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title: **The quantitative evaluation of the catchment available groundwater resources – the case study**

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INTRODUCTION

In Poland there are officially two categories of the groundwater resources: the available resources determined for a given area and exploitation resources assessed for a given well or a group of wells.

The objective of the presented case study was to determine the amount and spatial distribution of the available groundwater resources in the Cenozoic productive aquifers in the catchment of the Łeba river in Poland. The resources distribution was calculated using the author's method incorporated into the modeling process. In this method the assessment of the renewability of the modeled groundwater flow system was the first step in the resources evaluation process.

CHARACTERISTICS OF THE INVESTIGATED CATCHMENT

The investigated catchment of the 97 km long Łeba river is located in northern Poland. The catchment area is 1800 km^2. The hydrogeological investigations and groundwater flow modeling covered larger area of 2420 km^2 (Fig. 1) (Kwaterkiewicz et al., 2001).

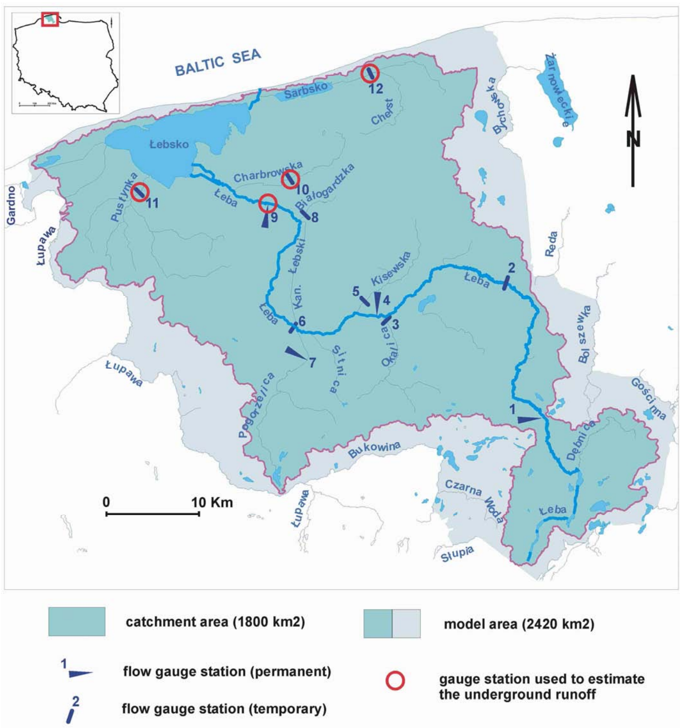

Figure 1. The Łeba river catchment.

The catchment groundwater flow system is recharged by the infiltration from the precipitating water. The mean annual precipitation varies from 644 mm in the central part of the sea coast to 823 mm in the nearby glacial upland (Kuroś, 1999). Higher precipitation was recorded in the elevated upland areas while lower values were measured in the wide Łeba river valley which originated as the marginal structure during the last deglaciation.

The groundwater resources investigations within the Łeba catchment were focused on the Cenozoic geological system (Kwaterkiewicz et al., 2001). This system comprises the paleogene, neogene and quarternary sediments. The paleogene is represented mainly by silts and clays. The neogene series also include the dominant low permeability series like silts and clays however with the presence of the permeable sand layers (Morawski, 1990). The thickness of the quarternary system is highly diversified in this catchment ranging from 0 m in one locality in the northern part to more than 250 m in the south (Morawski, 1990). The geological sketch of the catchment surface is shown in Fig. 2.

