IAH 2010 Krakow

BIULETYN PAŃSTWOWEGO INSTYTUTU GEOLOGICZNEGO 441: 183–192, 2010 R.

# THE QUANTITATIVE EVALUATION OF THE CATCHMENT AVAILABLE GROUNDWATER RESOURCES – THE CASE STUDY

Lech Śmietański[1]

**Abstract.** The paper presents the author's approach to the quantitative assessment of the river catchment available groundwater resources in case of the Łeba River catchment in Poland. A strong emphasis is put on the evaluation of the groundwater flow system renewability which should always precede the resources model simulations. After assessing the catchment recharge using river flow records and a big lysimeter approximation the recharge distribution was calculated using the author's constant volume transformation (CVT) method. The subsequent construction of the groundwater flow model and application of the CVT method coupled with the virtual wells concept led to the evaluation of the amount and distribution of the available groundwater resources in the catchment.

**Key words:** big lysimeter, constant volume transformation, renewability, catchment, virtual wells, available groundwater resources.

## INTRODUCTION

The groundwater resources evaluation is this part of the practical activity with which a hydrogeologist deals very frequently and the realization of which usually finalizes hydrogeological studies and investigations.

In Poland the geological and mining law (Prawo..., 1994) defines two categories of the groundwater resources: the available resources determined for a given area and exploitation resources assessed for a particular well or a group of wells. The assessments of the available groundwater resources in Poland was assigned the top priority on the list of the hydrogeological works aimed at achieving the strategic goal which is the protection of these resources against quantitative and qualitative degradation (Jezierski, 1994).

The European Union Water Framework Directive (2000) says that water resources management in the EU states is realized within the hydrographic areas like river catchments and puts strong emphasis on the knowledge of the available resources as a key element of the overall water management.

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 northern 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 Łeba catchment is located in northern Poland. The catchment area is 1,800 km$^2$. The hydrogeological investigations and groundwater flow modeling covered larger area of 2,420 km$^2$ (Fig. 1) (Kwaterkiewicz *et al.*, 2001). The Łeba River is 97 km long and is the main hydrographic element in the investigated catchment.

The river flow records covering the period of 1966–1995 were collected from 12 gauge stations located on the main

[1] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-950 Warszawa, Poland; e-mail: lech.smietanski@pgi.gov.pl

