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# CHANGES IN GROUNDWATER STORAGE, KAMIENNA DRAINAGE BASIN, SOUTHEASTERN POLAND

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**Abstract:** Water-table levels in the Kamienna River drainage basin, SE Poland, are presently measured at 14 observation points within the groundwater observation-research network of the Polish Geological Institute – National Research Institute, included in the monitoring programme during the period 1979–2007. They exhibit multi-year changes in groundwater storage near the observation points. The best documented cycle is that for the period 1982–2002, observed in the wells monitoring water in fractured-karstic formations, where the amplitude of the water-table level was 45 m at that time. The retention balance in the cycle was negative. At the beginning of the cycle, the water table in the fractured-karstic aquifers was 1.40 to 1.94 m higher than at the end. Further observations of the multi-year changes in retention will be the basis for possible corrections to calculations of groundwater resources in this drainage basin, as well as for model predictions of resources, performed for water management in connection with potential climate change.

**Key words:** Kamienna River basin, groundwater storage, water table, retention cycles.

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## INTRODUCTION

In general, retention is the process of retaining water or limiting the speed of water flow on the ground surface, in the soil and within the rock mass. Underground retention (groundwater storage) is related to water percolating into the soil and rocks. However, the retained groundwater is not strictly water that is completely stagnant within the pattern of circulation. It occurs where the circulation rate is decelerated (Pazdro and Kozerski, 1990). According to the *Hydrogeological Glossary* (Dowgiałło *et al.*, 2002), it is defined as: “ [the] amount of water, variable through time, stored in the underground environment.” Changes in underground retention are reflected in the water table levels: a rise of the water table means an increase in retention and a drop means a decrease in retention. The amount of underground retention depends on the amount of precipitation, run-off and evaporation. In wet years, additions of water exceed loss (runoff and evaporation) and as a consequence there is an increase in underground retention. In dry years, the situation is reversed” (Dowgiałło *et al.,* 2002). By definition, the state of the water table in unconfined aquifers and the piezometric head in confined aquifers reflect the relationship between the hydrodynamic recharge and underground drainage and are indicators of retention. However, water-table levels change over time and are both seasonal and long-term. Seasonal changes result from the periodic recharge of aquifers by precipitation during the hydrological year, while long-term changes take place over longer periods of climate change. The understanding and characterisation of long-term changes require analysis of long observational series of water-table levels in a number of observation wells, with regard to the hydrogeological conditions in the area.

This paper presents multi-year cycles of changes in groundwater storage in the Kamienna River drainage basin, based on the published results of water-table measurements at groundwater monitoring points of the Institute of Meteorology and Water Management (IMGW) and the hydrogeological stations and observation points of the Groundwater Observation-Research Network (GORN) of the Polish Geological Institute – National Research Institute (PGI-NRI). The effect of the groundwater fluctuations on groundwater resources have been assessed on the basis of their parameters.

## STUDY AREA

The study area covers 2000 km$^2$ of the Kamienna River drainage basin, a second-order drainage basin and a tributary of the Vistula River, in SE Poland.

In accordance with the geographic regionalization of Poland, this area is included in the Kielce Upland, and the S part of the drainage basin embraces the N slopes of the Świętokrzyskie Mountains (Holy Cross Mountains), which

