# Delineation of wellhead protection area based on the analytical elements method (AEM) – a case study with comparative research

Maciej Nikiel[1], Robert Zdechlik[2]

[1]*AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Krakow, Poland, e-mail: mnikiel@agh.edu.pl, ORCID ID: 0000-0002-0716-365X*
[2]*AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Krakow, Poland, e-mail: robert.zdechlik@agh.edu.pl, ORCID ID: 0000-0003-2808-0527*



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***Abstract:*** The delineation of protection zones for groundwater intakes is a difficult task resulting from the significant variability of regional and local environmental conditions. Different methods are used, both simple (analytical or graphic), giving estimated results, and the most reliable, but also the most time-consuming ones, based on numerical groundwater flow models. An alternative method for the delineation of protection zones is the analytical elements method (AEM), which gives solutions like those obtained using FDM/FEM modelling methods with a relatively low degree of complexity. The estimated ranges of protection zones obtained with the use of four methods are presented for the selected test area (groundwater intake around Olesno). Results obtained with the use of the FDM model were taken as reference and CFR and SimpleWHPA were used as simplified methods. Comparative studies indicate that the results obtained by the CFR method differ significantly from the results of other methods, and their reliability is low. The results of the SimpleWHPA method are satisfactory, given the relative simplicity of the method. On the other hand, the results obtained with the AEM are close to the results obtained with the FDM treated as a reference. Considering that AEM is less time-consuming than FDM (which requires the most effort for proper model preparation), the use of AEM in the practice of protection zone delineation seems to be an interesting alternative.

***Keywords:*** groundwater source protection zone, WHPA – wellhead protection area, Olesno intake, groundwater modelling, CFR – calculated fixed radius, FDM – finite differences method, FEM – finite elements method

## INTRODUCTION

The use of groundwater for municipal purposes is inseparably connected with the need to ensure its proper quality. Minimizing the negative impact on groundwater quality of a few potential geogenic threats is usually considered in terms of hydrodynamic issues, e.g., limiting the possibility of the infiltration of waters with increased mineralization or specific physicochemical compositions, which could occur because of generating excessive pressure differences, e.g., because of increased exploitation. The protection of abstracted waters against negative anthropogenic impact, to which groundwaters, as well as other elements of the natural environment, maybe subjected, is a different issue. Therefore, any effective protection of the groundwater intake should aim at eliminating the possibility of anthropogenic threats in the area where the hydrodynamic field indicates water inflow to the intake.

The proper protection of intake water quality is possible by establishing an adequate groundwater source protection zone (GSPZ), also called a wellhead protection area (WHPA). A wellhead protection area means the surface and subsurface area surrounding a well or well field that supplies a public water system. Contaminants are likely to flow through this region and finally reach the water well or well field (NARA 2022). Groundwater source risk assessment should follow the delineation of wellhead protection regions (Duda et al. 2021). The World Health Organization has recommended that a drinking water safety plan and risk management system be implemented to manage groundwater resources (WHO 2017). This is required to avoid potential risks within wellhead protection zones.

The obligation to create special protection areas around intakes started to be introduced into law already before the Second World War. For example, in France, mandatory protection zones for certain intakes were introduced as early as 1935 (Mather & Howden 2013), and in Poland, the issue was first addressed by a law of 1962 (*Ustawa…* 1962).

Currently, protection zones for groundwater intakes in most countries are divided into two main areas. The first, called the direct protection zone, is located directly around the intake and the equipment operating in the intake. In this area, any activity other than water exploration is prohibited. In most countries this zone is a strip around the intake with a minimum width of a few meters (usually 10 m) up to as much as 100 m or expressed in terms of the 24 h seepage time of the water into the intake (Macioszczyk et al. 1993, Łyp 2018). The second area is referred to as the intermediate protection zone (called wellhead protection zone/area, groundwater protection zone/area or groundwater source protection zone/area). In this zone, there are significant restrictions on agriculture and construction, as well as the use of hazardous or petroleum-based substances. The size of the protection area is usually determined by the duration of water inflow to the intake from the surface calculated in years (Łyp 2018), starting from 10 (Netherlands) up to even 100 years (Hungary).

The water law act currently in force in Poland (*Ustawa…* 2017), which relates to the EU Water Framework Directive (*Directive…* 2000), provides for a two-zone division of the protection zone: a direct protection zone covering the immediate neighbourhood of the intake (with no specific value defined) and an intermediate protection zone delimited to the boundary of the intake recharge area or the isochrone 25 years of water inflow to the intake.

The correct delineation of a groundwater intake protection zone is a difficult task, which is due to the usually significant variability of regional and local nature of geological structure and hydrogeological conditions (Duda et al. 2013) and also the spatial variability of land use in the study area and the potential impact of land use on groundwater (Bujnovský et al. 2016, Duda et al. 2020). In addition, factors such as well yield, type of intake (single or multiple wells), and hydrodynamic interaction with other neighbouring intakes influence the shape of the area from which water flows to the intake. Additional complications in the interpretation may also result from the possible impact of mining drainage (Motyka & d'Obyrn, 2022). The necessity to apply specific land use restrictions within the designed protection zones results in a diversified approach to their designation. Moreover, the target range of the designed protection zones is also influenced by various formal and legal conditions. As a result, it is difficult to unify the way of delimiting protection zones and to indicate unambiguously the possible methods of their delimitation.

In the practical implementation of establishing protection zones of groundwater intakes, different methods are used. Some of them are simplified and give only approximate results. Such methods include traditional analytical or graphical methods, which are far from perfect, and their implementation is sometimes time-consuming. The most reliable methods are based on numerical models of filtration processes, using FDM (Modflow) or FEM (Feflow) simulators. An overview of the software used to model filtration processes and contaminant migration in groundwater is presented by Zdechlik (2016) and Pietrzak (2021), among others. Examples of the application of different model methods for the same research area are presented by Zdechlik & Morański (2017) and Zdechlik & Kałuża (2019). The use of FDM/FEM requires the creation of a numerical model of all or part of the aquifer structure under consideration. However, constructing a properly working numerical model even for a small area consumes a lot of time and requires good knowledge of the distribution of hydrogeological parameters of the rock mass, also in the further surroundings of the intake. For prognostic calculations performed on the model to be characterized by adequate reliability, it is required to calibrate it beforehand, concerning the results of real observations (Kulma & Zdechlik 2009, Anderson et al. 2015). Only a model prepared in this way can be the basis for the reliable determination of the range of protection zones of intakes, and it also allows other complex hydrogeological problems to be solved (e.g., determination of aquifers or determination of the impact of exploitation on the hydrodynamic field system).

In many countries, especially in the United States, the analytical elements method (AEM) (Raymond et al. 2006) is increasingly being used to delineate protection zones of groundwater intakes. In a simplified form, it consists of mapping important factors that shape water inflow to the intake using analytical elements, together with equations that characterize them. Next, a system of equations is solved by the superposition method. This approach allows for the construction of relatively simple, more generalized models, which accuracy is usually sufficient to solve problems connected with establishing protection zones. In practice, determining the range of a protection zone based on AEM is usually faster than using traditional modelling studies. Moreover, due to the availability of suitable software tools dedicated to WHPA delineation in a no-cost form (US EPA 2022), it is less expensive compared to the use of commercial software for groundwater flow modelling with traditional FDM or FEM. These two features (time and cost savings), combined with satisfactory accuracy of calculations, are desirable during the preparation of documentation for intakes. Hence, the use of AEM in the problem of the delineation of protection zones of wells seems to be an interesting alternative, allowing for a relatively low cost to significantly improve the reliability of these operations in comparison with analytical and graphical methods.