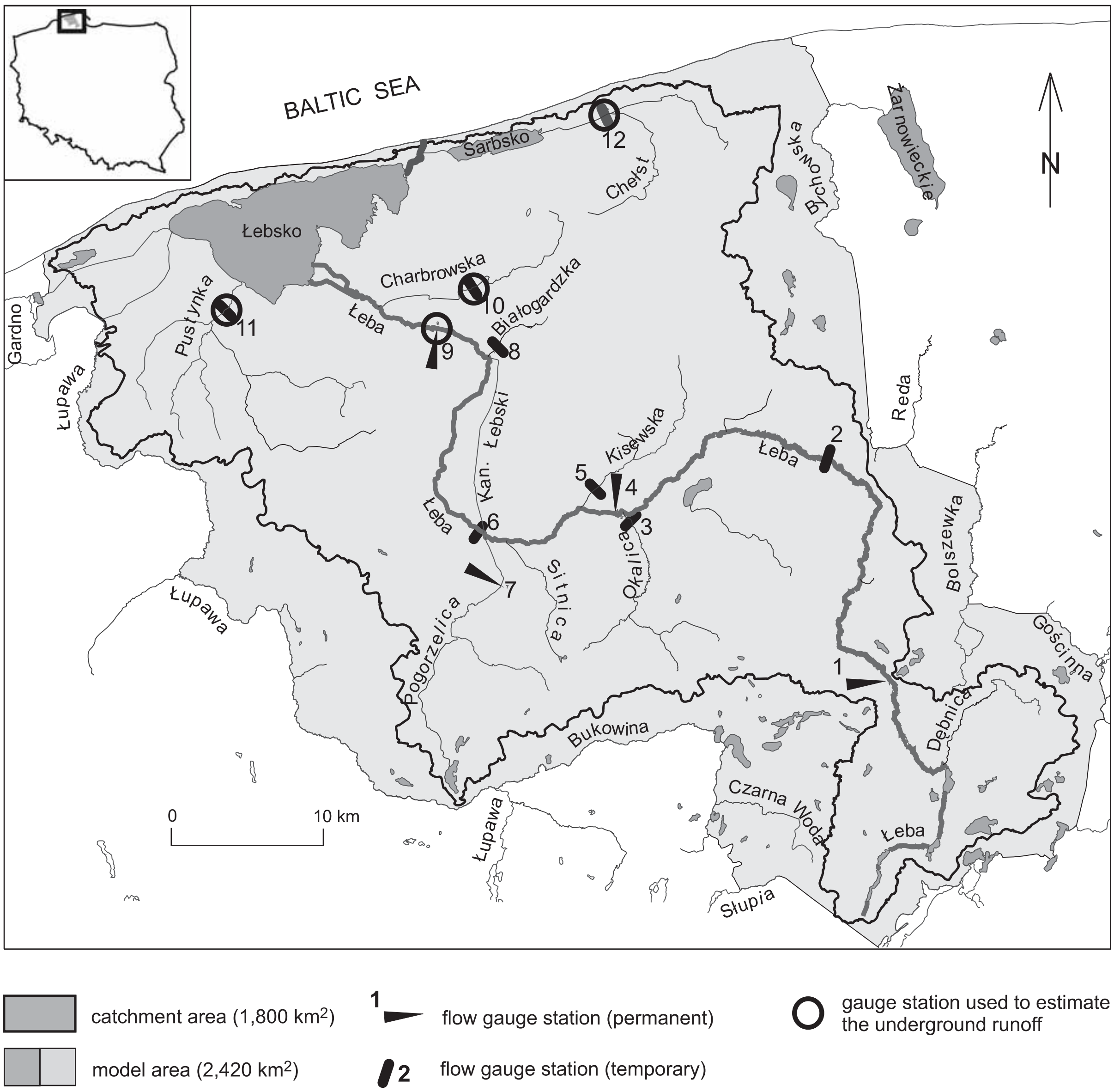



**Fig. 1. Location of the Łeba River catchment and its hydrographic elements**

river and its tributaries. The data from four stations was used to estimate the underground runoff to the river system to determine the renewability of the catchment groundwater resources.

The river flow data from these four stations is presented in Table 1 where among others the mean low flow (MLQ) is shown and assumed later on as a measure of the underground runoff.

There are numerous lakes in the Łeba River catchment with 40 lakes larger than 1 hectar. The largest is the Łebsko Lake with the area of 71.5 km$^2$.

The catchment groundwater flow system is recharged by the infiltration from the precipitating water. The distribution of the mean annual precipitation for the 1966–1995 period is shown in Figure 2. The recorded mean annual precipitation varies from 644 mm in the central part of the sea coast to 823 mm in the nearby glacial upland. 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 River catchment were focused on the Cenozoic geological system (Kwaterkiewicz *et al*., 2001). This system comprises the Paleogene, Neogene and Quaternary sediments. 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).

**Table 1**

**Statistics of the river flows in the catchment for the 1966–1995 period (Kuroś, 1999)**

| Gauge station No. | River | Gauge station | HHQ [m$^3$/s] | MHQ [m$^3$/s] | MMQ [m$^3$/s] | MLQ [m$^3$/s] | LLQ [m$^3$/s] | Qb [m$^3$/s] |
|---|---|---|---|---|---|---|---|---|
| 9 | Łeba River | Cecenowo | 45.9 | 29.5 | 11.6 | 6.29 | 4.33 | 4.75 |
| 10 | Charbrowska Creek | Charbrowo | 1.41 | 0.84 | 0.35 | 0.17 | 0.14 | 0.14 |
| 11 | Pustynka Creek | Kluki | 17.5 | 7.79 | 1.52 | 0.62 | 0.54 | 0.55 |
| 12 | Chełst Creek | Osetnik | 3.07 | 1.96 | 0.75 | 0.40 | 0.27 | 0.27 |

HHQ – highest flow, MHQ – mean high flow, MMQ – mean flow, MLQ – mean low flow, LLQ – lowest flow, Qb – base flow

