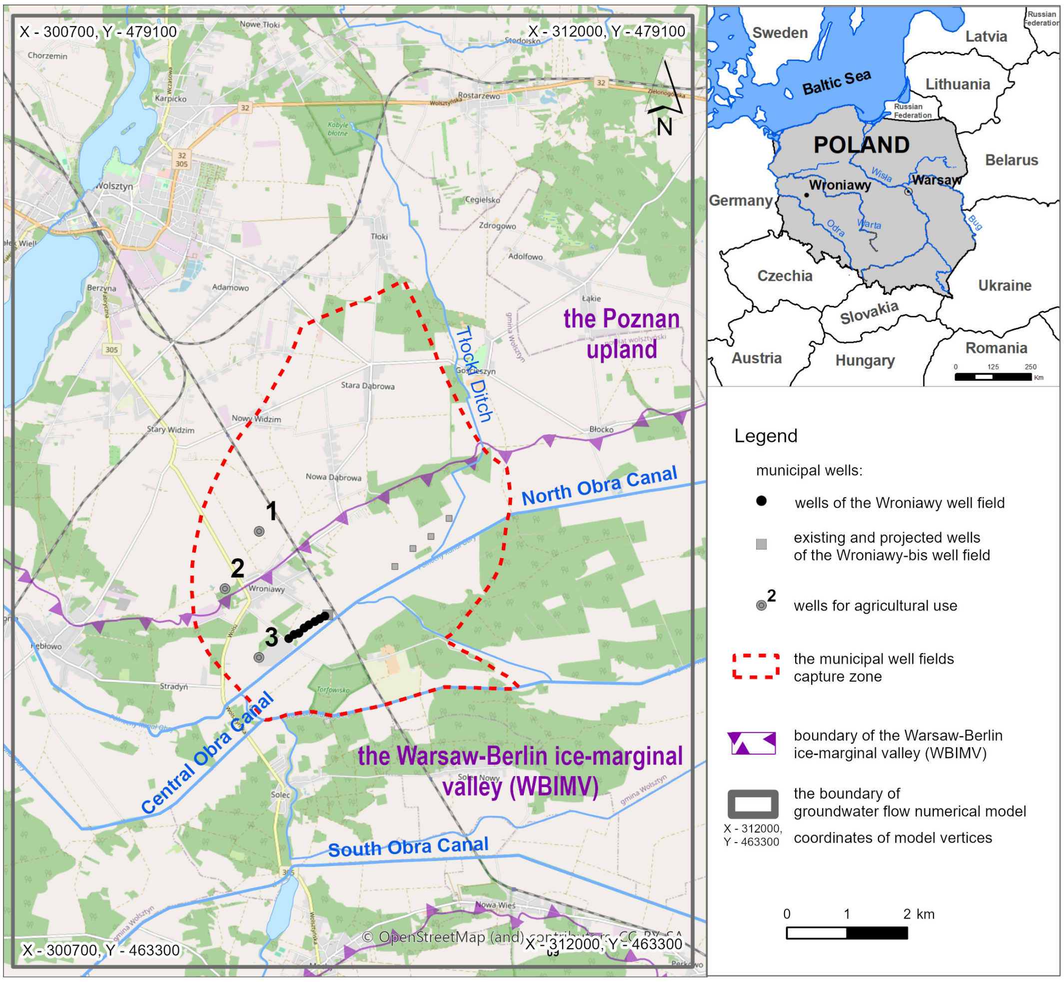

Fig. 1. Location of the study area.

