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HYDROGEOLOGICAL ASPECTS OF QUATERNARY SEDIMENTS IN POLAND

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Abstract. The major groundwater resources in Poland come from Quaternary aquifers. Rich in groundwater are structures of contemporary river valleys and of buried valleys, that comprise sands and gravels of glaciofluvial origin. Groundwater aquifers cover water demands of ca. 2.1 km^3 annually. 65% of drinking water in Poland comes from groundwater intakes. Recharge zones of these aquifers are usually located in highlands – moraine plateau, and discharge zones are located in deep and wide river valleys.

The average thickness of fresh water aquifers is about 200 m in Poland. The fresh water was stated even over 1,000 m depth in some places, but in the Mesozoic strata. The thickness of fresh water aquifer reduces, however, to only few metres in areas of salt water ascension or intrusion along the Baltic coast area. Recognition of groundwater circulation systems is the basis for delineation of a groundwater body (GWB). In Poland, the most productive parts of groundwater bodies that allow to abstract water at a rate grater that 10,000 m^3/day, are defined as Major Groundwater Basins (MGWBs).

The mean residence time of groundwater in Quaternary aquifers in Poland is estimated at some 50 yrs, whereas the residence time of water in sluggish circulation systems in deeper strata exceeds 10^4 yrs.

Quaternary aquifers situated close to the surface area are vulnerable to municipal and agricultural pollution. The geogenic pollution such as sea water intrusion or ascension of brines are observed mainly at lowlands along the Baltic coastline, in vicinity of water intakes, or on an axial zone of anticlinoria. Trends in lowering a groundwater table are noted in the central part of the Polish lowlands and are associated with climatic variability or lignite opencast dewatering.

Key words: Quaternary aquifers, porous aquifers, regional groundwater flow systems, hydrogeology of Poland.

INTRODUCTION

Over 80% of Polish territory is covered with Quaternary deposits. Tight structure of these deposits is typical for the entire area of the Polish Lowland and in parts of the strip of uplands (Herbich *et al*., 2004). Water bearing layers occur within these deposits in a form of accumulated sands of glaciofluvial origin. The most productive in water are valleys, proglacial stream valleys and buried valley structures. More than 95% of Polish territory constitutes the Baltic Sea catchment. Structure of the present hydrographical network and the Baltic Sea shore line result from geological activity of the last ice sheet – the Vistulian glacial period. The inland Baltic Reservoir is a young sea, whose history does not exceed 12 thousand years, and is a reservoir of brackish water.

Hydrogeological regionalization of Poland was conducted by applying two basic criteria, i.e. hydro-structural and hydro-dynamical. Geomorphologic criteria has been included indirectly into the hydro-dynamic criteria by differentiating between a depth of water circulation systems in which local, intermediate and regional systems were defined.

In general, four major hydrogeological regions have been defined in Poland, i.e. porous formations of the Cenozoic age which occur in the Polish Lowland; fissure-karst and fissure-porous Mesozoic and Paleozoic belt of the South Polish uplands; fissure-porous formations of the Sudeten and fissure-porous sediments of the Carpathians Mountains that are located along the southern boundary of Poland. In case of deep groundwater reservoirs that have considerably limited hydraulic contact with surface waters, the hydro-structural criterion remains fundamental for their regionalization, de-

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fining their occurrence and seizing of these aquifers. Major Groundwater Basins (MGWBs) were delineated in Poland by defining hydrodynamics of a system and establishing its quality and quantity. The total area of main groundwater reservoirs (MGWBs) cover 177,000 km^2 and comprise of groundwater resources that were estimated at 4,679 M m^3/yr (Paczyński, Sadurski, 2007). Until present day, detailed hydrogeological investigations have been accomplished for a total area of 32,500 km^2, that is some 10 percent of the country's area.

GEOLOGICAL SETTING OF POLAND

At the end of the Cretaceous, structural units of the Lowlands were formed during the Laramean phase of the Alpian orogeny. These units comprise Permian-Mesozoic strata and as Marginal Synclinorium, the Mid-Polish Antyclinorium, the Szczecin–Łódź–Miechów Synclinorium and the Fore-Sudeten Monoclinal were folded in front of the East European Platform. During the Paleogene and Neogene many upcast and downcast of the Mesozoic strata were active and lead to creation of horst and trough structures. The thick lignite seams were accumulated mostly in these troughs.