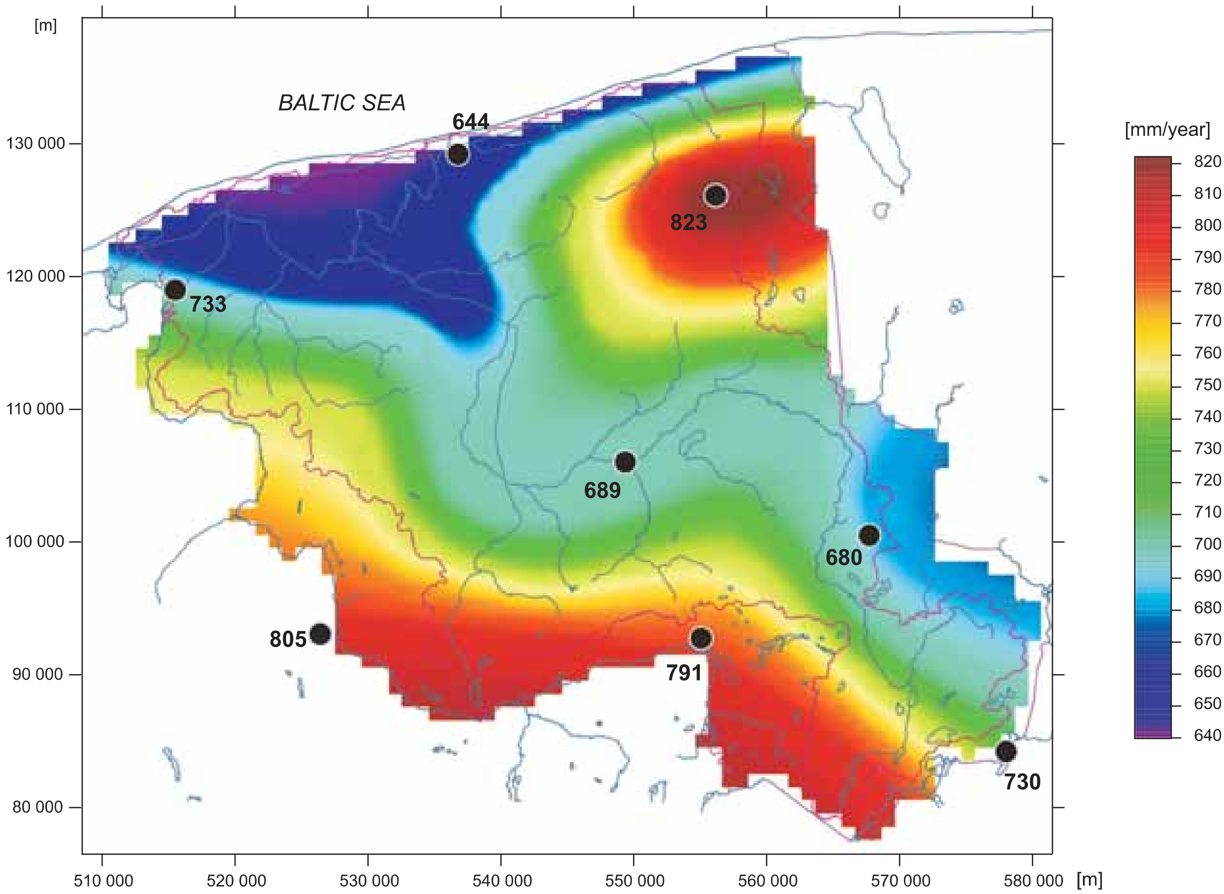



**Fig. 2. Interpreted distribution of the mean annual precipitation for the 1966–1995 period with the location of the meteorological stations (data after Kuroś, 1999)**

The thickness of the Quarternary sediments 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 (Mojski, 1979). The geological sketch of the surface sediments is shown in Figure 3. 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).