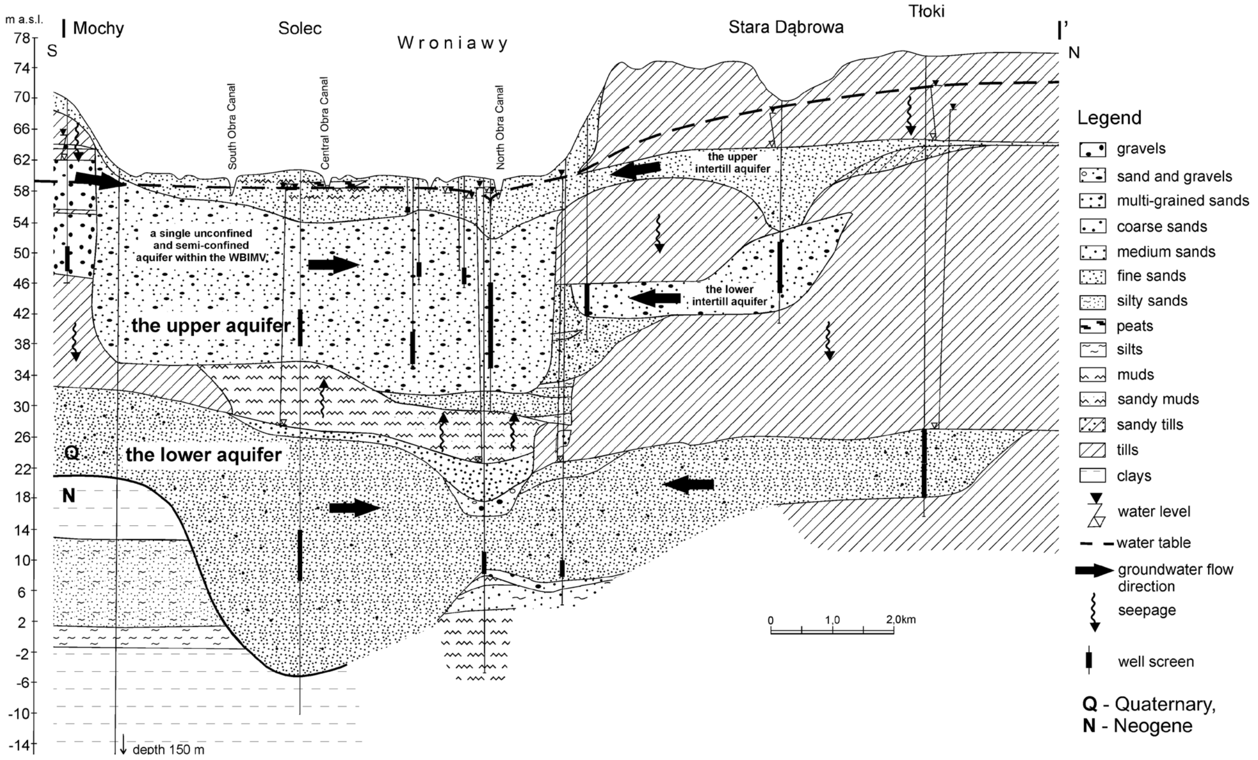

Fig. 2. Hydrogeological cross-section.

The upper aquifer within the WBIMV forms a single sandy and gravelly layer with a total thickness of ~20 to 35 m and varied hydraulic conductivity (K) of 6–36 m/d for silty sands and sands forming the upper part of the aquifer; and up to 72–144 m/d for its lower parts consisting of gravelly sediments. It is unconfined within higher terraces or semi-confined at floodplains due to muds that overlie the aquifer locally. In contrast, in the upland, it consists of one or two intertill aquifers, separated locally by glacial tills. The semi-confined upper intertill aquifer comprises fluvioglacial sands (5 to 16 m thick) with a K of approximately 12 m/d, overlain by fine-grained sands, silty sands and glacial tills up to 8–12 m thick. The lower intertill aquifer, with its top located 20–30 m below ground, is mostly confined. It consists of fine sands (with K of 8–15 m/d) and sandy gravel deposits (with K of 35 m/d). This approximately 6–13 m thick aquifer is favoured for abstraction by wells for agricultural purposes. The two intertill aquifers are connected laterally to the unconfined aquifer in the WBIMV and vertically with each other via a hydrogeological window in the vicinity of the village of Stara Dąbrowa (Fig. 2).

The lower aquifer is uniform both in the WBIMV and in the upland. This confined aquifer, with a thickness of up to 25 m, was found at depths in excess of 30 m below ground in the WBIMV and more than 50 m in the upland. It consists of multi-grained sediments with a K varying from 2–8 m/d (silty and fine sands) to 35 m/d (sands and gravels), at conductivities ranging from a few to 570 m^2/d.

According to regional groundwater flow modelling (Dąbrowski et al., 2018), aquifers in the upland are fed by precipitation recharge, while those within the WBIMV are fed both by precipitation and drainage of the underlying Miocene aquifer. Groundwater generally flows north to south towards the WBIMV and to the Wroniawy and Wroniawy-bis well fields (Fig. 3).

2.1.3. Description of water abstraction in the municipal well field capture zone

The Wroniawy well field, capturing the upper aquifer from depths of ~30 m, is the oldest part of the water supply system. Due to a systematic rise in water production, the system was expanded to include the Wroniawy-bis well field with screens located ~40–50 m below ground in the lower aquifer. The maximum permissible abstraction of the Wroniawy well field is 7,200 m^3/d, and that of the Wroniawy-bis at 1,200 m^3/d with a depression of 1.2 to 1.8 m adjacent to the wells. Groundwater flow modelling attempts to increase these abstractions and water quality risk assessment have shown contra-indications due to the potential for excessive inflows of contaminated water.

For over 30 years, the Wroniawy well field water treatment has been carried out using the unique „treatment in the aquifer" method (Górski, 2010a). However, the poor quality of the inflowing water, particularly in terms of manganese content, limited the effectiveness of the treatment method and reduced the well field production capacity, which was particularly noticeable during hydrological droughts.

In recent years, the upper aquifer has become a site of interest to agriculture as a water source for crop irrigation and livestock farming. Consequently, between 2010 and 2019, i.e., prior to the establishment of the Wroniawy well field WHPZ the three sets of such water facilities were drilled in the municipal well fields capture zone (Fig. 1). These wells are mostly operated seasonally, potentially reaching capacities of 96 m^3/d (No. 1), 1,200 m^3/d (No. 2) and 228 m^3/d (No. 3) during the summer half year.

2.1.4. Water quality

According to Górski (2001, 2017), four zones with different hydrogeochemical types of groundwater may be distinguished in this area (Fig. 3).

The central parts of the WBIMV (Zone 1) contain coloured water (even up to 60 mgPt/L) with oxidisability up to 20 mgO_2/L related to very high concentrations of iron (up to 15.3 mgFe/L), manganese (over 1.17 mgMn/L), ammonium ion (up to 1.35 $mgNH_4/L$) and organic matter, far exceeding the limits allowed for drinking water. These substances are being released into the groundwater due to the decomposition of organic matter accumulated in large quantities on floodplains. In addition, sulphide and organic matter oxidation processes periodically occur here, accounting for iron concentrations of up to 60 mgFe/L and sulphates of up to 288 $mgSO_4/L$ recorded locally in shallow observation boreholes (Górski, 2017).