Quaternary evolution of Poland started 2.5 million years ago and comprised of two stages; the Early Pleistocene (Preglacial) – time before glaciations, and the Pleistocene comprising glacial and interglacials stages. The interglacial sediments are associated with loamy and silty sands, often with organic matter and peats accumulated in lakes, swamps and river valleys. Present interglacial – the Holocene – comprises soils, eolithic or alluvial sands, lake sediments and regoliths that are present on the ground surface.

Fundamental climatic changes that occurred at the end of the Pliocene are evident from new type of sediments deposited in those times. The period, called the preglacial period, continued for 1.5 mln years. Sediments of those times certify the radical change in erosion conditions and great transport capabilities of rivers flowing through this area. These sediments comprise usually sands and gravels, with usually well sorted material with occasional pebbles and cobbles. A characteristic feature of preglacial deposits is a lack of crumbs of crystalline rocks of Scandinavian origin and a lack of, in sandy fraction, northern feldspars. Thickness of these sediments is variable a locally, in the area of the Polish Lowland, it reaches few dozens of meters. Type of sediments and occurrence of polygonal soils prove cold and subarctic climate.

A river system with eroded deep valleys existed in the pre-Pleistocene, but the river network was oriented towards the Black Sea, the White Sea and the North Sea. Marine sediments in vicinity of the present Baltic Sea area are said to emerge in the Eemian Interglacial. Within the Polish territory, rivers have started to orientate towards the Pre-Baltic (Eemian) Sea. Deep erosions have repeated at early stages of subsequent glaciations periods, creating hollows which filled up later by gravels and sands. These processes created so called buried valleys with depths reaching 200 m deep. The biggest groundwater aquifers in Poland occur in places of interference of these structures with fluvioglacial sands developed in forms of sandurs. These aquifers are separated by glacial tills and silts strata.

It is broadly accepted at present times that there were six major continental glacial events in Poland. Extent and thickness of the best documented Quaternary glacial deposits are presented in Figure 1.

Deposits of the Sanian Glaciation occur mainly in the southern Poland, whereas in the Polish Lowland area, these deposits could have probably been retained at bottoms of deep structural denudations.

From the period of the Odranian Glaciation, the main type of deposits are boulder clays with thickness ranging from few to few dozens of meters; however, their average thickness increases from south to north. Apart from boulder clays, other sediments include silts, muds and sands.

Within the Mazovian Interglacial period (so-called the Great), two major series of deposits are apparent and are associated with processes of erosion and accumulation. These are mainly sands, gravels and river mudstones, lacustrine deposits and residual sands, gravels and pebbles.

The third phase of cooling, called the Wartanian Glaciation, consisted of six glacistadials and five interglacistadials, which means that the extent of the ice was oscillating. Typical deposits of that period, apart from boulder clays, sands and gravels, are postglacial silts that were created within the Warsaw stagnation which covered the central part of the Mazovian Basin.

Geological processes that occurred in the latest interglaciation period (Eemian) were different from those of the Great interglacial. First of all, denudation processes were far less developed, thanks to which the ground surface that was formed during the Wartanian glaciation did not deform much and moraine forms remained nearly untouched. The Eemian deposits comprise mostly organic and mineral lacustrine sediments including peat, gytia, silts and lacustrine sands.

The last glaciations period (Vistulian) started some 110,000 years ago and an ice cap of the continental glacier covered only the northern part of Poland (Fig. 1) some 70,000–80,000 years ago. Activity of the glacier and sediments deposited by it had the final influence of the present topography of the area covered by the glacier and its foreland.

Quaternary deposits comprise successive layers of glacier deposits of boulder clays, alluvial sands and gravels and lacustrine sands, silts and muds with variable spatial distribution and thickness.