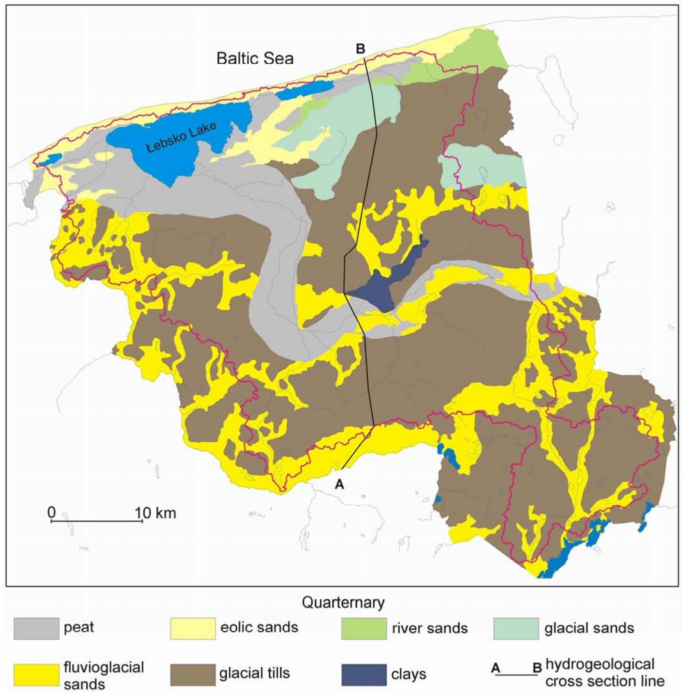

Figure 2. The geological sketch of the surface sediments (on the base of the Geological Map of Poland 1: 200 000).

This area underwent several quarternary glaciations but the sediments of the three youngest ones were identified. The glacial tills of the last glaciation (vistulian) are dominant on the surface of the upland part of the catchment. Also significantly large upland areas are covered with the vistulian fluvioglacial and glacial sands.

The hydrogeological drillings made in the Łeba river marginal valley revealed the presence of the 40–60 m thick highly permeable sand and gravel series of the fluvioglacial origin. According to the geological investigations these series were deposited in relatively short time in one sedimentation cycle during the recession of the vistulian glaciation (Morawski, 1990).

The insight into the structure of the catchment Cenozoic system is presented in the hydrogeological cross section (Fig. 3) which also shows the location of the main productive aquifers which were assigned the status of the mathematical model layers.

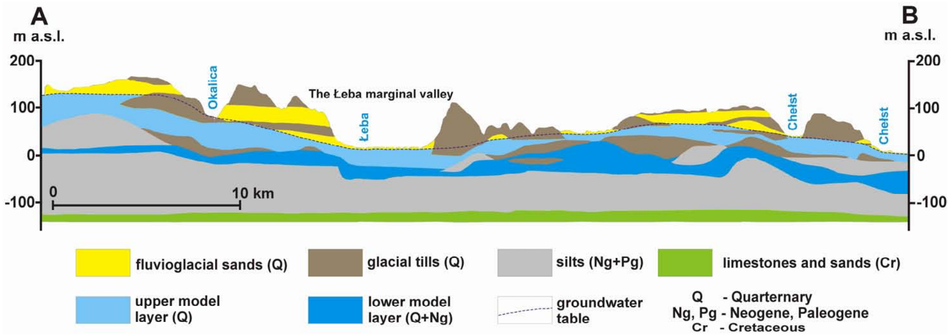

Figure 3. The hydrogeological cross section (Kwaterkiewicz et al., 2001).

RENEWABILITY OF THE MODELED GROUNDWATER FLOW SYSTEM

The applied approach to the renewability assessment assumes that the catchment subsurface system operates like a big lysimeter (BL) (Fig. 4) the outflow from which is measurable as the underground runoff Q_U to the river system. As the groundwater lateral flow Q_L across catchments boundaries can often be assumed as much less than Q_U the BL approximation can be applied in many cases. With this approximation the underground runoff Q_U is practically the same as the catchment recharge Q_{RCH} less the field evaporation Q_{EV} taking place in the river flood terraces mainly in the Łeba marginal valley and in the coastal lowland.

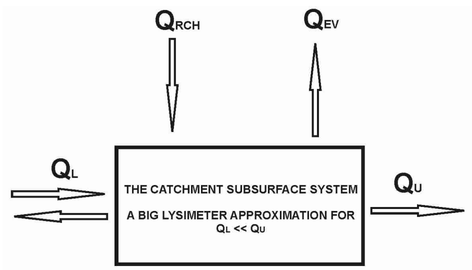

Figure 4. The concept of the catchment subsurface system as a big lysimeter; Q_U — underground runoff to the river system, Q_L — groundwater lateral flow across the catchment boundary (in or out), Q_{RCH} — recharge, Q_{EV} — field evaporation.

The construction of the steady-state model was preceded by the estimation of the flow through the model domain using the BL approximation and river flow records from the investigated catchment and from the neighboring catchments. The underground runoff Q_U from the model domain was estimated as 9.48 m³/s and this is assumed equal to the net recharge $Q'_{RCH} = Q_{RCH} - Q_{EV}$ called the recharge down the text and represents the renewability or flow through the domain. For the catchment itself the recharge was assessed as Q_{RCH}^{CATCH} = 6.0 m³/s = 21 600 m³/h. Dividing this by the catchment area we get the mean areal recharge q_{RCH}^{CATCH} = 106 mm/year.