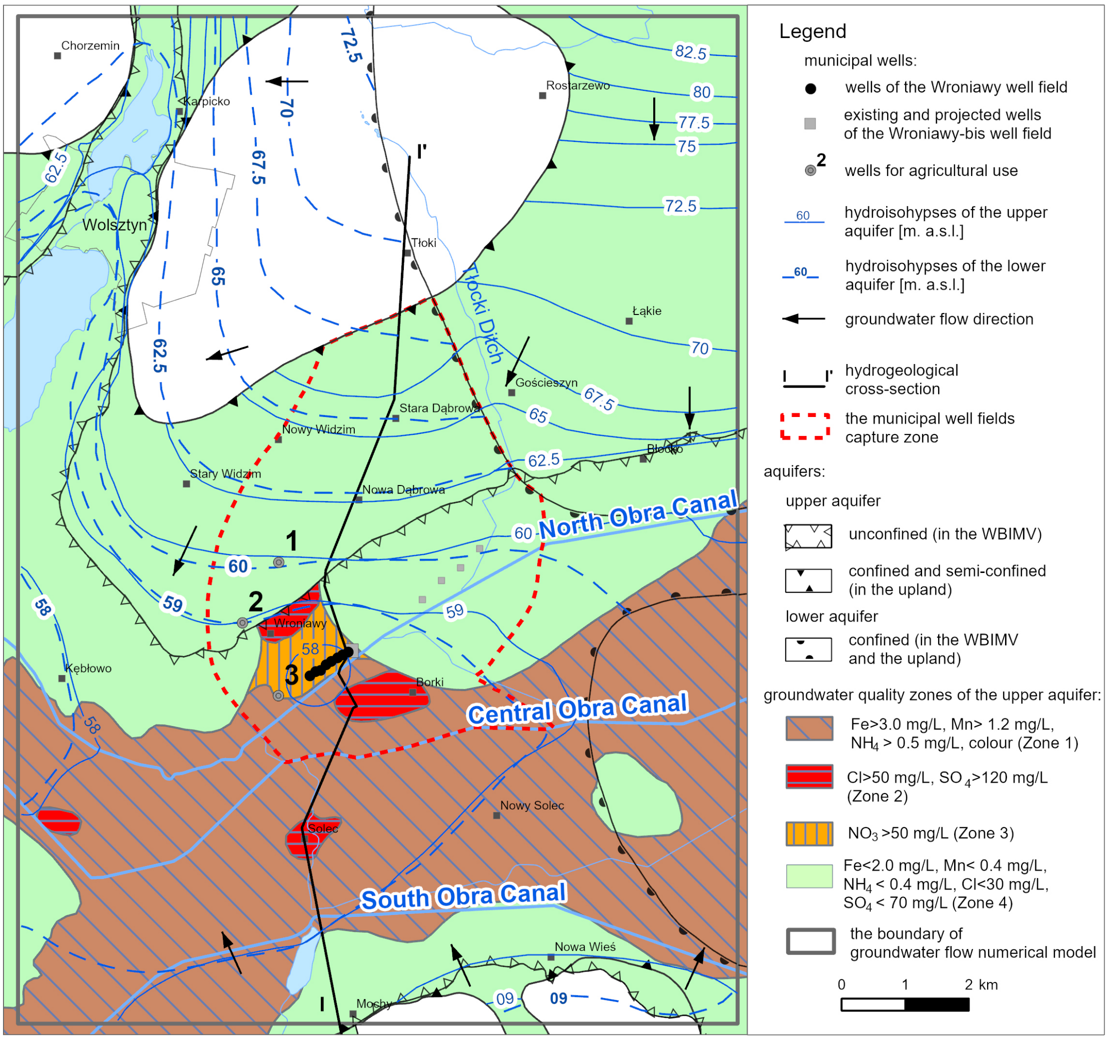

Fig. 3. Hydrogeological map of the study area.

Groundwater in the vicinity of the villages of Wroniawy, Borki and Solec (Zone 2) contains elevated concentrations of chlorides (> 50 mgCl/L) or is heavily contaminated with sulphates (270 $mgSO_4/L$, locally even up to 1215 $mgSO_4/L$ in the Solec region). They may also contain elevated concentrations of nitrates, ammonium ions, iron or manganese. In turn, water flowing from the village of Wroniawy towards the municipal well fields (Zone 3) is heavily contaminated with nitrates to levels above 50 $mgNO_3/L$. The best-quality water, usually requiring only simple iron and manganese treatment, comes from intertill aquifers and higher terraces of the WBIMV outside the influence of the village of Wroniawy (Zone 4). This water is nitrate-free and chloride concentrations are generally less than 30 mgCl/L, with sulphate < 70 $mgSO_4/L$, ammonium ion < 0.4 $mgNH_4/L$, iron < 2 mgFe/L and manganese < 0.4 mgMn/L.

2.2. Steps towards determining WHPZ

2.2.1. Numerical model construction and calibration

A numerical groundwater flow model of 178.5 km^2 was used for calculations (Fig. 3). The model was based on the finite difference method with the MODFLOW algorithm (McDonald & Harbaugh, 1988), and consisted of square blocks ranging in size from 10 to 100 m. According to the hydrogeology of the region, the geological structure was divided into six modelling layers (Fig. 4).

The complex pattern of the upper aquifer was mapped as numerical layers I–IV and the lower aquifer as layer VI. The municipal well fields, dominant in water withdrawal, represented 86 per cent of the abstraction in the model domain.

The model was calibrated based on field measurements of groundwater elevation at 82 points.