The thickest Quaternary deposits occur in the north of Poland (Fig. 1) in vicinity of valleys and topographic depressions and in upland postglacial areas or other local hills such

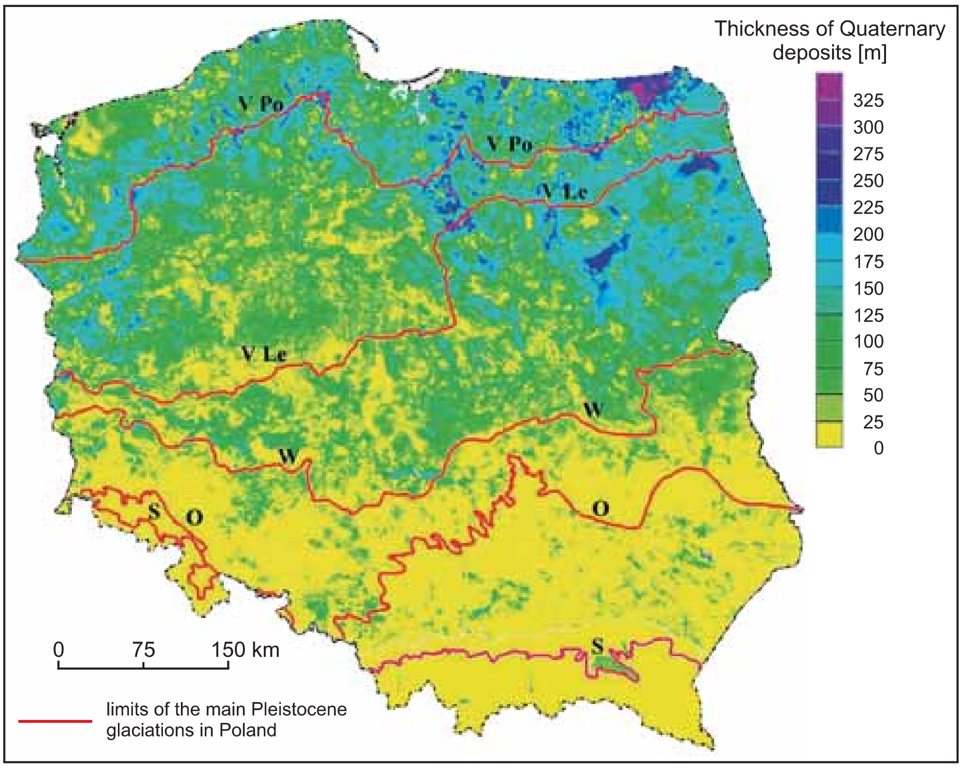

Fig. 1. Extent of main glaciations in Poland and thickness of Quaternary deposits (acc. to Piotrowska, 2007)

V Po – Vistulian, Pomeranian Phase; **V Le** – Vistulian, Leszno Phase; **W** – Wartanian; **O** – Odranian; **S** – Sanian

as for example Szeskie Hills, where the thickness of Quaternary deposits reaches 400 m. Moving in southern direction, the average thickness of Quaternary deposits decreases. In areas of the Polish Lowland, apart from the Masuria and the Pomerania lake districts, the average thickness ranges between 50 and 100 m and in the Upland Belt it rarely exceeds 25 m (Piotrowska, 2007). In mountains (the Sudeten, the Carpathian and the Świętokrzyskie Mts.) Quaternary deposits occur mainly in river valley areas as alluvial deposits (gravels, pebbles, sands) with a thickness of up to 10 m.

WATER-BEARING STRUCTURES

In the Polish Lowland, Quaternary deposits constitute the major groundwater level used for sustaining local drinking water needs; however, it is estimated that a share of this groundwater in the entire national resources is 80% of the disposable groundwater resources of Poland. In general, three major types of groundwater bearing structures have been distinguished:

- river valleys (of major rivers including the Vistula, Narew, Bug, Warta, Noteć and Pilica);
- sand and gravel structures of regional extent, occurring as layers/lenses within moraine deposits;
- water bearing fossil structures.