## METHODS

### Analytical element method (AEM)

The analytical element method (AEM) belongs to the group of model-based methods. The calculation is mainly based on Poisson's equation, however, in the representation of the individual analytical elements Darcy's law or the continuity equation and others are used (Wuolo et al. 1995, Kaluđerović et al. 2018). The individual analytical elements of the model are given a discharge potential function $\Phi_i(x, y, t)$. One element may represent a well, another an outflow to a single river segment, another an inflow of water from precipitation, and so on. Each function has a specific number of coefficients which determines the number of its degrees of freedom. The values of the coefficients are determined in such a way that the equation satisfies the boundary conditions set on the model at the so-called binding points. Ultimately, the potential outflow at a given point is the sum of the effects of all the elements introduced into the model (Equation (1)). A single system of equations can have multiple conditions. The complexity of the expression depends on the number of elements introduced into the model (Rogoż 2007, Fitts 2013). Based on the equation solved for the point under consideration, the position of the water table at that point is determined:

$$\Phi_t(x,y,t) = \\ = \Phi_1(x,y,t) + \Phi_2(x,y,t) + \Phi_3(x,y,t) + \ldots + C \quad (1)$$

where:

$\Phi_t$ – total discharge potential,
$\Phi_1, \Phi_2, \Phi_3$ – analytic functions associated with specific elements,
$C$ – constant of integration.

The construction of the AEM computer model begins with the adoption of a conceptual model that represents the real structure under consideration in a simplified schematic manner, considering external influences. This involves the need for a detailed reconnaissance of the study area and the determination of the filtration parameters of the modelled structure. Based on the conceptual model, the investigated structure is given the character of a coherent, homogeneous area in the AEM modelling software. Hydrogeological parameters are initially assumed in a simplified form to be uniform for the whole area. In case of the need to map parametric differentiation, corrections are made in the defined subareas (Fig. 1A). Due to the smaller possibilities of differentiating the distribution of parameters, AEM models in this respect represent reality in a simplified way. Elements like wells (Fig. 1C) or rivers (Fig. 1E) are introduced as points or linear elements with mapped real-world sizes. In comparison to FDM mapping (Fig. 1B, D, E), where boundary conditions and parameter sizes are determined for cells resulting from the adopted grid, the mapping of boundary and object locations in AEM models (Fig. 1A, C, E) is more precise, in locations corresponding to their actual occurrence. Due to the possibility of precise localization and considering the real size of analysed objects, as well as the possibility of reading the position of the water table at a particular point, the obtained AEM results may be easier for further elaboration in comparison to FDM/FEM, where the results are obtained concerning the adopted block partition grid.

## Other methods

Three other methods typically used in the delineation of groundwater intake protection zones (Kraemer et al. 2005, Duda et al. 2013) were selected for a comparative study: the FDM numerical modelling method and the analytical methods calculated the constant circle CFR and Simple-WHPA.

### *Numerical modelling*

There are two main computational methods in numerical modelling: FDM and FEM. They have been known for several decades and widely used (especially FDM), mainly in situations where the accuracy of obtained results counts, and time and cost of implementation are less important.

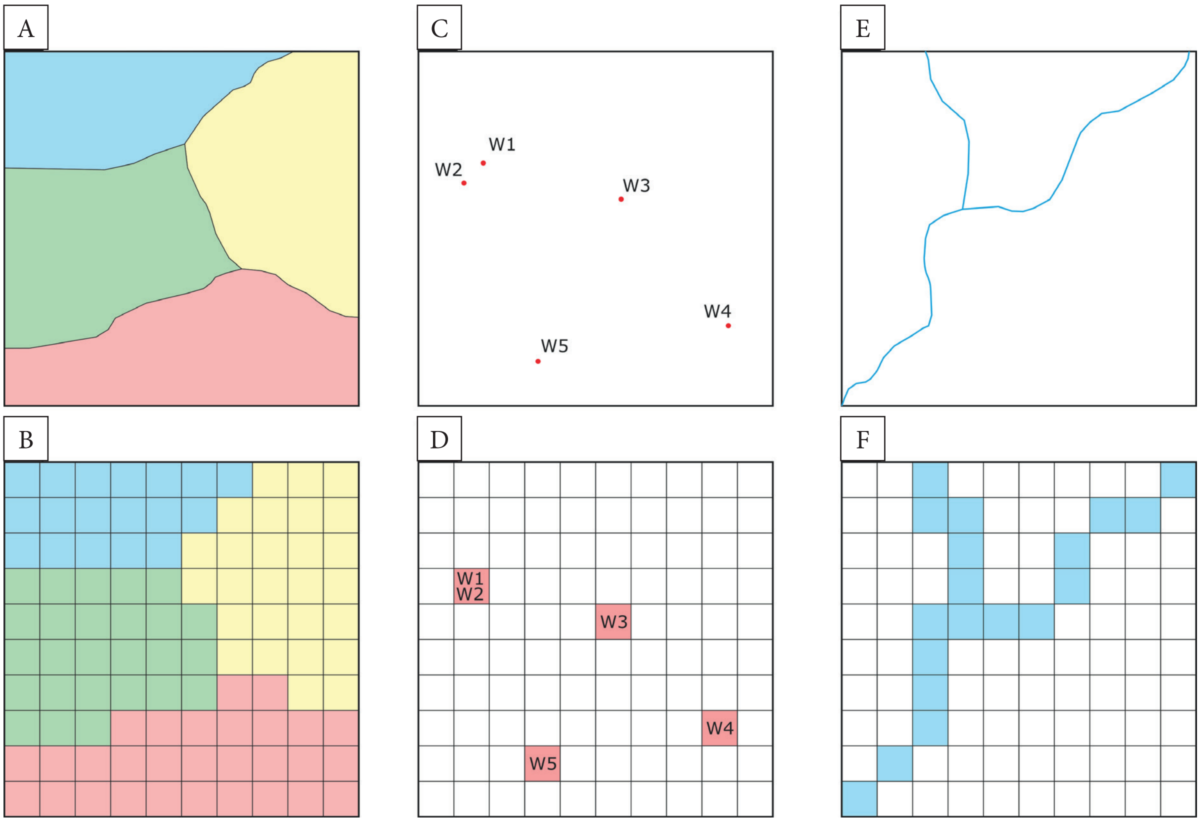


***Fig. 1.*** *Mapping on AEM model (A, C, E) and FDM model (B, D, F): parametric variation (A, B), wells (C, D), rivers (E, F)*

Detailed information on the principles of numerical modelling with the use of these methods is presented in numerous publications, e.g., McDonald & Harbaugh (1988), Spitz & Moreno (1996), Kresic (2006), Diersch (2014), Anderson et al. (2015), MIKE Powered by DHI (2022), and USGS (2022).

FDM and FEM are very accurate and reliable methods, but also, they are quite complicated, rather expensive, and time-consuming. For these reasons, they are usually used less frequently in the case of delineation of protection zones, especially for small intakes.

Model implementation begins, as in AEM modelling, with the adoption of a conceptual model of water circulation in the structure under consideration. In numerical modelling, it relates to the necessity of making a much more precise reconnaissance, as well as defining a larger number of parameters. Further course of action depends on the choice of modelling method. The study area is divided into cells, forming a computational grid. In the case of FDM models, the cells are rectangular, and the parameters are defined for the centres of each cell. In the FDM, the discretization mesh in the plan consists of triangular elements and the model parameters are assigned to the cells or mesh nodes. The accuracy of the representation of objects on the model depends on the size of computational cells, which are assigned certain features (boundary conditions) and parameters. The obtained results refer directly to the computational cells and not strictly to the specific objects. In some cases, this makes it necessary to refine the results by converting the values obtained for the cells to correspond to the location of the object (e.g., well). To improve the representation of objects, smaller cells can be used in selected zones by refinement of the discretization grid.

Once the model is prepared, it is necessary to calibrate it, which consists in bringing the model response into conformity with the effects observed. During calibration, the hydraulic head and inflow/outflow volumes obtained from the model are compared to those observed (Kulma & Zdechlik 2009). In case of differences, adjustments are made within the model (most often to the assumed parameters), and then the computational process is performed, and the results are compared again. The process is repeated until the model results coincide with the real observations, with the assumed tolerance. Only a properly calibrated model can be used for reliable prediction calculations, e.g., related to determining the range of intake protection zones.