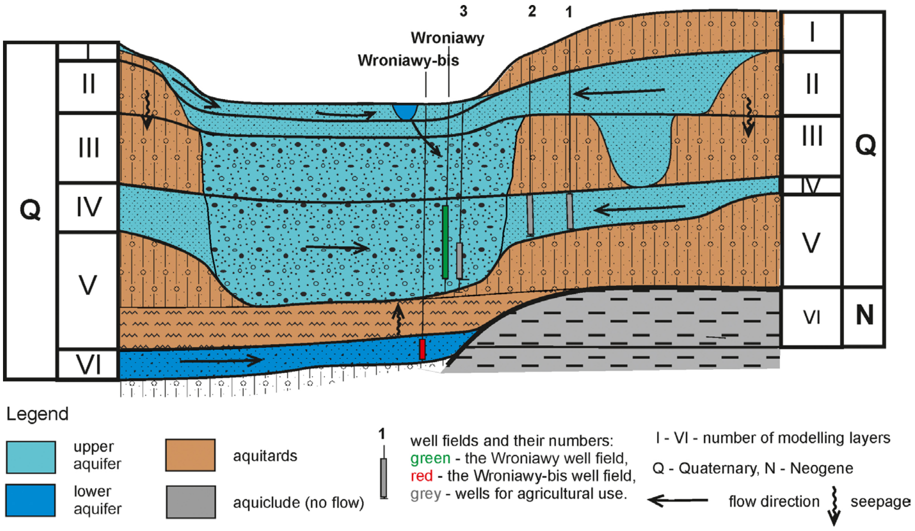

Fig. 4. Scheme of the modelled aquifer system.

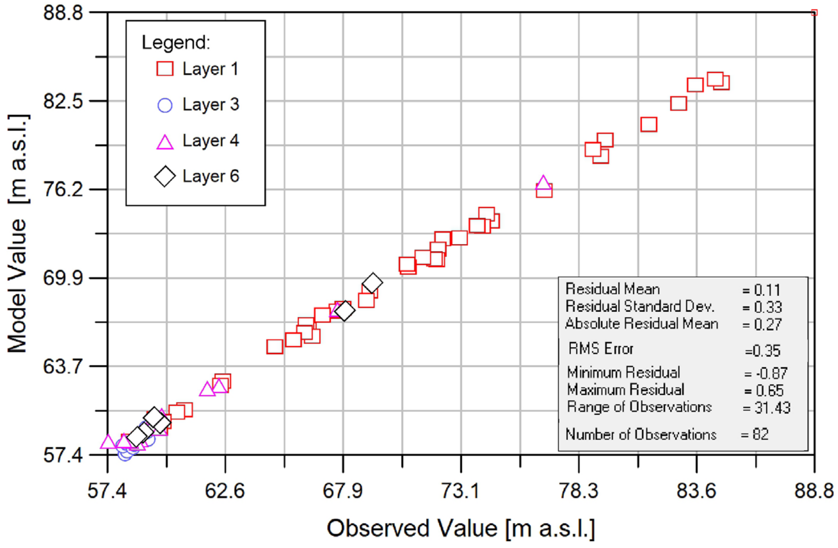

Fig. 5. Plot representing target statistics and discrepancies in groundwater elevation between field measurements and model calculations.

The final discrepancies between the measurements and model calculations in calibration points (targets) were within ± 0.87 m, with a Root Mean Square Error (RMS Error) of 0.35 m, confirming the correct calibration of the model (Fig. 5). The precipitation recharge of the aquifers in the model domain amounted to 218 $m^3/d\ km^2$ (i.e., 2.53 $L/s\ km^2$), representing 13.4 per cent of precipitation. This result fell slightly below regional groundwater flow models for the area and neighbouring well fields (Dąbrowski et al., 2018; Górski et al., 2021).

2.2.2. Delineating the municipal well field capture zone

To protect groundwater resources, it is crucial to delineate a well field capture zone, i.e., an area contributing recharge to production wells. This zone was determined using the MODPATH code (Pollock, 1989, 2016). This popular solution allows tracking groundwater particles so as to assess the spatial distribution of flow paths intercepted by active wells and the horizontal flow timing of these particles. In addition, defining this area allows for calculating components that recharge the well field or part of it (Matusiak et al., 2021).

2.2.3. Calculations of vertical and horizontal flow time

Following Polish regulations, the extent of the WHPZ is strictly dependent on the extensiveness of the well field capture zone and the 25-year isochrone of water inflow to that well field, calculated as the sum of horizontal inflow time (T_H) and vertical seepage time (T_a).

T_a is the time for a conservative pollutant to pass through the aeration zone from the land surface to the aquifer. It was calculated according to the Bachmat and Collin method (Witczak & Żurek, 1994), using the following formula:

$$T_a = \frac{m_a \cdot \omega}{I} \tag{1}$$

Following the study by Witczak & Żurek (1994), the volumetric soil moisture (ω) was assumed to be 0.15 (fine sands), 0.20 (sands and silty sands) and 0.30 (tills). Other data required in Equation 1 were extracted from the numerical model of groundwater flow for each of its elements and calculated using GIS tools. The thickness of the aeration zone (m_a), gained via subtracting the upper aquifer top elevation from the digital terrain model, reached 0.1–35.0 m the upland and 0.1– 6.0 m within the VBIMV. The annual precipitation recharge (I) amounted to 25–260 mm/year.

An effective porosity (n_e) used for estimating T_H with the particle-tracking method (Anderson et al., 2015) was based on the literature (Urumovic, 2016). Values of 0.30 were adopted for gravels, 0.25 for sands, and 0.08 for silts and tills.

2.2.4. Assessing the impact of groundwater withdrawal for agricultural purposes

The impact of groundwater abstraction for agricultural purposes, growing in the municipal well fields capture zone, was investigated by analysing changes in the recharge components of the municipal well field under the activation of abstractions from nearby wells for agriculture.

Two simulations were carried out: (A) the period prior to the construction of wells for agriculture and (B) the scenario concerning seasonal withdrawals for agricultural purposes. In simulation A, only the operation of municipal well fields was considered (with capacities of 7,200 m^3/d for the Wroniawy well field and 1,200 m^3/d for the Wroniawy-bis well field). In contrast, simulation B additionally triggered abstractions from three wells for agricultural purposes (with a total capacity of 1,524 m^3/d).