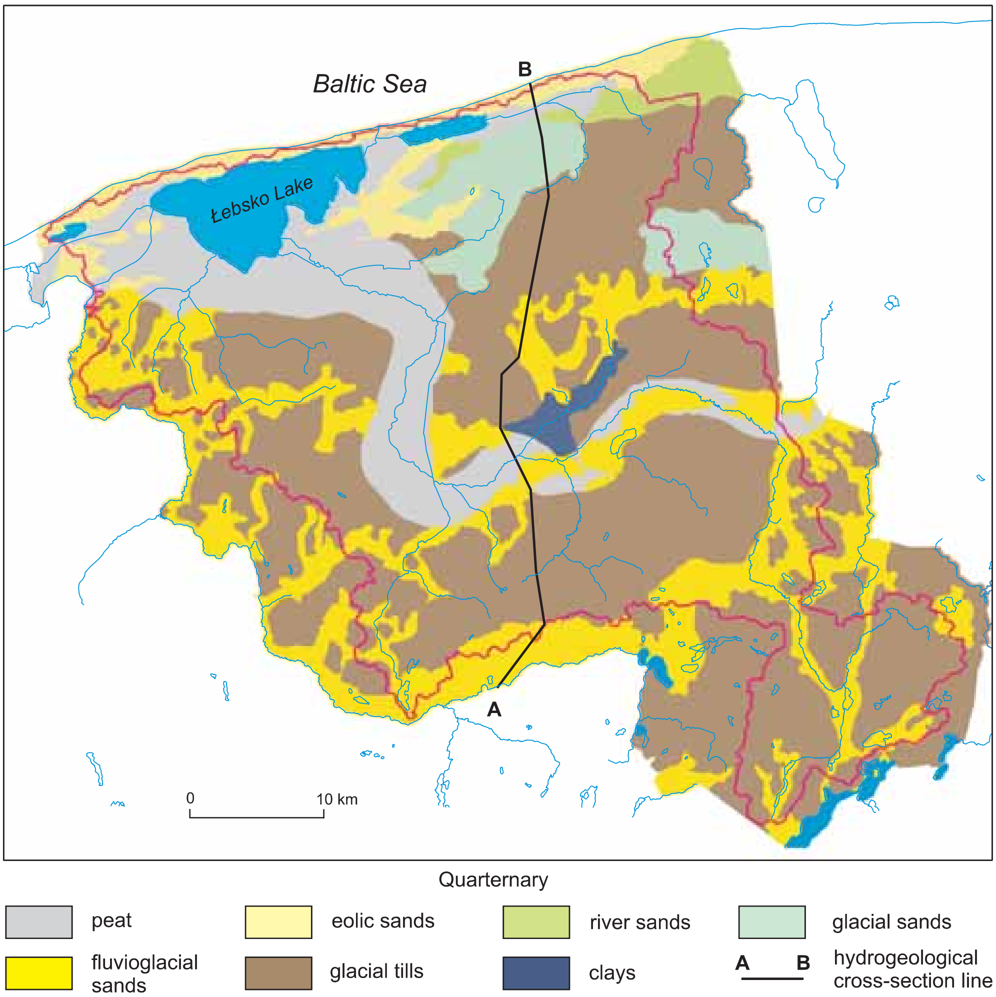



**Fig. 3. Geological sketch of the surface sediments (on the base of *Mapa geologiczna Polski 1:200 000*)**

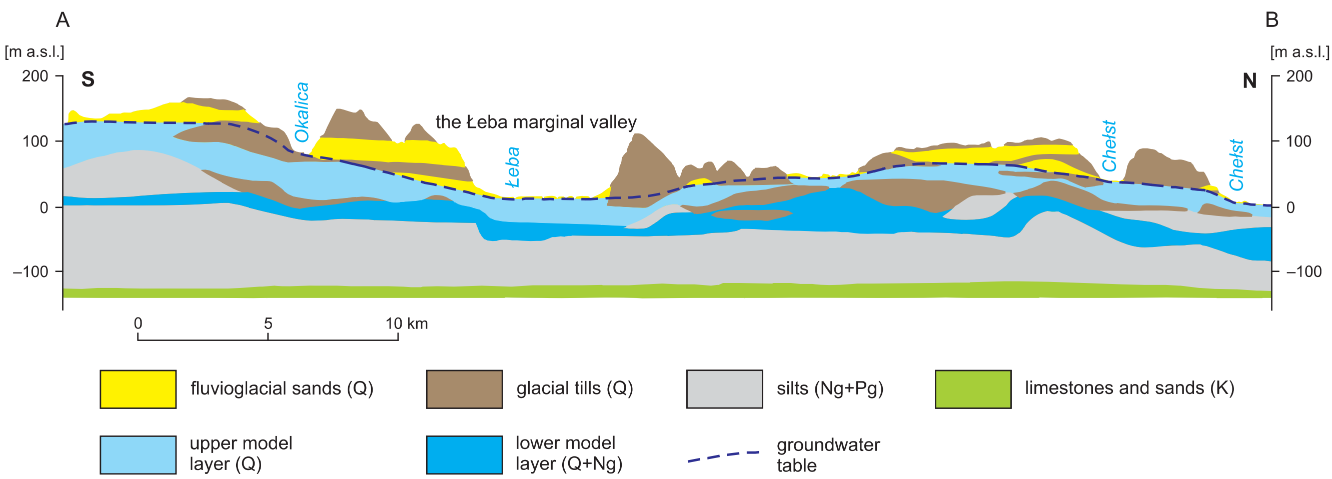



**Fig. 4. Hydrogeological cross-section (Kwaterkiewicz *et al.*, 2001)**

Q – Quarternary, Ng – Neogene, Pg – Paleogene, K – Cretaceous

The youngest Quaternary sediments are the peats and eolic sands present at the terrain surface in the Łeba marginal valley, in the lowland around the Łebsko Lake and along the sea coast.

The insight into the structure of the catchment Cenozoic system is presented in the hydrogeological cross-section (Fig. 4). This cross-section shows the location of the main productive aquifers which were assigned the status of the mathematical model layers. These two aquifers are separated by the defined aquitard (tills, silts, clays), however, in some areas they are not separated and show direct contact. This direct contact takes place in the middle section of the Łeba River marginal valley and in some places in the upland.

The Cenozoic geological system is underlain by the Cretaceous system which was the subject of the separate regional hydrogeological investigations (Sadurski, 1989). These investigations showed that in the presented catchment the Cretaceous system has no importance as a supply source of the groundwater.

## RENEWABILITY OF THE MODELLED GROUNDWATER FLOW SYSTEM

The steady-state two layer model used to evaluate the catchment groundwater resources covered larger area (2,420 km$^2$) than the catchment itself (1,800 km$^2$) (Fig. 1). The construction of the model was preceded by the estimation of the flow through the model Cenozoic domain using the river flow records from the investigated catchment (Table 1) and from the neighboring catchments. With the steady-state approach the underground runoff to the river system is equivalent to the infiltration recharge minus the evaporation in the river valley low terraces.

The sum of the mean low flows (MLQ) from the four gauge stations (indicated by the circles in Figure 1) is 7.48 m$^3$/s and this number was assumed to represent the underground runoff from the catchment area hydrologicaly locked by these stations. The underground runoff from the lower remaining part of the Łeba River catchment was assessed at 0.5 m$^3$/s.

In between the Łeba River catchment boundary (Fig. 1) and the model area boundary there are fragments of the neighboring catchments and the underground runoff from these fragments was estimated at 1.5 m$^3$/s. So, the total underground runoff from the model domain is 9.48 m$^3$/s. With the boundaries of this domain defined mainly along rivers and water divides it can be assumed that the value of 9.48 m$^3$/s represents the longterm mean recharge which generates the underground runoff of the same value to the river system. This value can also be seen as a mean groundwater flow through the model domain and as the measure of the renewability of the modeled groundwater flow system.

## EVALUATION OF THE RECHARGE DISTRIBUTION OVER THE MODEL DOMAIN

The applied approach to the renewability assessment assumes that the catchment subsurface system operates like a big lysimeter (BL) (Fig. 5), 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 is often 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 $Q_{RCH}$ minus the field evaporation $Q_{EV}$ taking place in the river flood terraces mainly in the Łeba River marginal valley and in the coastal lowland.

In the presented case the $Q_{EV}$ reliable value is unknown, so what could be evaluated was the value of the net recharge $Q'_{RCH} = Q_{RCH} - Q_{EV}$, called the recharge down the text. With the BL approximation we have $Q_U = Q'_{RCH} = 9.48$ m$^3$/s, what is the model domain recharge. Dividing this by the model area we get the mean areal recharge of the model domain $q'_{RCH} = 123$ mm/year.