### *CFR method*

The calculated fixed circle method is a very simple analytical method which does not consider the direction of water flow. As a result, the protection zone coverage is mostly characterized by overestimation in the area downstream of the intake (Fig. 2). The radius of the circle is calculated using the formula (Kresic 2006):

$$R = \sqrt{\frac{Qt}{I_e \pi t + n \pi H}} \tag{2}$$

where:

- $R$ – radius of the protection zone for the time of inflow [L],
- $t$ – travel time [T],
- $Q$ – pumping rate of the well [$L^3$/T],
- $I_e$ – effective areal recharge [L/T],
- $n$ – effective aquifer porosity [–],
- $H$ – saturated aquifer thickness [L].

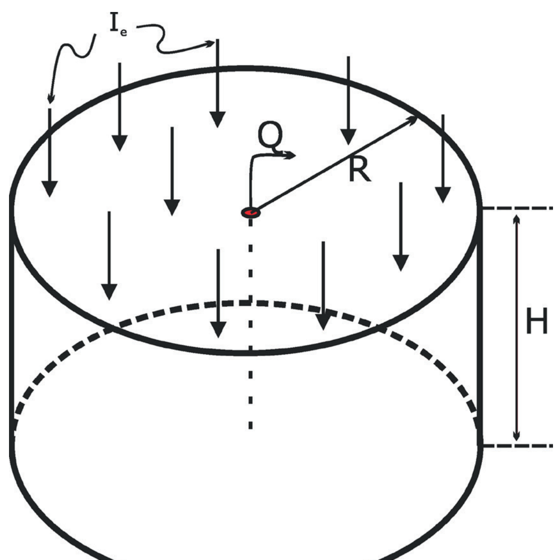


***Fig. 2.*** *Schematic of protective zone delineation using the CFR method (after Kresic 2006, modified)*

### *SimpleWHPA method*

The SimpleWHPA calculation package is available at no cost from WhAEM software (US EPA 2022). It uses uniform flow estimation in an aquifer based on analytical formulas for water flow and parameters such as hydraulic gradient or aquifer conductivity (Kraemer et al. 2005). It allows for a very quick estimation of the size and range of the protection zone.

The calculation of protection zone shapes and sizes for intake wells requires the determination of a dimensionless travel time parameter for the aquifer, according to Equation (3). The reference time is calculated using Equation (4), based on aquifer parameters and pumping rate of the well, as well as the unit measure of uniform flow calculated according to Equation (5). The obtained value of the time parameter allows the selection of the predicted basic shape of the protection zone (Fig. 3).

$$\tilde{T} = \frac{T}{T_0} \tag{3}$$

where
- $\tilde{T}$ – dimensionless travel time parameter [–],
- $T$ – time-of-travel [T],
- $T_0$ – reference time [T],

$$T_0 = \frac{nHQ}{2\pi Q_0^2} \tag{4}$$

where:
- $n$ – effective aquifer porosity [–],
- $Q$ – pumping rate of the well [$L^3/T$],
- $H$ – saturated aquifer thickness [L],
- $Q_0$ – magnitude of the uniform flow [$L^2/T$],

$$Q_0 = kHI \tag{5}$$

where:
- $k$ – hydraulic conductivity [L/T],
- $I$ – hydraulic gradient [–].

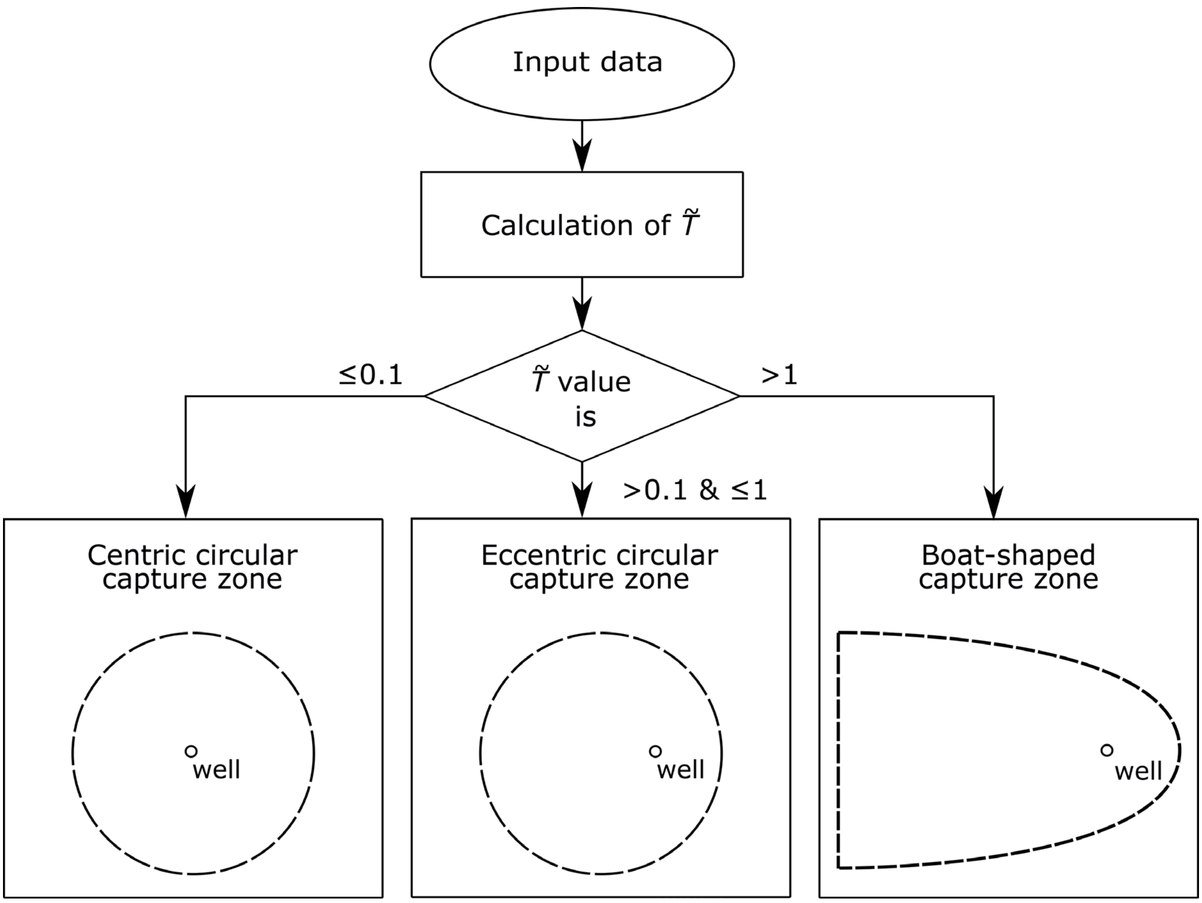


***Fig. 3.*** *Basic protection zone shape selection scheme applied in SimpleWHPA method (after Kraemer et al. 2005, modified)*

## CHARACTERISTICS OF THE STUDY AREA

A comparative analysis of methods of delineation of protection zones was carried out for a selected study area – groundwater intakes situated near Olesno village in the Opole Voivodeship, south-western Poland (Fig. 4). Groundwater is exploited by three groups of wells comprising the following intakes: Olesno (Ps-2 and 2Baw wells), Wygoda (2 and 1aw wells) and Wysoka (S Ibis2, S IIbis, S IIaw, S IIIbis wells).

The wells are located outside dense buildings, in agricultural areas, except for the Olesno intake, which borders on dispersed urban buildings in the north.