QUANTITATIVE EVALUATION OF THE CATCHMENT AVAILABLE GROUNDWATER RESOURCES

The catchment available groundwater resources Q_{AVAIL} must be viewed as a certain fraction of the catchment estimated recharge Q_{RCH}^{CATCH} according to the formula:

$$Q_{AVAIL} = C \cdot Q_{RCH}^{CATCH}; 0 \leq C \leq 1 \qquad (1)$$

From the conceptual point of view the groundwater available resources can be defined as the withdrawal by virtual wells distributed in the regular model mesh over the catchment area (Szymanko, 1980). Adapting this concept the amount of the available groundwater resources and their distribution over the catchment area were calculated using the author's constant volume transformation algorithm (CVT). The presented results are for the upper model layer.

The model based optimization process allowed to estimate the maximal allowable value of C in the formula (1) and calculate the resources distribution in the presented upper model layer for the defined weight functions (Fig. 5).

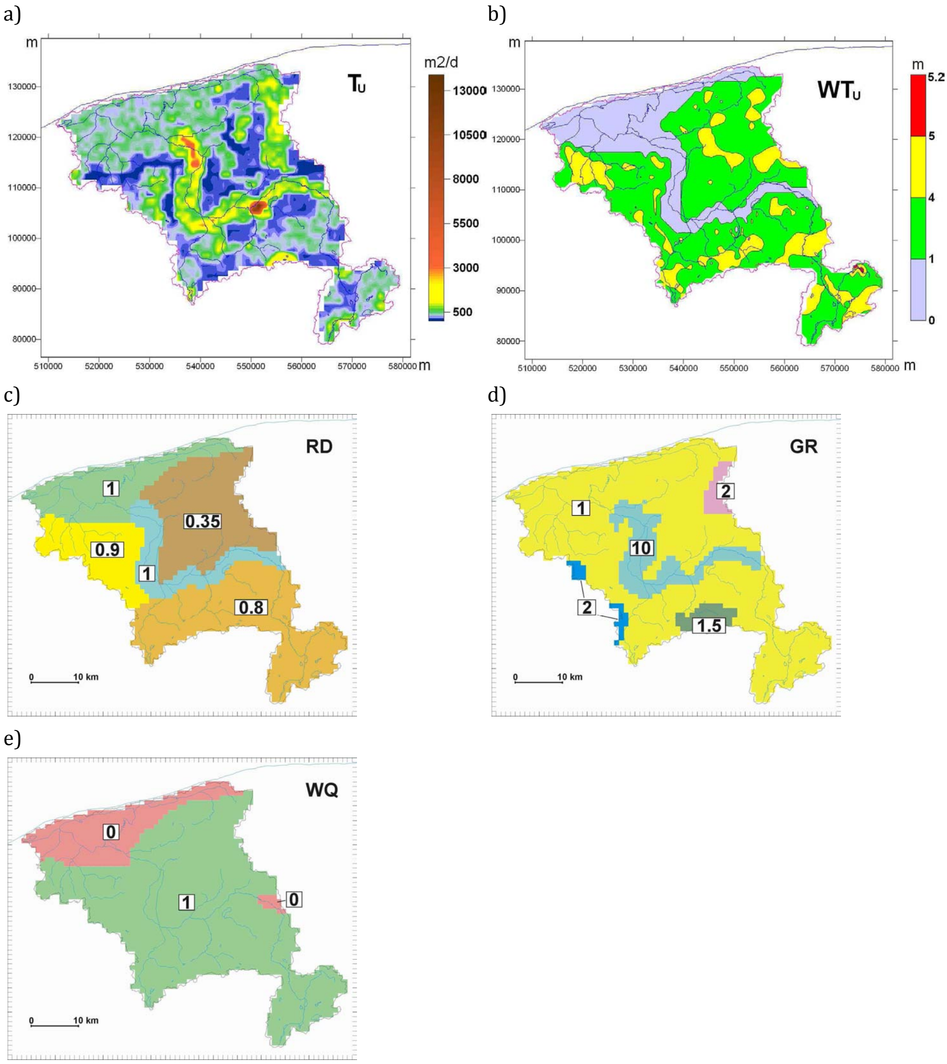

Figure 5. The definitions of the weight functions used to calculate the distribution of the available groundwater resources with the final weight values for RD and GR.