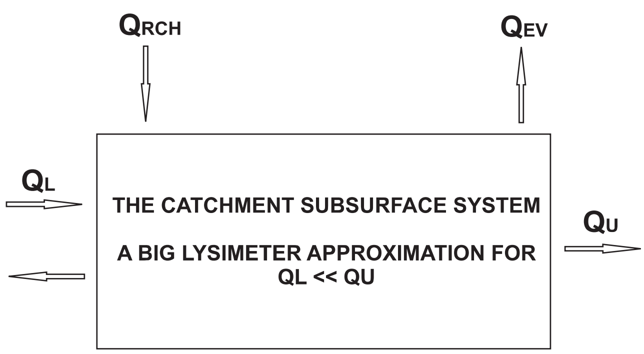



**Fig. 5. Concept of the catchment subsurface system as a big lysimeter**

$Q_U$ – 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 distribution of $Q'_{RCH}$ over the model domain was calculated using the author's constant volume transformation (CVT) method. The CVT is the algorithm that changes the shape of a given surface saving the volume contained between this surface and the reference level. This algorithm calculates according to the previously defined weight functions. To evaluate the $Q'_{RCH}$ distribution these weight functions were the distributions of:

– the mean annual precipitation P (Fig. 2),
– the lithology of the surface sediments LIT (Fig. 3) with the assigned infiltration weight value to each type of the sediment (Tab. 2).

In this case the CVT algorithm is of the below presented form:

$$RCH(i,j) = \frac{P(i,j) \cdot LIT(i,j)}{\langle P \cdot LIT \rangle} q'_{RCH} \qquad [1]$$

where:

RCH(i,j) – calculated recharge in the model node (i,j) [mm/year];
P(i,j) – precipitation in the model node (i,j) [mm/year];
LIT(i,j) – infiltration weight value in the model node (i,j) [-];
$q'_{RCH}$ – mean areal recharge of the model domain (123 mm/year);
$\langle P \cdot LIT \rangle$ – mean product value over the model domain.

The distribution of the recharge $Q'_{RCH}$, calculated according to the formula [1] that is equal to the assessed underground runoff $Q_U$ is shown in Figure 6.

**Table 2**

**The weight values assigned to each lihological type**

| Type of the sediment (Fig. 3) | LIT weights |
|---|---|
| Peat | 1 |
| Clays | 1 |
| Glacial tills | 10 |
| Fluvioglacial sands in the marginal valley | 12 |
| Glacial sands | 20 |
| Eolic sands in the upland | 20 |
| Eolic sands in the coastal lowland | 25 |
| Fluvioglacial sands in the upland | 25 |
| River sands | 25 |

The calculated mean annual recharge values vary from few milimeters in the very shallow groundwater table areas in the Łeba River marginal valley and coastal lowlands where high evaporation can be expected to above 250 mm in the upland south.

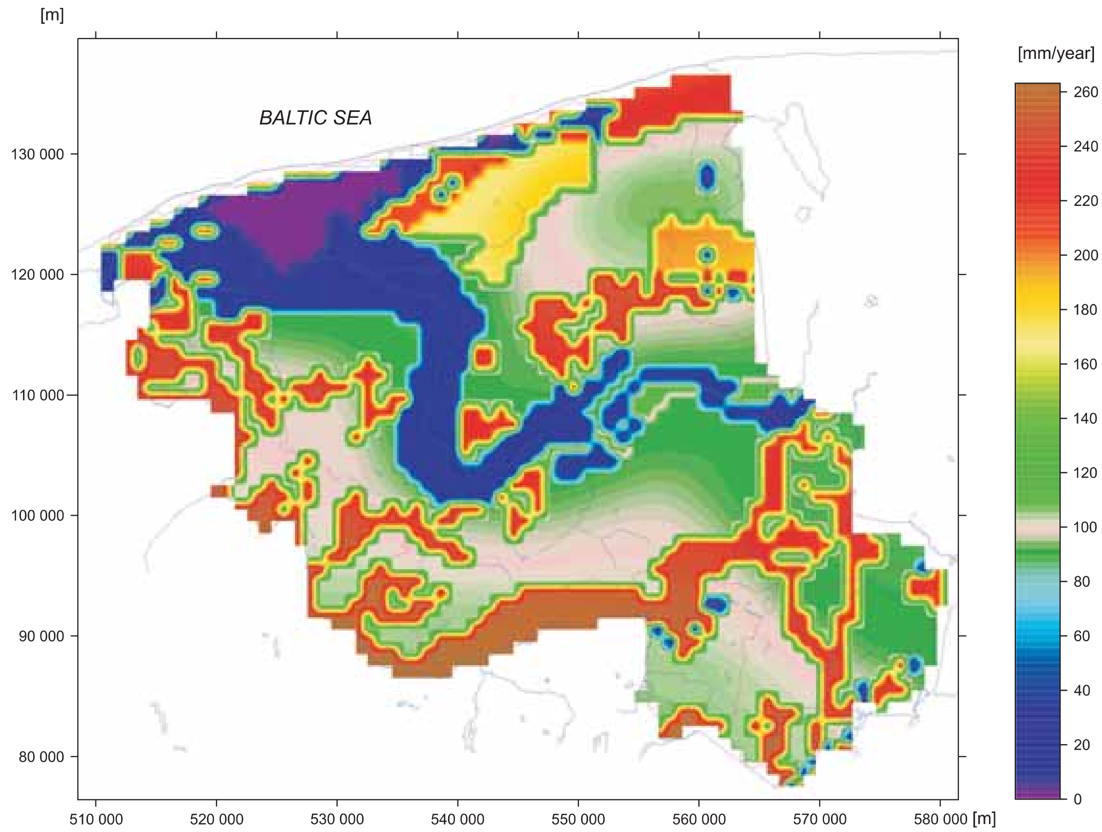



**Fig. 6. Distribution of the model domain recharge $Q'_{RCH}$ = 9.48 $m^3/s$ with the mean areal value of 123 mm/year**

## QUANTITATIVE EVALUATION OF THE CATCHMENT AVAILABLE GROUNDWATER RESOURCES

Integrating the recharge distribution (Fig. 6) over the Łeba River catchment area we get the value of $Q_{RCH}^{CATCH} = 6.0\ m^3/s$, which is the estimated recharge of the catchment itself. Dividing this by the catchment area makes the mean areal recharge of $q_{RCH}^{CATCH} = 106$ mm/year.