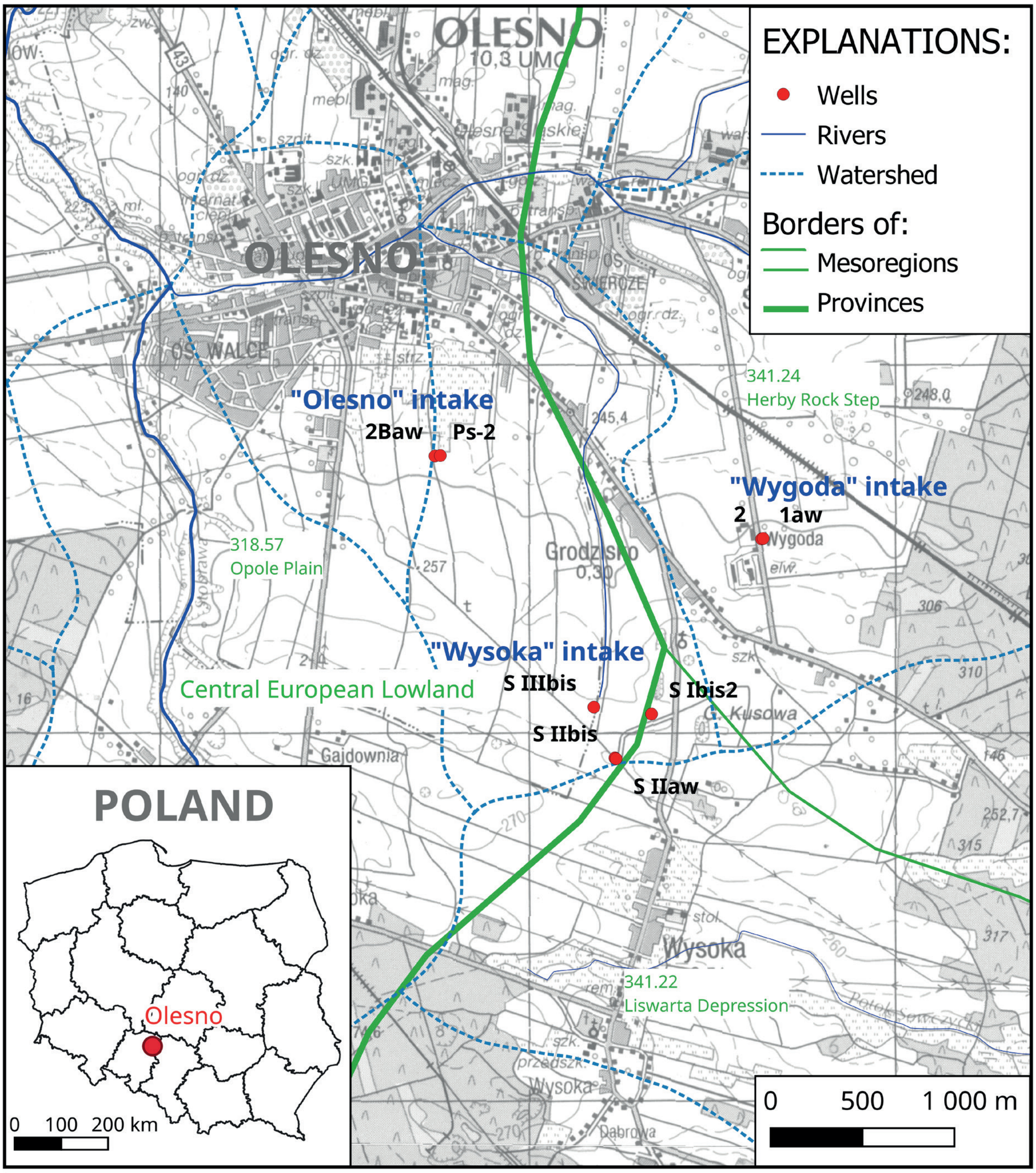


*Fig. 4. Location of the study area*

The study area by physico-geographical regions (Solon et al. 2018) is in the border zone between the Central European Lowland province (on the western side) and the Polish Uplands (on the eastern and southern side – Fig. 4). The upland zone includes the Herby Rock Step (where the Wygoda intake is situated) and Liswarta Depression (where a part of the Wysoka intake is situated). The Olesno intake and the remaining wells of the Wysoka intake are in a fragment of the Central European Lowlands (Opole Plain).

In most of the area, the land surface is almost flat, descending in the northern direction towards the Starobrawa River. South of the intakes there are gentle hills which are terminal moraines, and in the north – a complex of hills forms the Herby Rock Step unit. The hydrographic network is not very complex. It is formed by the Młynówka River, which flows from the east to the west through the town of Olesno, and on its left bank, quite numerous, small tributaries (including the Wysoka stream). The Młynówka River joins the Starobrawa River, flowing west of the discussed intakes (Fig. 4).

The geological structure of the region includes a Mesozoic basement covered by Quaternary formations. The bedrock is formed by the structure of the Silesian-Cracow Upland, which is a monocline stretching SE-NW, with NE dipping. In the study area, the youngest formations of the Mesozoic period are in the form of Upper Triassic sediments – claystone and mudstone deposited at the depth of approx. 50 m (Haisig & Wilanowski 1990). Directly on the Mesozoic rocks lie Quaternary rocks, developed in the form of gravels and sands of fluvial sedimentation, with thicknesses up to 15 m. On top of these, there are bifacial till deposits, interlayered with sands of variable thickness. The upper layer of clays is characterized by a greater thickness (even up to 20 m) and in part of the area, it reaches the surface. The lower layer of clays is often reduced and replaced by a layer of sands of increased thickness, even up to 20 m. There are sands and gravels and boulders of end moraine directly under the land surface in the prevailing area.

In the studied area, the main aquifer is in Quaternary formations. North of Olesno, groundwater is also extracted from Upper Triassic formations, whereas in the eastern direction there are intakes in Lower Jurassic formations. The wells of these intakes extract water from Quaternary aquifers, where the aquifer is composed of sand and gravel about 20 m thick. The layers are locally separated by clays, which in part of the area lie directly under the land surface. Water from individual layers of sandy formations remains in full hydraulic connection.

## WELLHEAD PROTECTION AREA CALCULATIONS

According to Polish law, protection zones have been designated to isochrone 25 years of water inflow to the intake (*Ustawa…* 2017).

### AEM model

The program of U.S. Environmental Protection Agency's – WhAEM (Wellhead Analytic Element Model for Windows) (US EPA 2022) – was used to delineate protection zones for the intakes with the AEM. This program is a free and open-source groundwater hydrology computer application designed to help state or tribal Wellhead Protection Programs (WHPP) and Source Water Assessment Planning (SWAP) for public water sources in the United States. WhAEM is a computer program that allows one to build protection zones using radius approaches, well in uniform flow solutions, and hydrogeology modelling methods.

The prepared AEM model (Fig. 5) covers an area of about 110 $km^2$, larger than the considered FDM numerical model. Increasing the model coverage helped to not only consider environmental conditions located in the immediate surroundings of the intakes but also those located farther away (e.g., possible interaction of groundwater with river waters outside the immediate run-off area). In technical terms, the extension of the study area is not too time-consuming, which should be considered one of the characteristics of using the AEM.

The actual hydrogeological conditions were mapped on the model in a simplified form. A single confined-unconfined aquifer, the thickness of 15 m (modified during calibration to 16 m), hydraulic conductivity of 15 m/d (after calibration 17 m/d) and porosity of 0.2 was assumed.