These weight functions were the distributions of:

- the calibrated upper layer hydraulic transmissivity T_U (Fig. 5a),
- the upper layer maximal allowable regional water table drawdown WT_U (Fig. 5b),
- the flow system recharge and discharge zones RD (Fig. 5c),
- the areas of the main groundwater reservoirs GR (Fig. 5d),
- the areas of good, bad and potentially bad groundwater quality WQ (Fig. 5e).

The CVT formula used to calculate the distribution of the available groundwater resources in the upper model layer in case of the applied square model mesh is as follows:

$$Q^{U}_{AVAIL}(i,j) = \frac{T_U(i,j)\cdot WT_U(i,j)\cdot RD(i,j)\cdot GR(i,j)\cdot WQ(i,j)}{\langle T_U(\,)\cdot WT_U(\,)\cdot RD(\,)\cdot GR(\,)\cdot WQ(\,)\rangle}\cdot P_U\cdot A\cdot C\cdot q^{CATCH}_{RCH} \qquad (2)$$

where:

- Q^{U}_{AVAIL} (i,j) — rate of the virtual well in the upper layer model node (i,j) [m^3/h],
- T_U(i,j), WT_U(i,j), RD(i.j), GR(i,j), WQ(i,j) – weights in the node (i,j),
- P_U — fraction of the resources allocated to the upper layer ($P_U = 0.85$),
- A — area of the model cell (in the presented case A = 1000 m × 1000 m),
- q^{CATCH}_{RCH} — fraction of the catchment recharge defining the amount of the available resources,
- q^{CATCH}_{RCH} — catchment mean areal recharge (q^{CATCH}_{RCH} = 1.21×10^{-5} m/h = 106 mm/year),
- ⟨T_U( )·WT_U( )·RD( )·GR( )·WQ( )⟩ — mean product value over the catchment area.

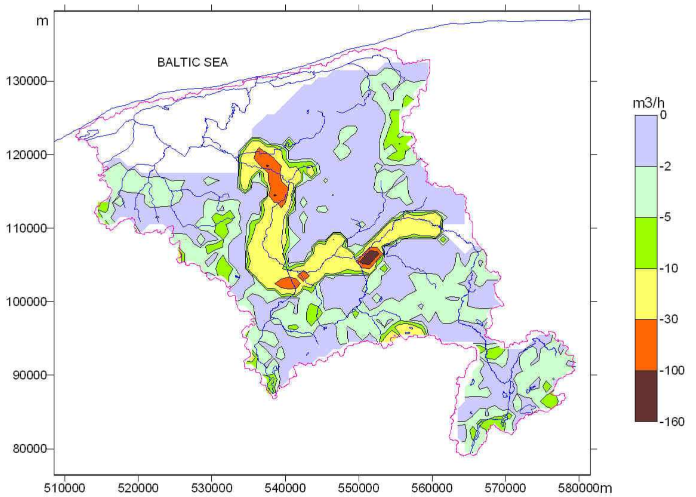

Figure 6. The calculated according to the formula (2) distribution of the upper layer available groundwater resources Q^{U}_{AVAIL} = 7383.6 m^3/h for C = C_{MAX} = 0.4.

The resulting distribution of the upper layer available groundwater resources Q^{U}_{AVAIL}=7383.6 m^3/h is shown in Fig. 6. In white catchment areas these resources equal zero due to the bad or potentially bad groundwater quality (red colour in Fig. 5e).

The total amount of the resources evaluated in the model based optimization process for both layers is 8686.6 m^3/h (Tab. 1). This is 40% of the catchment assessed recharge Q_{RCH}^{CATCH}, so the C maximal allowable value in the formula (1) and (2) was determined as C = C_{MAX} = 0.4. The optimization variables were: the C coefficient, the RD weights (Fig. 5c) and GR weights (Fig. 5d). There were two optimization objectives: the simulated leakage to the rivers not less than the river base flow and less than 15% increase of the lateral inflow across the catchment boundary both as the effect of the modeled resources withdrawal.

Table 1. The available groundwater resources and existing withdrawal.

Model layer	The available resources (m^3/h)	The existing withdrawal (m^3/h)
upper	7383.6	568.3
lower	1303.0	453.2
both layers	8686.6	1021.5

CONCLUSIONS

- The presented method directly connects the available groundwater resources to the renewability of the investigated flow system and its hydrogeological characteristics.
- The prior awareness of the quantity of the flow through the model domain is the elementary precondition for the reliable model assessment of the groundwater resources. This implies that practically only river catchments can be the subject of the successful regional groundwater modeling aimed at the proper quantitative evaluation of the groundwater resources.

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