3. Results

The municipal well field capture zone, with an extent of 26.9 km^2, stretches from the Central Obra Canal in the south to the structural boundary of the upper intertill aquifer near the village of Tłoki in the north.

3.1. Flowtime analysis

The T_H from the edges of the municipal well field capture zone ranged from 17 years in the WBIMV to over 90 years in the upland. The T_a was likewise shortest in the WBIMV area (from a single month to one year), growing longer in the upland (from 2 to 20 years) (Fig. 6). T_a calculations confirmed the high vulnerability of aquifers to pollution from land surface in a considerable part of the municipal well field capture zone, justifying the need to designate a WHPZ.

The 25-year water inflow isochrone (Fig. 6), which is the limiting value for determining the coverage of WHPZ, comprises an area of 19.2 km^2, including WBIMV (up to the edges of the municipal well field capture zone) and the neighbouring section of the upland with a reduced thickness of poorly permeable aquifer cover (T_a of 0–5 years in the south-facing strip between the villages of Stara

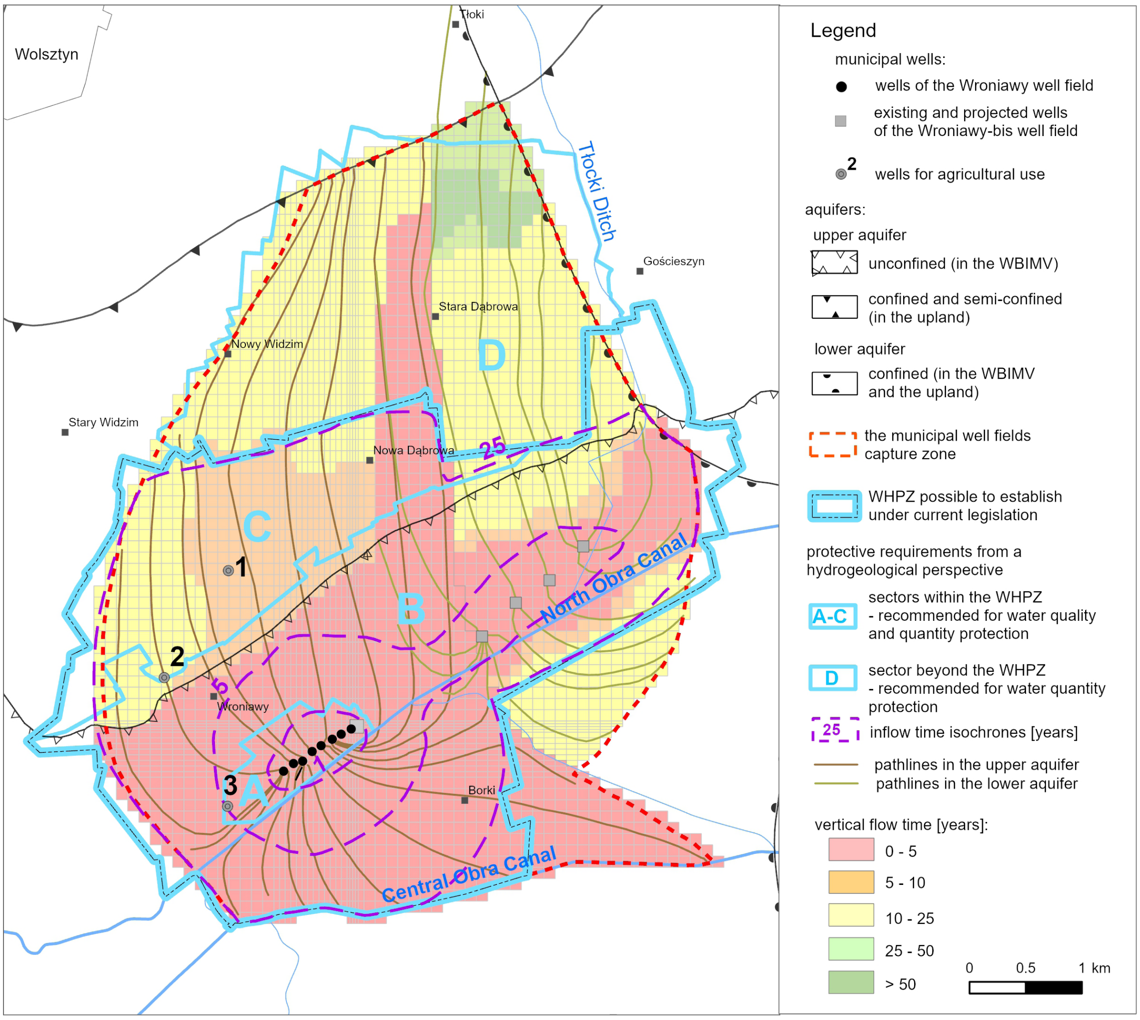

Fig. 6. Map of the protection zone (possible to establish under current legislation vs recommended due to hydrogeological requirements) against the background of the vulnerability and inflow times towards municipal well fields.

and Nowa Dąbrowa, and of 5–20 years close to the WBIMV). Outside the 25-year water inflow isochrone was the northernmost part of the municipal well field capture zone, with T_a well above 25 years.

3.2. Groundwater flow balance

As the wells for agriculture capture the upper aquifer, only the recharge balance of the Wroniawy well field was addressed in detail (Table 1).

3.2.1. Recharge balance of municipal well fields

Prior to the construction of wells for agriculture (simulation A), the recharge balance of the Wroniawy well field was dominated by inflow from the northern part of the capture zone, covering the upland and upper terraces of the WBIMV, which accounted for 73.4 per cent of the recharge components (Table 1). The largest contributor was water flowing from intertill aquifers (45.5 per cent). The remainder was inflow from the WBIMV, resulting from precipitation recharge (22.0 per cent) and ascending flow from the lower aquifer (5.9 per cent).