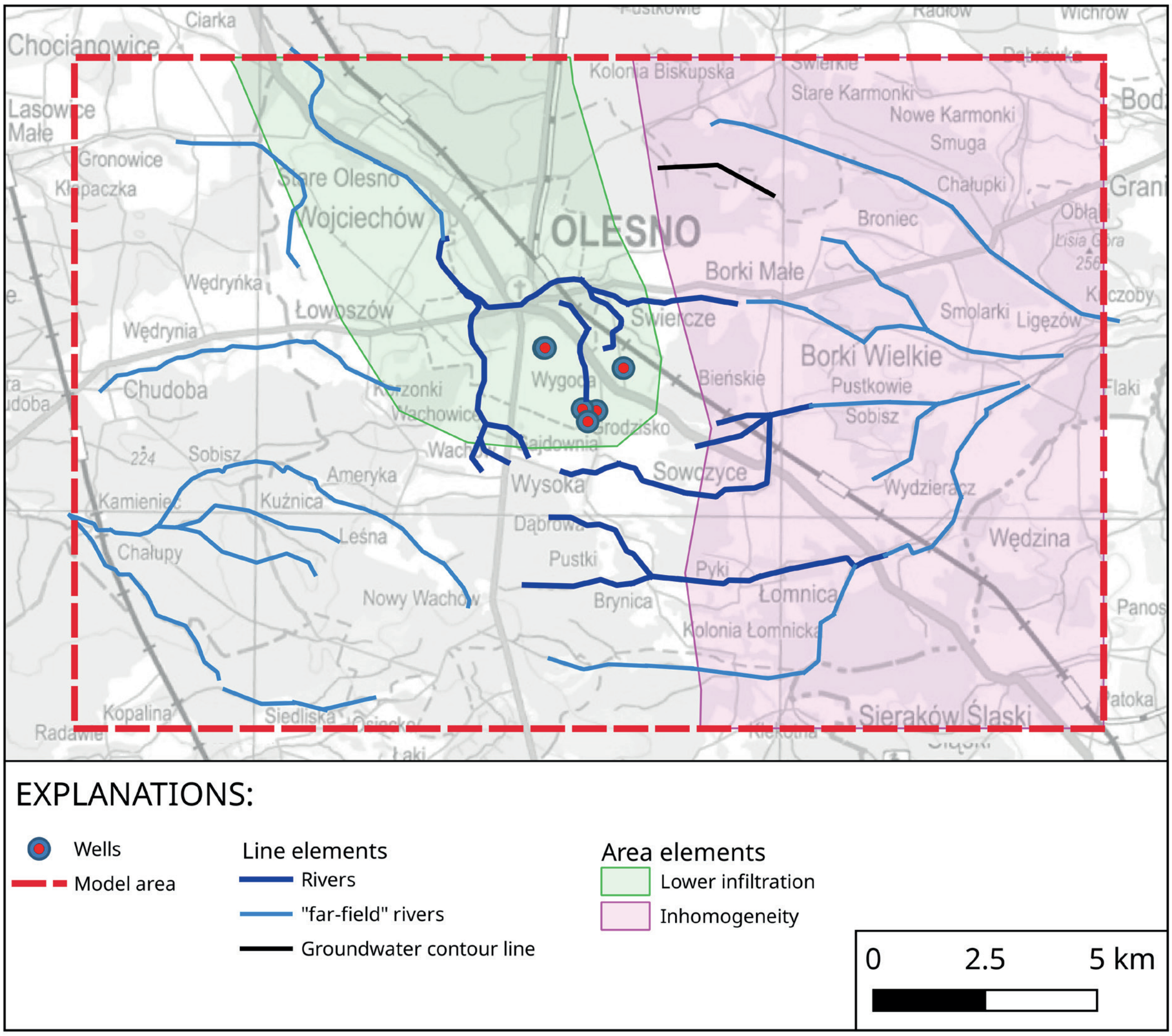


***Fig. 5.*** *Environmental conditions mapped on the AEM model*

Within the model, rivers were mapped using line-sinks elements as analytical objects. To simplify model construction, only main rivers were mapped away from the intakes. They were mapped as *far-field* elements by assigning only a parameter reflecting the linearly varying position of the water table, while river channel and bottom sediment parameters were not considered. The ordinates of the water level assigned to elements were read from topographic maps or digital elevation models. The purpose of such elements is to stabilize the groundwater table in areas distant from intakes. This way of simulating rivers by keeping the water table at the assumed level corresponds to boundary conditions of I type ($H$ = const) from numerical models (FDM or FEM). As a result, the exchange of groundwater with surface water (recharge or drainage) assumes unlimited character.

In the immediate neighbourhood of the intakes, the rivers were given a higher accuracy, using line-sinks elements. Unlike the distant rivers, this also allows for considering river channel parameters (resistance, width and depth). River sections located closer to the intakes were mapped with this type of element, assuming river channel filtration parameters corresponding to those presented in Kryza et al. (2014), as well as appropriate hydraulic gradients (by assigning the starting and ending ordinates of the nodes of each section). These parameters, at the model calibration stage, were significantly modified (like in the FDM model).

In addition, a linear element was assumed on the AEM model to reflect the groundwater contour lines course with a known value (Fig. 5). The condition of constant piezometric pressure was assumed for this element to stabilize the groundwater level further from the intakes under consideration.

The recharge from effective infiltration of precipitation was given as surface elements over the whole modelled area. In the process of model calibration, corrections were made, modifying the magnitude of recharge using inhomogeneities of the cover formations and variability of near-surface zone parameters. As a result, in most of the model (in the zones with alluvial deposits in the east and south of the area), the recharge from infiltration per unit area took the value of $4.8 \times 10^{-4}$ m/d. Only in a relatively small zone, covering directly the area of the intakes and the area northwest of them (Fig. 5), a limited infiltration recharge of $2.5 \times 10^{-4}$ m/d was assumed.

The model calibration was based on data presented in the hydrogeology documentation (Kryza et al. 2014) and obtained from the "Bank Hydro" database (CBDH 2022). During calibration, the parameters assigned to each element were modified by comparing the quantities observed (water level position at the assumed calibration points) with the values obtained from the AEM model. The mean difference in the water table position obtained after model calibration is about 0.1 m and the median of 0.3 m. The greatest difference (3.9 m) was recorded at the point far from the intake well, around simplified river inflow (*far-field*). The arrangement of measurement points directly in the vicinity of the diagonal of the calibration plot (Fig. 6) means that there is a good fit of the model response to the actual observations (Anderson et al. 2015).

Based on the calibrated AEM model, the groundwater table location was mapped and the area of water run-off to the intake limited by the 25-year isochrone was determined, which corresponds to the extent of the wellhead protection area (Fig. 7). The maximum discharge of intake wells, equal to approved exploitation resources, were assumed in calculations.

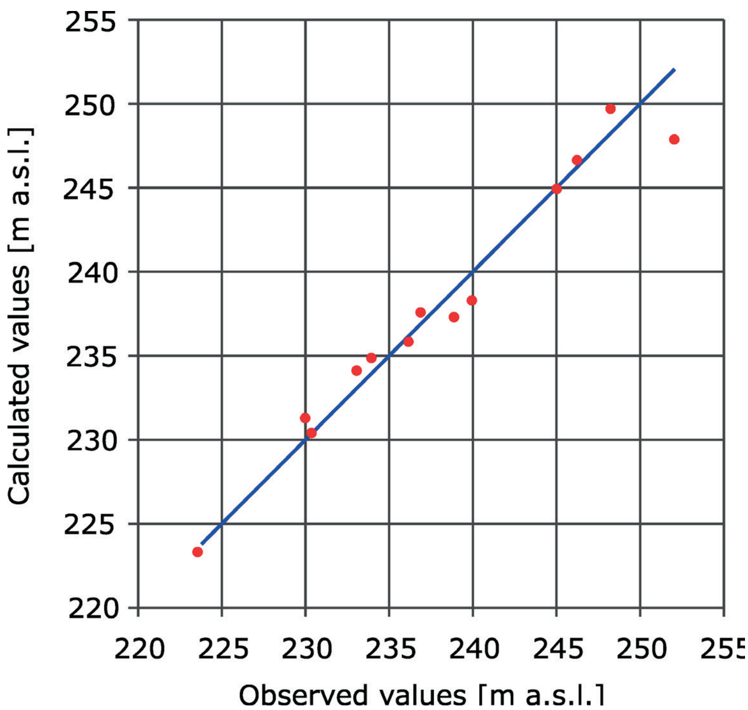


***Fig. 6.*** *Comparison of the water table ordinates obtained from the model (calculated values) and observed in reality (observed values) for the adopted calibration points*