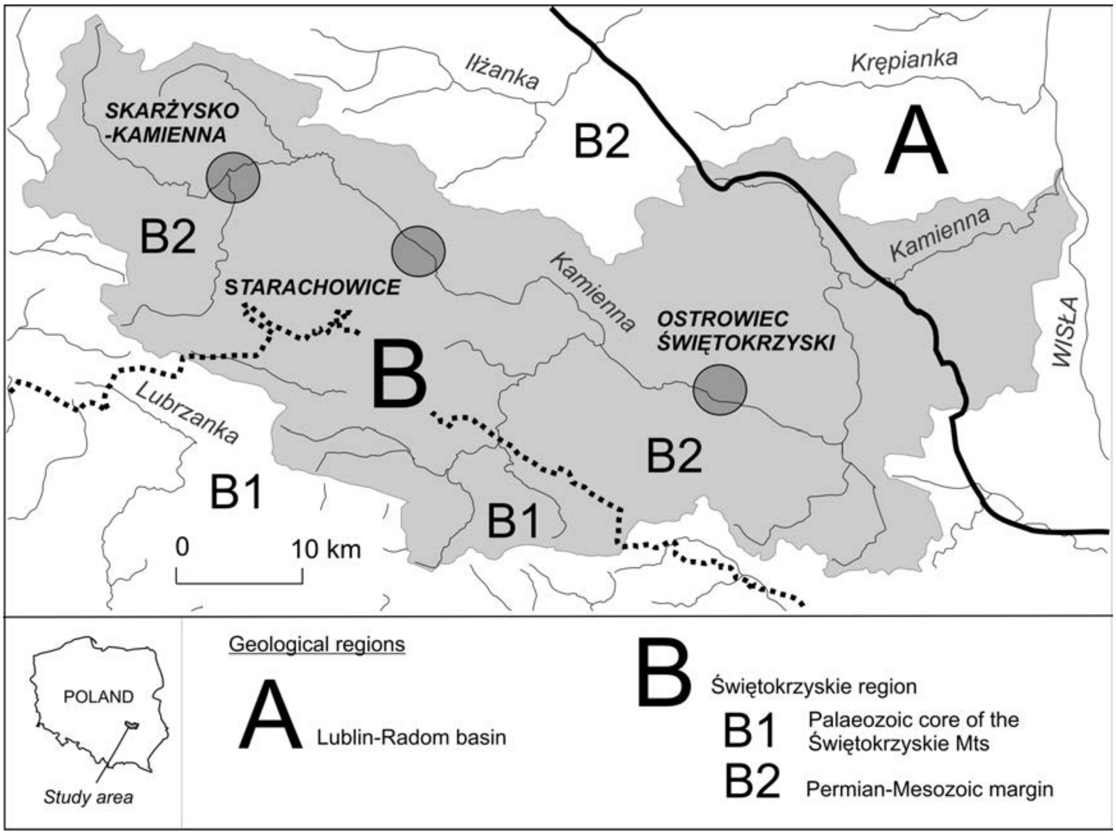

**Fig. 1.** Location of Kamienna River drainage basin against background of geological regions

also belong to this upland (Kondracki, 2001). The upland is transected by the valley of the W–E-running Kamienna River, 0.5 to 2 km in width, and the predominantly narrow river valleys of its tributaries.

The Kamienna River flows generally from W to E. Its length from the springs to the mouth is 138 km, and the average flow rate at the confluence with the Vistula River is about 10 $m^3$/s. The land use of the drainage basin area is mainly agriculture and forestry, except in the areas of the three towns of Skarżysko-Kamienna, Starachowice and Ostrowiec Świętokrzyski, located on the Kamienna River, where large metal industry plants operate. The water for the residents, agriculture and industry comes in general from local groundwater resources of the drainage basin. Only the town of Starachowice uses water from the adjacent drainage basin of the Iłżanka River, located to the north (Fig. 1).

According to the geographic regionalization of Poland, this is the Świętokrzyskie Mts region (B), excluding the NE part of the drainage basin, which is situated in the Lublin–Radom basin (A). The Świętokrzyskie Region consists of the Palaeozoic core (B1) and the Permian–Mesozoic margin of the Góry Świętokrzyskie Mountains (Fig. 1). The regional geological structures are consistent with the regional hydrogeological structures, presented in the *Hydrogeological Atlas of Poland* (Paczyński, 1993):

– Lublin–Radom basin (A), region IX, Lublin–Podlasie Region;

– Świętokrzyskie region (B), region X, Central Małopolska Region;

– Palaeozoic core (B1), subregion $X_1$, Świętokrzyskie Region.

According to the drainage-basin hydrogeological regionalization of Poland, the study area is located within the Vistula Province, Middle Vistula Upland Region (Herbich *et al.*, 2007).

The hydrogeological conditions of the study area are highly variable. There are eight stratigraphically different multi-aquifer formations: Quaternary, Cretaceous, Jurassic, Triassic, Devonian, Silurian, Ordovician and Cambrian (Figs 2, 3).

Quaternary deposits cover about 70% of the area. The cover is discontinuous and the basement rocks frequently outcrop on terrain elevations. On the plateau, these are mainly tills and glaciofluvial and glacial sands of the Wartanian Glaciation, as well as aeolian loess of the Vistulian Glaciation. In the Kamienna River valley and in the valleys of its tributaries, fluvial sands, sands with gravel, and gravels predominate. The total thickness of the Quaternary sediments is variable and ranges from a few to about 30 m. Owing to the lithological diversity and variable thickness, the Quaternary aquifer is usually considered unusable; the potential discharge rates of a drilled well are <10 $m^3$/h. However, before the development of the rural water supply system, the groundwater was extracted more commonly from the Quaternary aquifer by means of hand-dug wells. Only fluvial sands, sands with gravel, and gravel of the valleys of the Kamienna River and its tributaries are of greater significance, because the deposits are porous and have good per-