Total inflow from the southern part of the capture zone, covering lower terraces of the WBIMV, represented only 26.6 per cent of the well field recharge components. These waters were provided by four primary sources: precipitation recharge (7.5 per cent), ascending flow from the lower aquifer (6.3 per cent), surface water recharge mostly from the North Obra Canal (6.7 per cent) and groundwater inflow from the WBIMV centre (6.1 per cent).

In comparison, 88.3 per cent of the Wroniawy-bis well field recharge originated from the northern part of the capture zone. This value consisted of water flowing from the lower intertill aquifer (77.8 per cent) and seepage from the unconfined aquifer within the WBIMV (10.5 per cent). Inflow from the south accounted for only 11.7 per cent of the well field recharge.

3.2.2. Recharge balance of municipal well fields under the influence of abstractions for agricultural purposes

Simulation B reveals that the operation of wells for agricultural use will decrease the inflow from the north to 67.6 per cent of the Wroniawy well field recharge components. The main reason for this decline will be a 8.5 per cent drop in the inflow from intertill aquifers (to 37 per cent). Moreover, these abstractions will affect the extent of the Wroniawy well field capture zone, thus lowering precipitation recharge within WBIMV (to 18.6 per cent). Activating wells for agriculture can also trigger an inflow from ditches, initially draining in the north (up to 4.9 per cent of the Wroniawy well field recharge components).

At the same time, this will contribute to a significant growth in water inflow from a southerly direction (up to 32.4 per cent). The reasons for this are found mainly in the increased surface water recharge from the North Obra Canal and the activation of leakage from the Central Obra Canal (up to 9.1 per cent). In addition, there will be a 3.8 per cent increase in the inflow from areas south of the Central Obra Canal (to 9.9 per cent).

Summarising the results of the recharge balance for the Wroniawy well field (Table 1), it may be concluded that activating groundwater abstractions for agricultural purposes in the Wroniawy well field capture zone would contribute to the degradation of the withdrawn water quality by capturing the unpolluted water from intertill aquifers (Zone 4) and forcing replacement of missing quantities by poor-quality water from the WBIMV centre (zones 1 and 2) and surface water.

The commissioning of wells for agriculture in the upper aquifer has not significantly changed the recharge components of the Wroniawy-bis well field.

3.3. WHPZ designation pattern

Polish legislation mandates a 25-year water inflow isochrone as a benchmark that, after reference to land ownership divisions, provides the base for delimitation of WHPZ (Fig. 6). However, the analysis of changes in the Wroniawy well field recharge components (Table 1) raises concerns over limiting the extent of the WHPZ for this well field to an area that may be insufficient to protect the withdrawn groundwater from quality deterioration. Therefore, it is concluded that a WHPZ should, in this case, cover the entire well field capture zone, including 7.7 km^2 of upland north to the 25-year water inflow isochrone.

In order to reduce costs and restrictions associated with implementing WHPZ recommended from a hydrogeological perspective, it was divided into four sectors (A, B, C and D), differing in the scope of limitations, in spite of the fact that this is not common under Polish Water Law. Sector A covers the intermediate protection zone and includes the enclosed water supply system with wells and water facilities. It generally overlaps the one- or five-year water inflow isochrone limited from unauthorised access. Sector B comprises the WBIMV and the slope of the moraine upland with the highest groundwater pollution vulnerability. Sector C

Table 1. Components of the Wroniawy well field recharge balance.

Balance component	Simulation A		Simulation B	
	m^3/d	%*	m^3/d	%*
Inflows from the north				
inflow from the upland (intertill aquifers)	3,272	45.5	2,669	37.0
precipitation recharge (within WBIMV)	1,586	22.0	1,339	18.6
surface water recharge of the Tłocki Dith	0	0.0	353	4.9
ascending flow from the lower aquifer	427	5.9	509	7.1
Total inflow from the north	5,285	73.4	4,870	67.6
Inflows from the south				
precipitation recharge (within WBIMV)	540	7.5	545	7.6
surface water recharge of the North and the Central Obra Canals	480	6.7	655	9.1
ascending flow from the lower aquifer	454	6.3	417	5.8
inflow from the central part of WBIMV (south of the Central Obra Canal)	441	6.1	713	9.9
Total inflow from the south	1,915	26.6	2,330	32.4
Total inflow	7,200	100	7,200	100.0

* % of Wroniawy well field withdrawal Q = 7,200 m^3/d

includes the remaining moraine upland within the 25-year water inflow isochrone range, with high to moderate vulnerability. Sector D encompasses the remaining part of the capture zone in the upland, outside the 25-year water inflow isochrone.

Sectors A–C require qualitative and quantitative protection against infiltration of pollutants and restrictions on constructing new groundwater facilities, while only quantitative prevention measures are required in sector D.

4. Discussion

Well fields located in the ice-margin valleys are characterised by special protection requirements. Their unique location implies that their recharge includes water from the surrounding uplands, which are to some extent protected from the infiltration of pollutants by overlying glacial tills, and water from highly vulnerable ice-margin valleys.

The complex relationship between recharge sources makes determining protection zones for well fields in ice-margin valleys challenging. One reason for this difficulty is the high heterogeneity of sediments overlying the aquifer, with variable vulnerabilities affecting precipitation recharge and migration potential of surface pollutants. This complexity also includes the ability to receive waters of different hydrogeochemical statuses, including unpolluted waters from neighbouring uplands, anthropogenically contaminated water from rural development areas, poor-quality surface water and geogenically polluted groundwater from floodplains in the centre of ice-margin valleys (Górski, 2010b; Dąbrowski et al., 2018). Delineating a suitable WHPZ in such compound settings requires understanding geological heterogenity and the diversity of the well field supply components, and therefore implies the use of groundwater flow modelling.