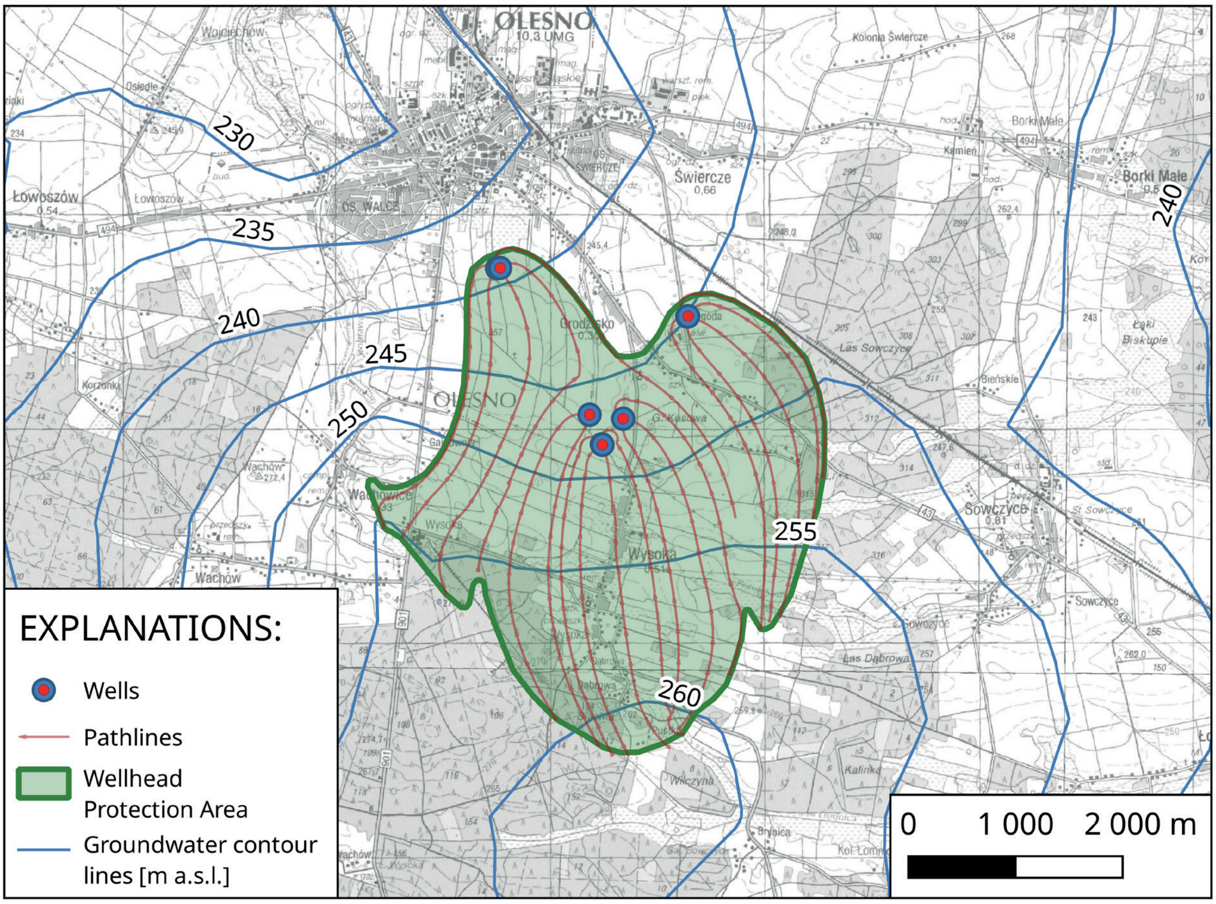


***Fig. 7.*** *Groundwater contour lines and wellhead protection area obtained from the AEM model*

## Other methods

### *FDM model*

The ranges of protection zones determined based on numerical modelling of filtration processes with the FDM are considered to be the most reliable. The numerical model of groundwater filtration, realized within the scope of documentation of admissible volume of extracted groundwater in Olesno (Kryza et al. 2014), was prepared in Visual MODFLOW software, using FDM-based simulators from the widely used MODFLOW family (USGS 2022). The boundaries of the study area were based on natural conditions: watersheds and river segments. As a result, the model covers an area of 110 km$^2$ (10 km × 11 km). Initially adopted fixed size of grid cells (200 m × 200 m) was modified at the calibration stage by linear double refinement in the well location zone; finally, the grid consisted of 68 columns and 63 rows.

In the vertical division, the modelled structure was represented as three layers. The first layer corresponds to sandy loams, with low filtration parameters (originally assumed to be $k$ = 0.1 m/d), bottom elevations ranging from 220 m a.s.l. (in the northern part) to 250 m a.s.l. in the Wysoka intake area. The deeper, second layer is formed mainly by well-permeable water-bearing sediments ($k$ from 0.5 m/d in the peripheral part to 17–21 m/d in the intake area, average $k$ = 15 m/d). The bottom elevations range from about 210–217 m a.s.l. in Olesno and Wysoka intakes to over 242 m a.s.l. in the area of Wachowice. The third layer of the model corresponds to impermeable Pleistocene clays and Mesozoic sediments, only locally (in the eastern part) – to water-bearing Jurassic sandstones of 7 m thickness.

River fragments were simulated with Type I (larger rivers) or Type III boundary conditions. Recharge from effective infiltration of precipitation was differentiated depending on the type of near-surface sediments, assuming from 43 to 52 mm/year in the southern and central parts and from 14 to 28 mm/year in the northern part. The intake wells on the model were mapped with a boundary condition of the second type, assuming the actual discharge achieved by them.

Within the calibration, values of recharge from infiltration of precipitation, vertical hydraulic conductivity component, parameters of stream channel bottom sediments and, to a lesser extent, filtration parameters (mainly in the areas of rivers and intakes) were modified locally. The validity of calibration was checked based on water table measurements from 8 drilled wells located in the intake areas. After calibration, the mean difference between the measured and modelled water tables is 0.4 m, while the normalized mean squared reaches 5.1%. According to contemporary accepted modelling principles (Anderson et al. 2015), the calibration results achieved can be considered acceptable, while the model itself can be treated as reliable for predictive purposes.

A prognostic solution was implemented on the calibrated model, assuming the operation of the intakes with flow rates corresponding to the approved exploitable resources. The obtained layout of hydrodynamic field made it possible to define an area of groundwater flow to the intake. An isochrone of 25 years of inflow to the intake was delineated within its boundaries. Such a limited area of 12.61 km$^2$ corresponds to the wellhead protection area (Fig. 8).