In river valleys, most often only one water bearing layer occurs that is unconfined and with a thickness of few meters. The only exception is the Vistula River valley in vicinity of the Vistula–Varta ice marginal valley where the thickness of water bearing Quaternary deposits most often ranges from 40 to 80 m, and locally it exceeds 100 m. Hydrogeological parameters of the Quaternary water level are very good here. Transmissivity usually ranges from 1,000 to 1,500 m^2 per day, water permeability coefficient varies from 10 to 20 m/day and locally, north of Warsaw, the groundwater transmissivity can exceed 1,500 m^2/24hr. Potential well yields are very high and usually they exceed 120 m^3/hr. The Quaternary water level is generally devoid of any isolation from the ground surface, thanks to which its recharge is high and exceeds 300 m^3/km^2/24hr. These structures, which contain significant groundwater resources with very good renewability, are especially predisposed for locating large groundwater supplies. On the other hand, lack of isolation from the ground surface makes these resources very vulnerable to pollution from sources located at the surface.

Fluvioglacial sand and gravel structures occurring within boulder clays dominate spatially and they are the most often exploited groundwater levels. In general, there are three elemental water levels with a staging structure: bottom, middle moraine and subsurface.

This diversification is very general due to high spatial changeability of specific water levels. In many places there are no usable groundwater levels.

Thicknesses of water-bearing structures reach dozen or so meters with transsmisivity of 25 to 500 m^2/d. A common feature of all the above groundwater levels is their high lithological complexity, from silt and small grain sands to large grain sands and gravels.

Water-bearing buried structures. Most of regional buried structures within Polish territory is associated with the early Pleistocene period (Paczyński, 1980) and a definite minority of them is associated with older interglacial periods. These structures constitute two systems directed towards different lines. The first group comprise of structures that are linked to the present hydrographic network and its direction is approximate to a meridian. The second group are associated with proglacial stream valleys directed parallel to the equator which is linked with an outflow from a head of a glacier. The biggest marginal ice valleys of northern and central Poland are: Noteć–Warta valley, Pomeranian system of ice marginal valleys, Reda–Łeba valley, Warsaw–Berlin ice marginal valley and others (Fig. 2).

A characteristic feature of groundwater occurrence in the Polish Lowland district are structures of buried valleys (Fig. 3). Thickness of groundwater bearing deposits of sands within these structures often exceeds 100 m, for example valleys located in the western Mazovia. It is common that

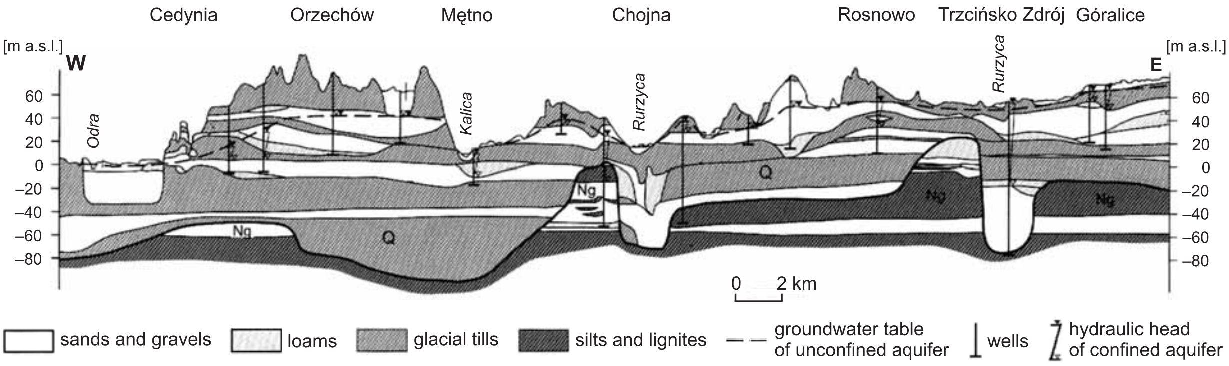

Fig. 2. Hydrogeological cross-section in the Western Poland, up to Odra River valley (acc. to Wiśniowski, 2007)