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

$$Q_{AVAIL} = C \cdot Q_{RCH}^{CATCH}\ ;\ 0 \le C \le 1 \qquad [2]$$

With the usually already existing groundwater withdrawal the available resources should be seen in practice as a certain part of the catchment recharge that can be exploited additionally from the catchment area. This possible additional withdrawal evaluated on the base of the natural constraints is often called the resources reserve but down the text it will be referred to as the available resources. The constraints which had to be addressed in this case were for instance the maximal allowable regional water table drawdown and keeping the river flow at least at the base flow level.

From the conceptual point of view the groundwater available resources can be defined as the total withdrawal by virtual wells distributed in the regular mesh over the catchment area (Fig. 7) (Szymanko, 1980). In this approach the distribution of their withdrawal rates is in fact the resources distribution.

Adapting the above concept, the amount of the available groundwater resources and their distribution over the catchment area were calculated within the environment of the mathematical model using again the constant volume transformation algorithm (CVT). The results presented in this paper are for the upper model layer which, according to the model budget, transmits 85% of the overall flow through the model domain in the catchment area.

The model based optimization process allowed to estimate the maximal allowable value of C in the formula [2] and calculate resources distribution in the upper model layer for the defined weight functions (Fig. 8). These functions were the distributions of:

- the calibrated upper layer hydraulic transmissivity ($T_u$) (Fig. 8A);
- the upper layer maximal allowable regional water table drawdown ($WT_U$) (Fig. 8B);
- the flow system recharge and discharge zones (RD) (Fig. 8C);
- the areas of the main groundwater reservoirs (GR) (Fig. 8D);
- the areas of good, bad and potentially bad groundwater quality (WQ) (Fig. 8E).

The upland recharge zones were assigned lower weights than the discharge zones like the coastal lowland and marginal valley (Fig. 8C). The main groundwater reservoirs were assigned higher weights than the remaining part of the catchment (Fig. 8D). As far as the groundwater quality is concerned the whole coastal lowland was assigned the zero weight (Fig. 8E). In this area the coastal and Mesozoic basement saline water intrusions are observed or are highly probable (Sadurski, 1989). The zero quality weight was also assigned to the small area in the catchment eastern part with animal farms.

Like for the upper layer three weight functions RD, GR and WQ were used to calculate resources distribution in the lower layer with the defined $T_L$ and $WT_L$ for this layer. 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:

$$Q_{AVAIL}^{U}(i,j) = \frac{T_U(i,j)\cdot WT_U(i,j)\cdot RD(i,j)\cdot GR(i,j)\cdot WQ(i,j)}{\left\langle T_U\cdot WT_U\cdot RD\cdot GR\cdot WQ\right\rangle} \cdot P_U\cdot A\cdot C\cdot q_{RCH}^{CATCH} \qquad [3]$$

where:

$Q_{AVAIL}^{U}$ – rate of the virtual well in the upper layer node (i,j) [$m^3/h$];
$T_U$ (i,j), $WR_U$ (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 × 1000 m);
C – fraction of the catchment recharge defining the amount of the available resources,
$q_{RCH}^{CATCH}$ – catchment mean areal recharge ($q_{RCH}^{CATCH} = 1.21 \cdot 10^{-5}$ m/h = 106 mm/year),
$\left\langle T_U \cdot WT_U \cdot RD \cdot WQ \right\rangle$ – mean product value over the model domain.