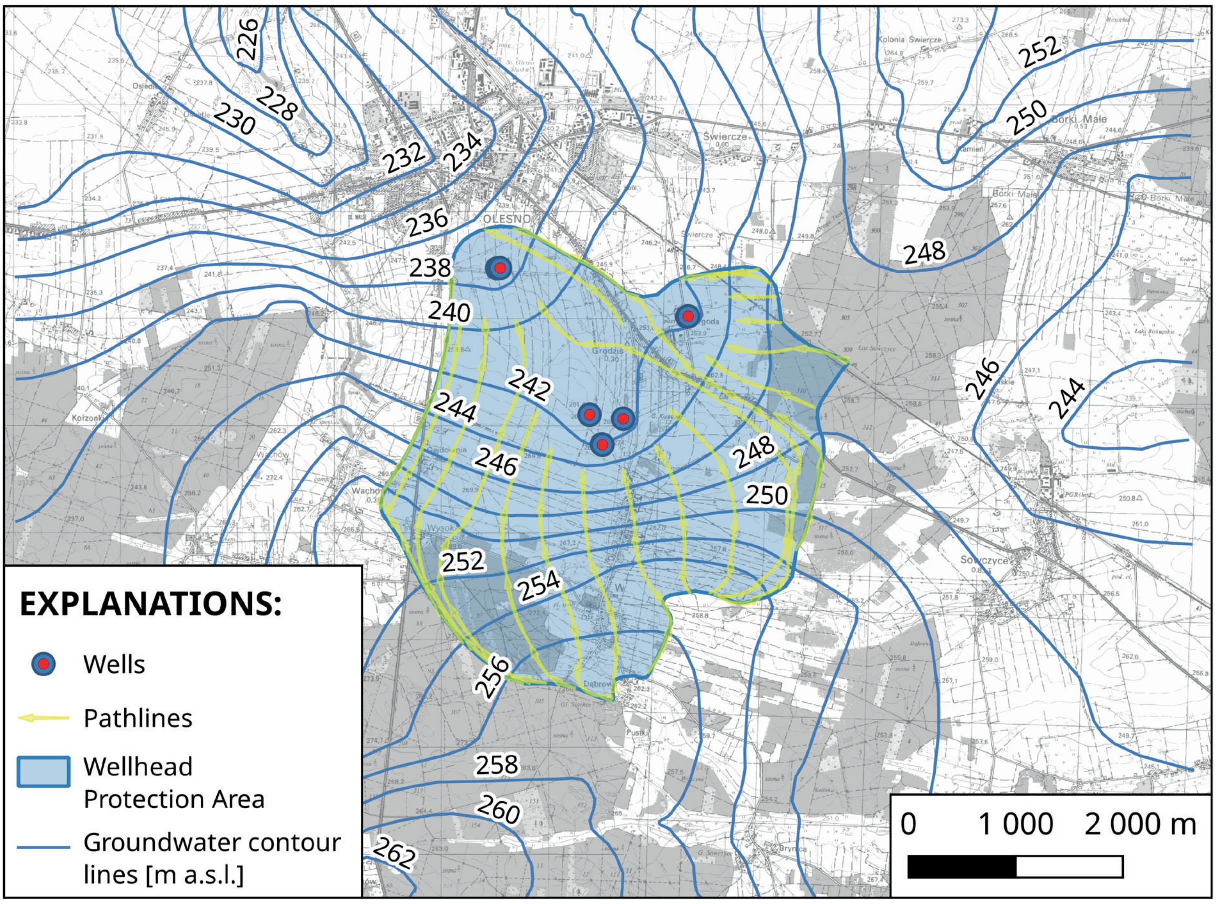


***Fig. 8.*** *Groundwater contour lines and wellhead protection area obtained with the FDM model (after Kryza et al. 2014)*

## CFR method

Because the considered intakes consist of multiple wells, calculations for each of them were performed separately, and the obtained results (Tab. 1) were aggregated, determining a common protection zone. Averaged values of parameters were adopted, based on information from hydrogeological documentation (Kryza et al. 2014) and well sheets from the Hydro Bank (CBDH 2022).

***Table 1***
*Parameters values adopted for calculations by the CFR method and obtained partial results*

| Well | Pumping rate [m³/h] | Effective recharge [m/h] | Porosity [–] | Aquifer thickness [m] | Calculated radius [m] |
|---|---|---|---|---|---|
| 2 | 52 | $1.0 \times 10^{-5}$ | 0.2 | 17.0 | 805.3 |
| Ps-2 | 88 | | | 18.0 | 1029.3 |
| S Ibis2 | 50 | | | 22.5 | 721.8 |
| S IIbis | 48 | | | 18.5 | 753.7 |
| S IIIbis | 72 | | | 26.0 | 824.1 |

## SimpleWHPA method

The SimpleWHPA method uses the estimation of steady-state flow in the aquifer based on analytical formulas for water flow and parameters such as hydraulic gradient or aquifer conductivity (Kraemer et al. 2005), allowing the size and range of the protection zone to be determined quickly. Parameter values were assumed for individual wells based on information from hydrogeology documentation (Kryza et al. 2014) and from well sheets from the Hydro Bank database (CBDH 2022) and flow rates corresponding to the volume of the approved exploitable resources (Tab. 1). Other calculation parameters were assumed to be averaged over the entire area (Tab. 2).

***Table 2***
*Averaged parameter values used in SimpleWHPA method*

| Parameters | Value |
|---|---|
| Time-of-travel [days] | 9125 (25 years) |
| Porosity [–] | 0.2 |
| Hydraulic conductivity [m/d] | 15 |
| Flow direction (relative to the X-axis) [°] | 135 |
| Dimensionless travel time parameter [m²/d] | 1.46 |

## SYNTHETIC RESULTS AND DISCUSSION

The results obtained with the four methods considered for the wells in the study area are presented in Figure 9. The figure presents synthesized (for all wells) ranges of wellhead protection areas calculated with the use of the applied methods. Table 3 summarizes the areas occupied by WHPAs and the relations between them. The WHPA determined based on FDM model calculations was taken as a reference. Numerous studies (e.g.: Spitz & Moreno 1996, Kresic 2006, Anderson et al. 2015, Zdechlik 2016) allow treating mathematical modelling methods as the most reliable for solving complex hydrogeological problems, provided that the model has been correctly calibrated. Hence, in the comparative analysis, the results (zone extent) obtained by the FDM modelling method were treated as a reference for the results obtained by the other methods. The "common part" should be understood as a fragment of the area which belongs both to the zone obtained by a particular method and to the zone obtained by the FDM. "Excess" means the difference between the area of the zone in the method and the area in common with the reference FDM. In contrast, "Deficiency" is the difference between the zone area from the FDM and the area in common between the method and the FDM.