Ng – Neogene, **Q** – Quaternary

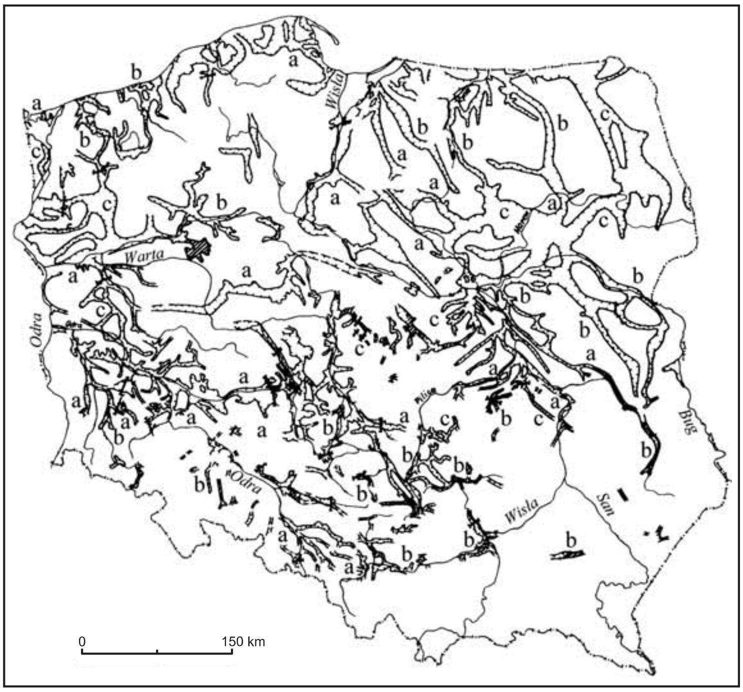

Fig. 3. Quaternary buried valley structures in Poland (acc. to Paczyński, 1980)

a – very productive, sufficient for big groundwater intake construction; **b** – productive, locally sufficient for big groundwater intake construction; **c** – little productive in groundwater, partly filled in by sediments of low permeability these deposits have good or very good hydrogeological parameters and can become an important source for drinking water supplies even for a town of more than 10,000 inhabitants. Buried valleys are often devoid of isolation and therefore, as anthropogenic pressures are likely to expand with time, these groundwater structures shall be legally protected due to its high importance as a resource.

GROUNDWATER CIRCULATION SYSTEMS

In conceptualisation of groundwater flow conditions in river catchments, a classic model of water cycle after Toth (1962) and Freeze, Witherspoon (1967, 1968) was adopted. In a simplistic way, local and regional groundwater circulation systems were defined. To visualise a circulation system, many separate water levels were aggregated into few major units of a limited number, including:

1. **Subsurface circulation system** (local), with unconfined water table or only locally confined in places where boulder clays or alluvial soils occur within a subsurface. This system is usually recharged by infiltration of precipitation. Natural drainage occurs via small surface watercourses, streams and river valleys. Water table follows topographic settings. The residence time of water is usually short and rarely ever exceed one year. The isotopic composition of this water shows seasonal changes in concentrations of tritium, oxygen and hydrogen.

2. **Deeper circulation system** (regional), includes water bearing layers occurring between clays. Water table in this system is confined. The system is recharged at uplands and raised grounds or by infiltration from subsurface systems and is drained by valleys of large rivers.

A schematic of groundwater circulation systems is presented in Figure 4.

Groundwater lines of water levels taking part in the regional groundwater flow system to high degree reflect most important geomorphological units. Culminations of high water table and depressions along rivers are clear. Groundwater flow between subsequent groundwater levels in a vertical profile results from differences in hydraulic heads. Differentiation in intensity of the groundwater flow is supported by results of groundwater chemical analyses. Studies that researched concentrations of tritium, undertaken between 2004 and 2006 (Nowicki, 2004, 2005, 2006), proved that the average exchange time in groundwater in Poland, at depths from 30 to 35 m, which is mainly within Quaternary deposits, is circa 50 years.

Within large rivers' valleys (e.g. the Vistula and the lower Narew rivers), Quaternary water levels connect with one another in border zones where full hydraulic connectivity is preserved. It happens sometimes, that subsurface water levels that occur in upland areas, disappear in lowlands where water seeps out via springs or seepage zones and then the same water infiltrates into an alluvial groundwater level.