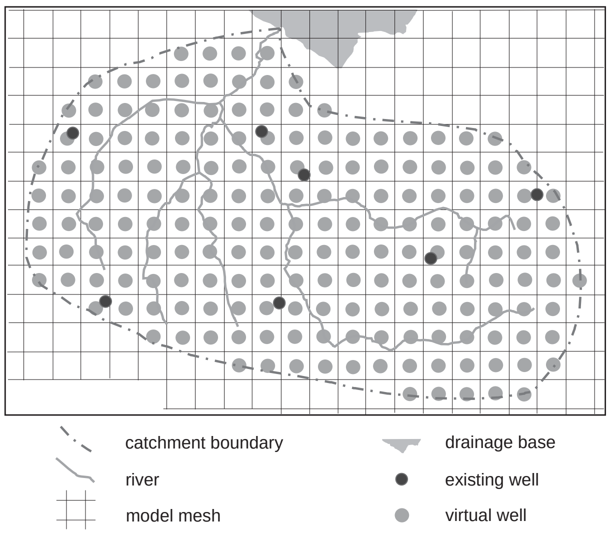
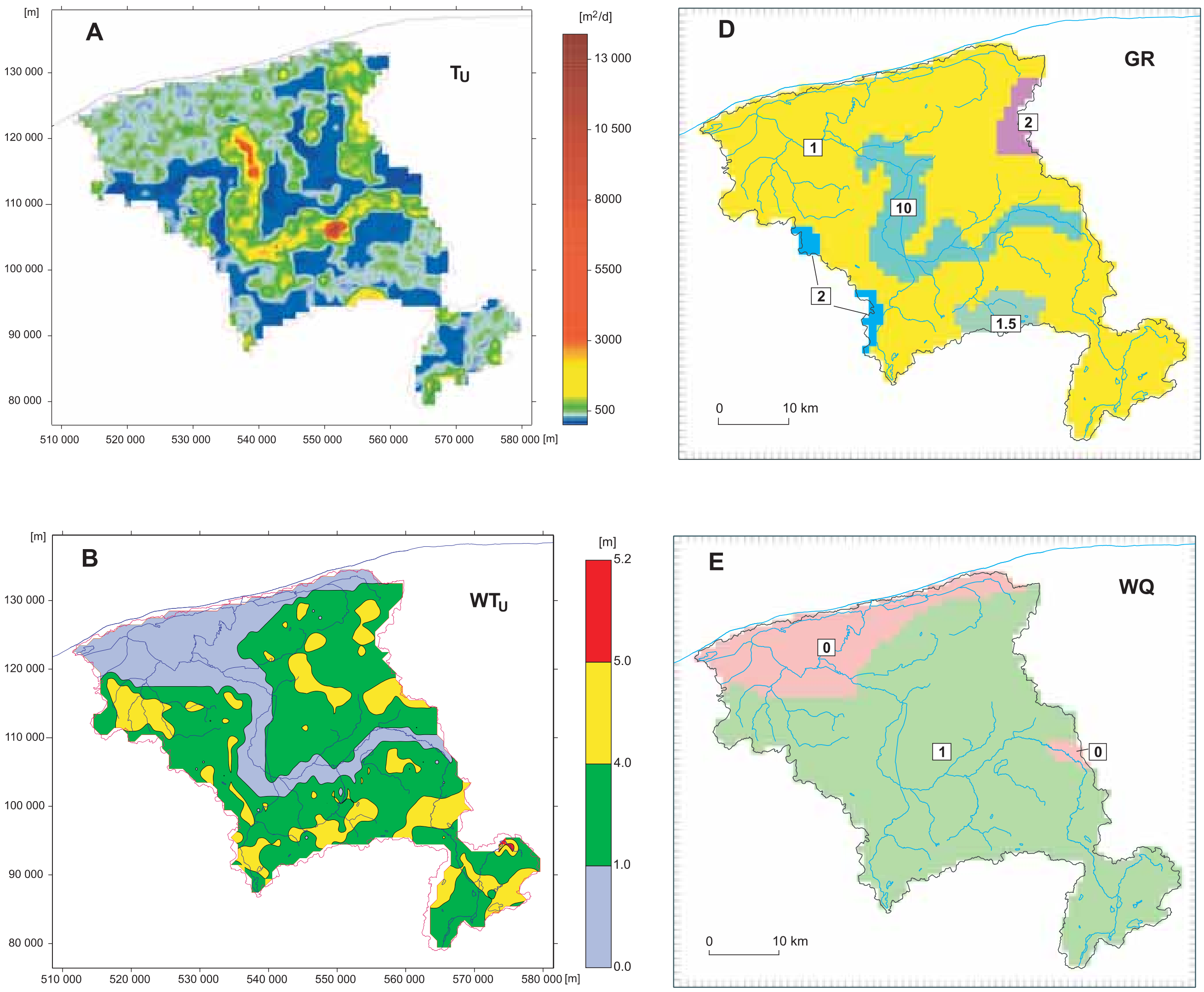



**Fig. 7. Virtual wells concept of the catchment available groundwater resources**



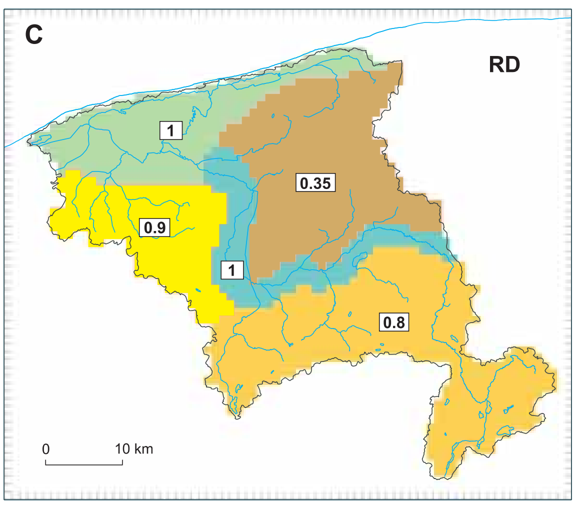




**Fig. 8. Definitions of the weight functions used to calculate the distribution of the available groundwater resources with the final weight values for RD, GR and WQ**