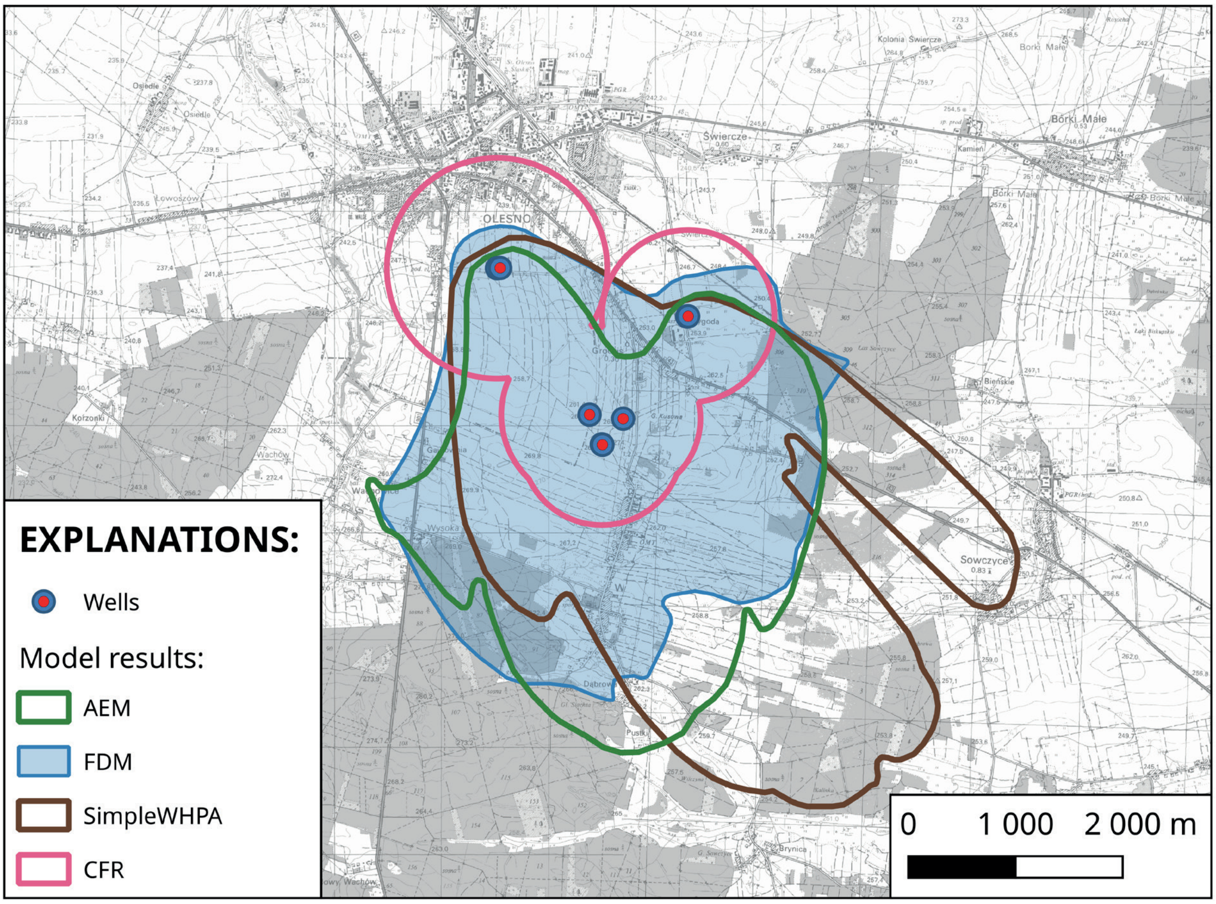


***Fig. 9.*** *Comparison of the wellhead protection area obtained using different methods*

***Table 3***
*Calculated wellhead protection areas and relations between them*

| Method | Area [km$^2$] | | | |
|---|---|---|---|---|
| | WHPA<br>$F$ | Common part<br>$F \cap F_{FDM}$ | Excess<br>$F - (F \cap F_{FDM})$ | Deficiency<br>$F_{FDM} - (F \cap F_{FDM})$ |
| CFR | 7.53 | 5.29 | 2.24 | 7.32 |
| SimpleWHPA | 16.39 | 9.91 | 6.48 | 2.70 |
| AEM | 12.27 | 10.71 | 1.56 | 1.90 |
| FDM | 12.61 | – | – | – |

The range of the protection zone delineated with the use of the FDM mathematical modelling method is determined by the layout of the hydrodynamic field, which shows the directions of groundwater flows to particular intakes predicted with the assumed discharge rate. When the hydrodynamic field is influenced by local drainage and infiltration zones resulting from the character of river sections, the area from which water flows to the intake is visibly stretched upstream (Fig. 8) and reaches area of about 12.6 km$^2$ (Tab. 3). As a result, the range of the protected zone, which is additionally limited by 25-year isochrones, extends in the direction of water flow, and due to the interaction of several wells of three different intakes, its width also increases (Fig. 9).

The results obtained using the CFR method differ from the results of other methods. The designated protection area is the smallest (Tab. 3) and, additionally, its range extends significantly beyond the zone from which inflow to the well comes (results from the FDM). This results from the considerable simplification of the research methodology and assumption of the symmetric shape of protection zones of individual wells. Such an assumption does not consider the real directions of groundwater flow, resulting in the lack of protection in the areas of actual water flow. The deficit of the area that should be protected is significant (Fig. 9, Tab. 3). For typical situations of in-stream intakes, the results obtained by the CFR method should be considered too simplified, not adequately reflecting the boundaries of the areas that should be protected. The validity of the CFR method is limited to cases of single wells, exploiting groundwater under simple hydrogeological conditions, without a clear direction of flow under natural conditions. The advantages of the method can be its simplicity and the resulting small amount of time required to perform the calculations.

SimpleWHPA, as an analytical method, takes into consideration basic averaged parameters of groundwater filtration flow. As a result, the shape of obtained WHPA is relatively close to the range of the zone delineated by the FDM model as a reference method (Fig. 9). However, due to considering averaged parameters, the area of the obtained zone is significantly larger than the area of the zone obtained by the reference method (Tab. 3). This is also a result of taking into account for calculations the filtration parameters obtained from tests performed during the construction of individual wells, which are naturally located in areas with more favourable parameters. This leads to the oversizing of zones due to higher velocities of groundwater flow resulting from the assumption of more favourable filtration parameters from the immediate vicinity of the wells, without reflecting on the deterioration of parameters at a distance from the intakes. The applied method also does not consider watersheds, as well as does not take into account recharge from precipitation and infiltration from surface watercourses. The direction of inflow zone extension upstream of the inflowing water flow obtained with the SimpeWHPA method is a result of assuming the average azimuth of groundwater flow direction (315°) and is of general nature, not fully reflecting the flow path diversity obtained in the FDM calculations. It is not possible to represent local changes in flow directions determined by the morphology of the terrain and the complete system of surface watercourses. As a result, a significant overprotected area is observed relative to the reference method (Tab. 3), mainly in the direction southeast of the intakes, and a small, unprotected area (north and northwest of the intakes).

The advantage of the SimpleWHPA method is the significantly shorter time needed to determine the extent of the protection zone concerning the FDM model methods while maintaining generally similar shapes, although without the ability to provide details that are possible with the model methods. This method can be an interesting alternative to traditional analytical or graphical methods. The possibility of performing calculations for many wells simultaneously and considering in a very limited way, a selected single surface watercourse should also be counted as an advantage.

The results obtained using AEM are very similar to those obtained using FDM as a reference modelling method (Fig. 9, Tab. 3). Both methods consider practically all key conditions shaping a hydrodynamic field of groundwater, which significantly influences the correctness of delineation of protection zone boundaries. Some differences in the range of delineated zones occur in areas directly neighbouring intakes because of technical aspects of zone delineation. In the AEM, water flow tracking points were set directly at the well sites, whereas in the case of the FDM model, starting particles were set on circles around the centres of computational cells used for mapping individual wells with boundary conditions of the second type. As in the AEM, the starting points can be precisely defined at an explicitly defined well location, it should be considered that the course of the WHPA boundary in the area north of the intake determined by this method is at least as correct as that determined by the FDM reference method. The different initial location of the particles also results in a certain, relatively small, difference in the width of the two zones: in the AEM, the run-off zone has a smaller width. Despite the similar areas (Tab. 3), the AEM shows a slight excess relative to the common area from both methods (1.56 $km^2$, mainly in the southern part) and a slightly larger undersize (1.90 $km^2$), mainly near the intakes themselves.

## SUMMARY AND CONCLUSION

As a result of the various test methods, a synthetic comparison of the applicability of the methods can be made (Tab. 4). The CFR method is simple and quick to apply, but the results obtained are characterized by low reliability. The SimpleWHPA method requires more work and is more time-consuming, so the results obtained have satisfactory reliability. Compared to CFR and SimpleWHPA, AEM is more time-consuming and requires more time to properly prepare the data and perform the calculations. However, it is still less time-consuming than the FDM, which typically requires the greatest amount of effort for proper model preparation. This is due to the adoption of generally more generalized parameter values in AEM and, in the case under consideration, to the adoption of fewer hydrodynamic stress. The influence of such simplifications on the accuracy of the range of the determined zone is partially compensated by the possibility of a more precise location of elements on the model. This is due to the unambiguousness of the location indications of the elements taken into account in the considered structure (AEM), relative to the slightly simplified cell mapping in the FDM. It can be concluded that the reliability of both methods is comparable, and their results are similar.

***Table 4***
*Comparison of the applicability of different methods*

| Method | Feature | | |
|---|---|---|---|
| | complication | results reliability | time-consuming |
| CFR | ↓ | ↓ | ↓ |
| SimpleWHPA | ↓ | → | ↓ |
| AEM | → | ↑ | → |
| FDM | ↑ | ↑ | ↑ |

| | | | |
|---|---|---|---|
| Symbols explained: | ↓ low | → average | ↑ high |
| Colours explained: | ■ favourable | ■ acceptable | ■ unfavourable |

Previous studies indicate that in the case of wells drilled in regions with varied geological structures and complex hydrogeological conditions, or in the case of multi-well intakes, the extent of the protection zone can only be fully correctly determined by using mathematical modelling methods. Among them, FDM (Modflow) and to a lesser extent FEM (Feflow) play a dominant role. A noteworthy alternative is the AEM, characterized by a much shorter time of solving the problem than in FDM/FEM, and at the same time much higher reliability of the results than more basic methods such as CFR or SimpleWHPA. Although there may be relatively small differences in the range of zones obtained by the analytical elements method (AEM) to FDM/FEM, generally the results obtained are similar. It can be concluded that the AEM fulfils its role in a good enough way, and the improvement of obtained results is significantly influenced by the possibility of detailed mapping of environmental conditions in the form of analytical elements.

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