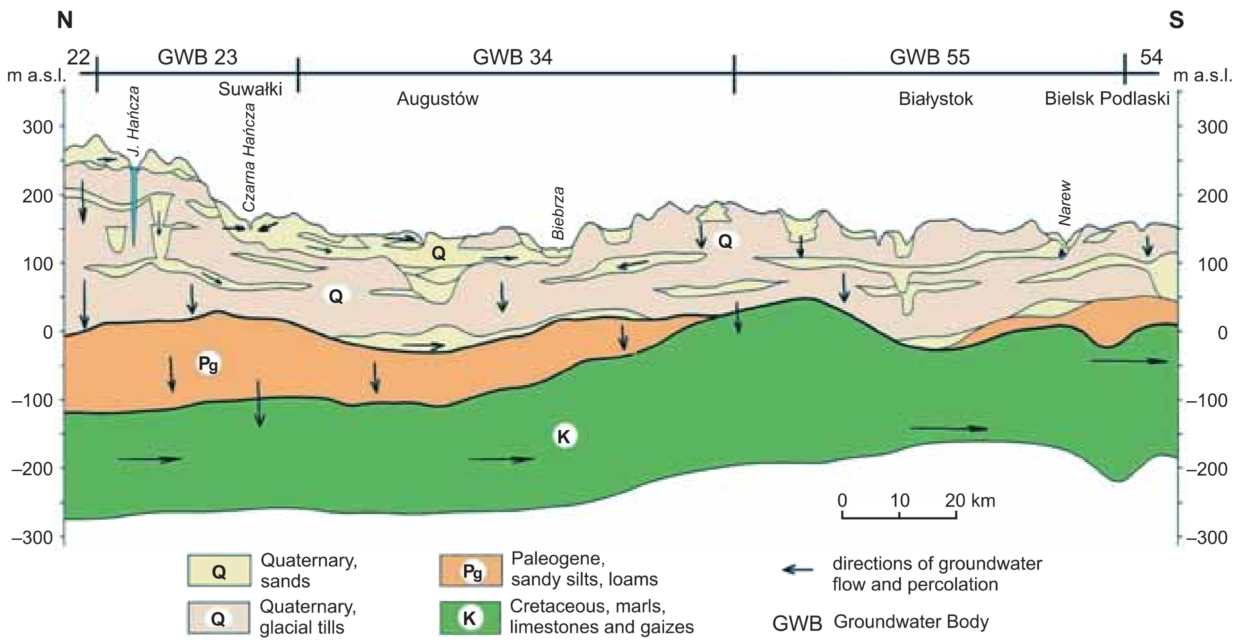

Fig. 4. Scheme of groundwater circulation systems in the Quaternary strata in the northeastern Poland (Masuria Lakeland, acc. to Nowakowski, Nowicki, 2007)

HYDROGEOCHEMISTRY

With respect to groundwater chemistry, water gathered in Quaternary deposits shows chemical signature typical for waters of a shallow zone with intensive exchange. Most often, these are HCO_3–Ca waters, and sporadically HCO_3–Ca–Mg. Any other type of water determined within these deposits explicitly indicates groundwater pollution from anthropogenic sources or ascension of brines.

Mineralisation of groundwater in Quaternary deposits is relatively low with an average of 350 to 450mg/l of dry solids; however, in some areas, (e.g. Suwalskie district) mineralisation very often does not exceed 200 mg/l. Groundwater is little alkaline (pH ranges from 7.0 and 8.0) with medium hardness (140–340 mg/l $CaCO_3$).

A characteristic feature of the chemical signature of Quaternary aquifers are elevated concentrations of iron (usually 0.2–1.1mg/l) and manganese (average 0.01–0.1mg/l). However, maximum amounts for these two parameters detected in groundwater samples are much higher and reach 20.0 and 1.5 mg/l respectively.

Locally, in shallow groundwater levels concentrations of ammonium, sulphates and chlorides are often elevated, which results from agricultural and communal pollution and in the Baltic Sea shore line, it results from intrusion of sea water (Sadurski, 2000).

Nearly 80% of groundwater resources in Poland is good quality and are acceptable for drinking without any treatment or they require simple removal of iron and manganese.

The average thickness of fresh water layer is ca. 200 m (Kleczkowski, 1987). Salt waters and brines of the sedimentary and palaeoinfiltration origin and of Cl–Na type occur commonly in the Polish lowlands, beneath the fresh groundwater lenses (Dowgiałło *et al.*, 1974).