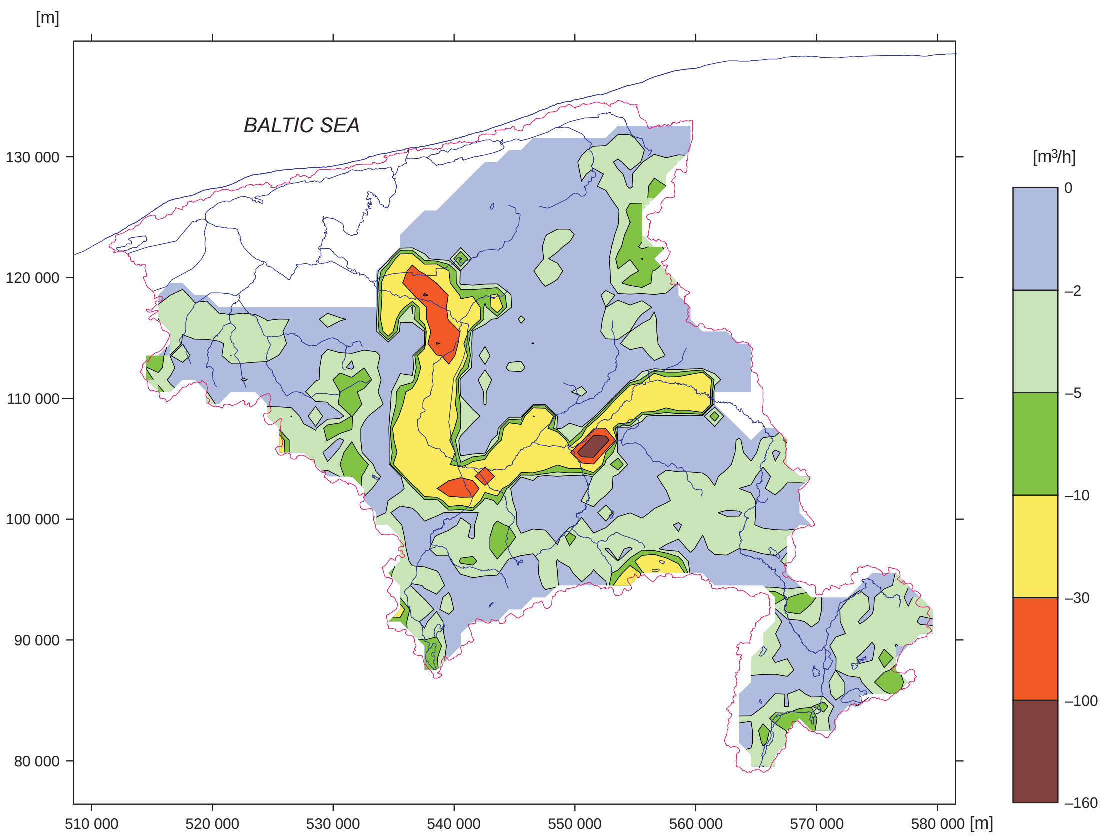



**Fig. 9. Evaluated upper layer distribution of the available groundwater resources $Q^{U}_{AVAIL}$= 7383.6 m$^3$/h**

The resulting distribution of the upper layer available groundwater resources $Q^{U}_{AVAIL}$= 7383.6 m$^3$/h is shown in Figure 9. In white catchment areas these resources equal zero because of the bad groundwater quality (Fig. 8E).

The total amount of the resources evaluated in the model based optimization process for both layers is 8686.6 m$^3$/h (Table 3). This is 40% of the catchment assessed recharge, so the C maximal allowable value in the formula [2] and [3] was determined as 0.4. The optimization variables were: the C coefficient, the RD weights (Fig. 8C) and the GR weights (Fig. 8D). There were two optimization objectives: the leakage to the rivers not less than the base flow and less than 15% increase of the lateral inflow across the catchment boundary both as the effect of the modelled resources withdrawal.

**Table 3**

**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

**1.** The model based constant volume transformation method together with the big lysimeter approximation and virtual wells concept allowed to evaluate the amount and distribution of the available groundwater resources in the Łeba River catchment.

**2.** The presented method directly connects the available groundwater resources to the renewability of the investigated flow system and its hydrogeological characteristics.

**3.** 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 modelling aimed at the proper quantitative evaluation of the groundwater resources.

## REFERENCES

EUROPEAN Union Water Framework Directive, 2000 — Directive 2000/60/EC of the European Parliament and European Commonwealth Council from 23th October 2000.

MAPA geologiczna Polski 1:200 000, arkusze: Łeba (1977), Puck (1976), Słupsk (1975), Gdańsk (1976). PIG, Warszawa.

JEZIERSKI H.J., 1994 — Polityka resortu w dziedzinie hydrogeologii. *Prz. Geol*., **42**, 11: 943–946.

KUROŚ L., 1999 — Dokumentacja hydrologiczna zasobów wód powierzchniowych zlewni Łeby. Inst. Meteor. i Gospod. Wodnej, oddział Słupsk.

KWATERKIEWICZ A., BRALCZYK M., LUBOWIECKI W., FLORCZYK J., PASIEROWSKA B., KŁOSOWSKA I., ŚMIETAŃSKI L., 2001 — Dokumentacja hydrogeologiczna zlewni Łeby zawierająca ocenę zasobów dyspozycyjnych kenozoicznych poziomów wód podziemnych. Przeds. Geol „Polgeol”, Gdańsk.

MOJSKI J.E., 1979 — The stratygraphy of the Pleistocene and the geology of its basement in the Gdańsk region. *Biul. Inst. Geol*., **317** [in Polish].

MORAWSKI W., 1990 — Szczegółowa mapa geologiczna Polski 1:50 000, arkusze: Łeba i Lębork. Państw. Inst. Geol., Warszawa.

PRAWO Geologiczne i Górnicze — Dz.U. 1994 nr 27, poz. 96 z 4 lutego 1994.

SADURSKI A., 1989 — Górnokredowy system wód podziemnych Pomorza Wschodniego. *Zesz. Nauk. AGH*, **46**.

SZYMANKO J., 1980 — Koncepcje systemu wodonośnego i metod jego modelowania. Wyd. Geol., Warszawa.