The recharge balance of the Wroniawy well field indicates that it is supplied mostly by the inflow from the northern side of the capture zone (73.4 per cent). This concerns mainly (45.5 per cent) high-quality water of the intertill aquifer (groundwater quality Zone No. 4; see Fig. 3) that requires only simple treatment of iron and manganese compounds. Furthermore, a significant portion of this inflow (22.0 per cent) comprises high-quality water from the upper terraces of the WBIMV (Zone 4), locally affected by pressure from the village of Wroniawy, associated with elevated concentrations of chlorides and sulphates (found in Zone 2) and agricultural activities inducing elevated nitrate concentrations (Zone 3). The remaining part (5.9 per cent) includes ascending flow from the lower aquifer.

In contrast, inflow from the southern part of the capture zone, located entirely within an ice-margin valley carrying mostly coloured water contaminated with iron, manganese and ammonium ions (Zone 1) and some elevated concentrations of chlorides and sulphates reported in the vicinity of the village of Borki (Zone 2), accounts for 26.6 per cent with sources including precipitation recharge (7.5 per cent), ascending flow from the lower aquifer (6.3 per cent), surface water recharge from the Central Obra Canal (6.7 per cent) and some poor-quality groundwater inflow from the ice-margin valley centre (Zone 1), south of the Central Obra Canal (6.1 per cent).

Agricultural withdrawals, becoming increasingly numerous in the municipal well field capture zone, pose a significant threat to the water quality of the Wroniawy well field by intercepting groundwater streams from the upland. These withdrawals, particularly for crop irrigation, are seasonal, peaking in summer when water demand is highest and precipitation is lowest (Graf & Przybylek, 2018).

According to numerical simulations an increased groundwater abstractions in the Wroniawy well field capture zone, arising from commissioning of wells for agriculture, will only slightly lower the water table at the Wroniawy well field (about 0.25 m), which may seem harmless due to high storage capacity of the ice-margin aquifer. However, the recharge balance indicates that it would contribute to adverse consequences on recharge constituents by decreasing the volume of components with high-quality water (Zone 4), such as the inflow from intertill aquifers (by 8.5 per cent) and precipitation recharge (by 3.3 per cent) in the WBIMV (Table 1). The losses would be compensated by increases in poor-quality components such as surface water inflow from the Tłocki Ditch (4.9 per cent), which was previously draining and the North and Central Obra canals (rising by 2.4 per cent). An enhanced abstraction may also trigger a 3.8 per cent increase in the inflow of geogenically contaminated waters from the central parts of the WBIMV south to the Central Obra Canal (Zone 1). In this regard, the overexploitation-induced inflow from the vicinity of the village of Solec (Zone 2), with the highest sulphate concentrations, may be particularly detrimental for the Wroniawy well field as geogenic contaminants could significantly reduce the efficiency of the treatment method applied (Górski, 2017). The proportion of poor-quality water may intensify during hydrological droughts due to reduced or absent precipitation recharge (Graf & Przybyłek, 2018).

Apart from the inflow of poor-quality water, the deterioration in quality of abstracted water may also be linked to the development of sulphides and organic matter oxidation processes resulting from a decrease in piezometric pressure in the aquifer due to well operation (Górski, 2010c). This effect, specific to unconfined aquifers, has also been confirmed at the Zawada well field for Zielona Góra in the Odra ice-margin valley (Górski, 2010b).

Previous chemical investigations have similarly confirmed that excessive water abstraction has led to the successive deterioration of water quality from the Wroniawy well field (Górski, 2017). In this regard, it should be emphasised that overexploitation in the well field capture zone would exacerbate this process. This is especially true given that earlier reports by Dąbrowski et al. (2005) highlighted the need to restrict water abstraction in the WBIMV area due to its unsuitability for drinking.

A sustainable management of groundwater resources in the capture zone of municipal well fields situated in ice-margin valley aquifers is required to ensure that the high-quality water is captured, as even a small increase in depression due to uncontrolled water abstraction might be detrimental to the municipal well field water quality. Considering the above factors contributing to changes in the Wroniawy well field recharge components, it is recommended to implement quantitative protection of its most valuable high-quality recharge sources (Zone 4) by establishing the WHPZ that would cover the entire well field capture zone regardless of the 25-year water inflow isochone, in order to preclude adverse water quality changes. Such an approach is not practiced in Poland, however, it aligns with standards used in many other countries (for exampled, Slovenia, Finland and Austria) (Brenčič et al., 2009; Osmanaj et al., 2021).

In order to reduce costs and limitations, following the example of other countries, such as Argentina, Greece, Italy, Slovenia and the United Kingdom (Brenčič et al., 2009; Doveri et al., 2015; Paris et al., 2019; Osmanaj et al., 2021; Steiakakis et al., 2023), the WHPZ should be divided into four sectors (Fig. 6) differing in the scope of restrictions. Within the 25-year water inflow isochrone, the most vulnerable sectors A–C should prevent activities that may introduce pollutants into the environment and preclude the construction of new wells. In the furthest medium- and low-vulnerable sector D, only limited precautions are called for in order to prevent the construction of new well fields, so as not to deplete the high-quality water supply from this area.

Implementing a quantitative protection of groundwater contributing recharge to the municipal well fields is challenging worldwide, as in most cases, conservation of these well fields is solely identified with a qualitative protection against the influx of pollutants from the land surface (Ahmadi et al., 2023). Despite this, the literature reports cases highlighting that WHPZs defined by travel time criteria may protect an insufficient part of well field resources to prevent its water quality deterioration (Zhou et al., 2015). By limiting the extent of WHPZs to a 25-year water inflow isochrone concept, also Polish legislation may not provide sufficient preventive measures to protect water quality at the Wroniawy well field. Even the risk assessment required for such well fields cannot affect this phenomenon, because the Water Law Act does not provide for exceptions.