MAJOR GROUNDWATER BASINS

One of the most important duty of the country with regard to national protective measures is to assure its inhabitants with free access to good quality water, protection of groundwater resources as well as rational groundwater management. One element of fulfilling these responsibilities was delineation, in the early 1990s, of so-called Major Groundwater Basins (MGWBs), which constitute the most valuable parts of water bearing layers in Poland (Kleczkowski, 1990). Delineation of specific reservoirs was conducted based on selected criteria reflecting groundwater productivity and quality of water, including:

- yield of a typical well within a MGWB must exceed 70 m^3/h,
- transmissivity of water bearing layers must exceed >10 m^2/h,
- must have potential for building a large groundwater supply with an abstraction rate at least 10,000 m^3/24h,
- groundwater quality is very good and stable.

In total, 162 MGWBs have been delineated in Poland; however 104 of them comprises of Quaternary deposits only (Fig. 5). It is estimated, that national groundwater resources associated with Quaternary deposits amount to 50% of all MGWBs.

The most productive Quaternary MGWB is a reservoir called the Middle Vistula River Valley. It is located in vicinity and partly within borders of the city of Warsaw and constitutes a very important reserve of potable groundwater for the capital (Nowicki, 2007). Estimated disposable groundwater resources of this reservoir are sufficient for sustaining drinking water needs of Warsaw and few other satellite towns.

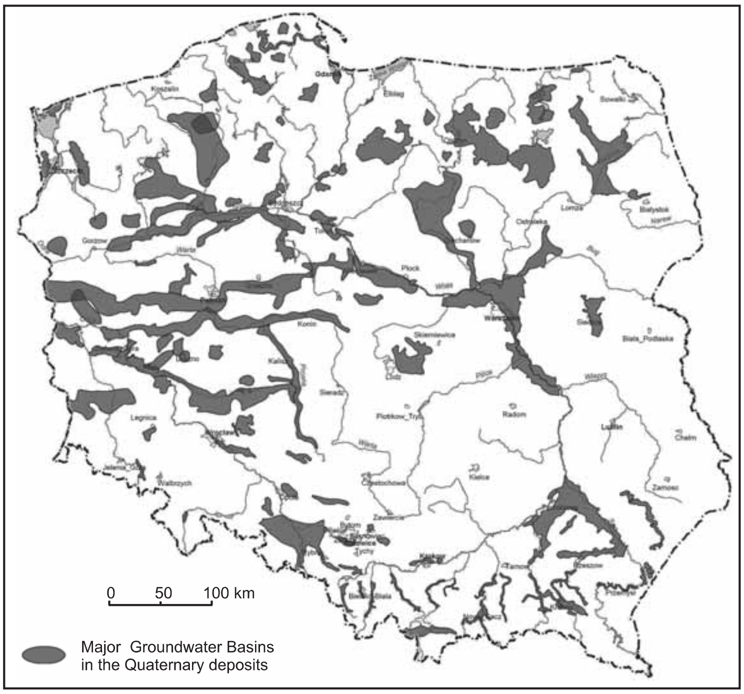

Fig. 5. Major Groundwater Basins in Poland

CONCLUSIONS

Multilayered Quaternary systems are common in the area of Polish Lowlands. Transmissivity of this water bearing strata often exceeds 200 m^2/h. Tremendous potential of these groundwater resources and their occurrence close to the ground surface allows for their large scale use, which is ca. 2.1 km^3 a year, which is approximately 51% of the total amount of exploited groundwater. Recharge zones of quaternary aquifers occur typically at belts of water divides and in highlands, while wide river valleys are their discharge zones. The mean resident time of water in Quaternary aquifers in Poland reaches 50 yrs, whereas the residence time of water in sluggish circulation systems, within deeper strata, exceeds 1,000 yrs.

The most productive aquifers are defined and protected as Major Groundwater Basins (MGWBs).

Quaternary aquifers are vulnerable to municipal and agricultural pollution. The geogenic pollution such as sea water intrusion or ascension of brines are observed mainly at lowlands along the Baltic coastline, in vicinity of water intakes. Trends in lowering a groundwater table are noted in the central part of the Polish lowlands and are associated with climatic changes.

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