Changing attitudes towards quantitative protection of water resources from low vulnerable aquifers are difficult to implement due to a lack of understanding among water users, geological administrators and the public. Especially since overexploitation arising from individual agricultural abstractions in municipal well field capture zones often does not cause immediately visible indications as a sharp increase in the depression at the municipal wells, and the process of deterioration in the water quality of abstracted water occurs slowly over several years, making it difficult to link it to these abstractions.

Thus, ensuring the most comprehensive protection possible under the WHPZs requires improving communication between hydrogeologists, the national water authority and society at large (Bjerre et al., 2020), as well as adaptation of Polish geological regulations to the overwhelming trend towards the construction of seasonal wells, among which those for crop irrigation predominate.

In such cases, the Quantitative Protection Zone concept, i.e., an area around a municipal well field where water extraction is permitted only through its wells (Ahmadi et al., 2023), could safeguard against deterioration in the chemical condition of water abstracted for public purposes. The well field capture zones, which are obligatorily designated in Poland at the well field resources documenting stage, could play such a role. Unfortunately, it has no practical use in planning regulations, whereas only the establishment of WHPZ can effectively block the construction of new wells, which makes it impossible to protect sector D effectively from the construction of new intakes.

The implementation of quantitative protection of aquifers serving as the main source of drinking water supply is urgent. Due to rising air temperatures over the past several years, Poland has witnessed an increased and often-uncontrolled groundwater abstraction for crop irrigation, frequently escalating local conflicts when performed within the capture zone of existing municipal well fields. It is favoured by Polish geological regulations that do not prohibit the placement of new well fields in the capture zones of existing ones. It should also be noted that the extent of the depression cone for crop irrigation wells is often underestimated, as the Geological and Mining Law (2011) dictates that it should correspond to the average annual water abstraction, just as in the case of year-round well fields. Meanwhile, these seemingly harmless wells are active only in the summer half year, operating at maximum water demand. Thus, they may jeopardise existing well fields, especially when operated simultaneously (Matusiak & Przybyłek, 2017).

Besides, simple analytical formulas are commonly used to estimate the extent of the depression cone for these wells, with the dominant equations being Sichardt or Kusakin (Desens & Houben, 2022), which tend to underestimate the extent of the depression cone (Louwyck et al., 2022). For this reason, the results often do not reveal the potential interference of the depression cones, and hence, the threat posed by the construction of seasonal wells for agriculture is often downplayed by geological administrations.

Meanwhile, the introduction of a statutory obligation to document the seasonal variation in the extent of the depression cones resulting from the operation of these wells employing numerical modelling would improve the safety of existing groundwater well fields, particularly in areas with a high density of agricultural wells with low average annual yields.

The example analysed above highlights the need for legislative changes to implement quantitative protection of the public water supply's most valuable recharge components. Currently, these waters are being diverted for agricultural use, with lower water quality requirements. Meanwhile, water for crop irrigation could be retrieved from surface water or groundwater from the WBIMV centre. Introducing groundwater resource valorisation in areas with such a high demand could prevent water quality and quantity depletion.

5. Conclusions

The present paper outlines principles of groundwater protection for a municipal well field located in an ice-margin valley aquifer exposed to overexploitation from individual wells for agriculture constructed in its capture zone, and proposes guidelines for designating a WHPZ.

The presented WHPZ delineating and zoning process is designed to protect the most valuable source of the well field recharge, which is high-quality water from geologically protected intertill aquifers adjacent to the ice-margin valley that is crucial for maintaining the stability of water quality in the municipal well field.

The results of groundwater flow modelling indicate that the uncontrolled operation of wells for agriculture will be followed by a slight and apparently harmless growth of depression in municipal wells. However, this will trigger changes in the recharge components of municipal well field, due to intercepting much of the high-quality water from intertill aquifers and compensating for this shortage by an increase in poor-quality components (surface water and geogenically polluted groundwater from the centre of ice-margin valley).

To protect this well field against adverse changes in water quality, it is recommended that the WHPZ cover its entire capture zone, including areas located outside the 25-year water inflow isochrone (sector D). However, this is not standard practice in Poland. The WHPZ should be divided into four sectors with different restrictions, introducing quantitative safeguards preventing the construction of new wells throughout its area (sectors A–D) and qualitative protection consisting of limiting activities that may introduce pollution in the most vulnerable areas near the well field (sectors A–C).

Implementing quantitative protection throughout the well field capture zone would protect high-quality water (Zone 4) that dilutes polluted water from rural areas (zones 2 and 3) and prevent geogenically contaminated water (Zone 1) from entering the well field. However, current Polish legislation, which limits WHPZ extent to the 25-year water inflow isochrone concept, fails to offer adequate protection for such well fields.

The lack of regulations governing the construction of non-municipal wells in the capture zones of existing municipal well fields and the lack of monitoring of the impact of these abstractions promote the depletion and deterioration of water quality for public use. Legislation must evolve to ensure quantitative protection of high-quality water flowing from low vulnerable aquifers and prioritise their use for public supply over agriculture, which can utilise lower-quality water sources. Implementing groundwater resource valorisation could help manage these resources better. Applying such an approach is believed to be valuable to improving protection principles in countries with WHPZs based on isochrones.

Acknowledgements

We wish to thank the Wolsztyn Waterworks Board for providing the data and information that allowed these investigations and two anonymous reviewers for their comments and suggestions; these contributed to improving the content of the present paper.

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Manuscript submitted: 6 August 2024
Revision accepted: 25 September 2024