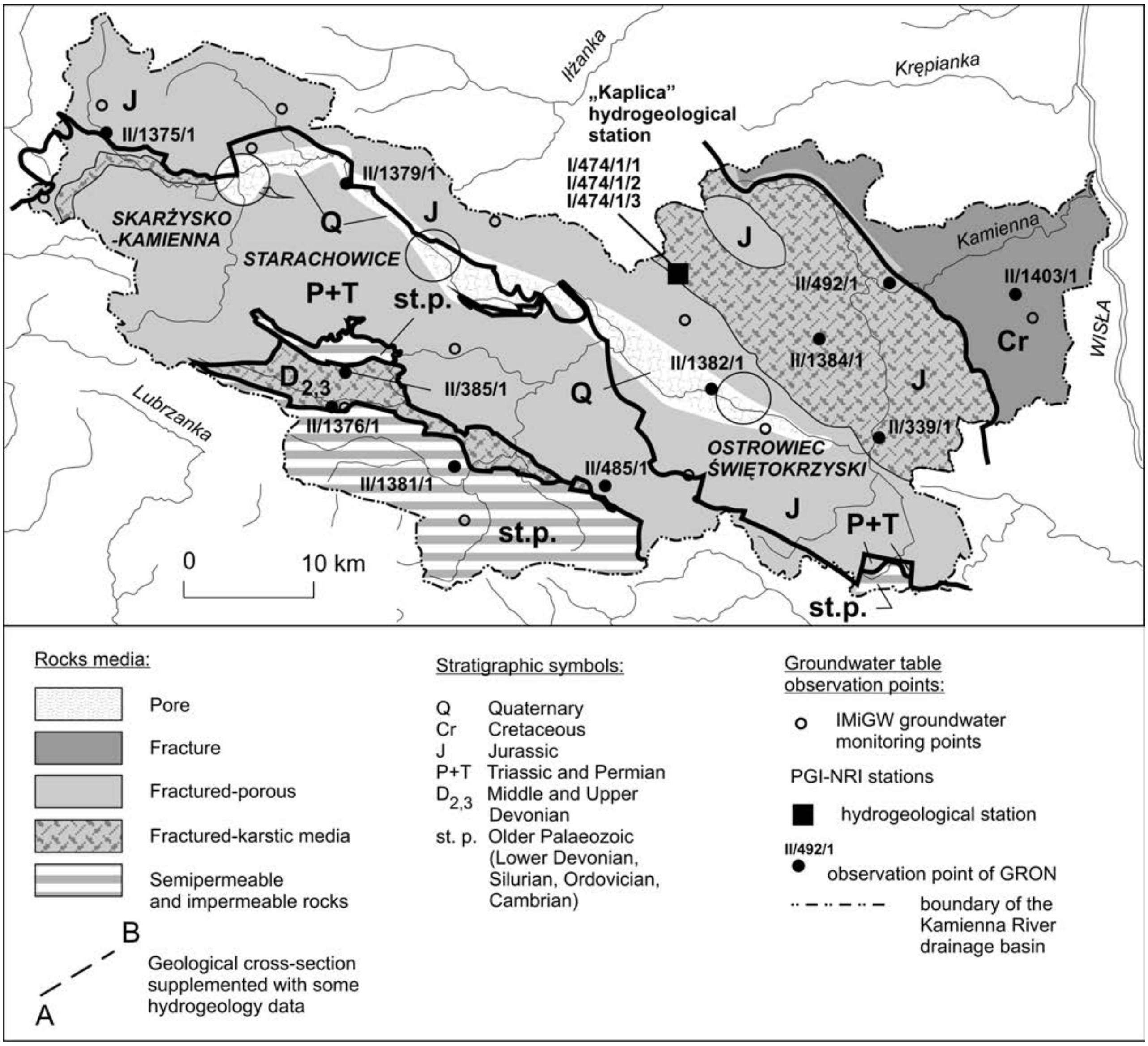

**Fig. 2.** Rocks media in Kamienna River drainage basin

meability. The average discharge rates, measured in drilled wells draining these deposits, vary from 10 to 30 m$^3$/h.

In the sketch map of the multi-aquifer formations of the Kamienna River drainage basin (Fig. 2), the Quaternary multi-aquifer is shown only in the areas, where it is the main aquifer alone or together with the multi-aquifer formation of the bedrock (Wróblewska and Herman, 1997a, b, 2002; Sokołowski, 2000; Wróblewska and Prażak, 2002a, b).

In the Lublin Trough, in the E part of the drainage basin, there is only one multi-aquifer formation in the Cretaceous rocks, represented by marls and opokas, a permeable, fractured formation, with the potential discharge of wells ranging from 30 to approximately100 m$^3$/h. The lowest part of the formation is represented by a several-metres-thick series of sandstones with glauconite, which are a permeable and porous medium, outcropping in a narrow zone along the SW boundary of the structure (Kos, 2000).

The Permian–Mesozoic margin of the Świętokrzyskie Mts is represented by Jurassic, Triassic and Permian multi-aquifer formations. These strata dip monoclinally towards the NE. The Upper Jurassic and Middle Triassic limestones are a fractured-karstic medium with good permeability and potential discharge of wells ranging from 30 to over 120 m$^3$/h. However, the Middle Jurassic, Lower Jurassic, Lower Triassic and Permian deposits are represented by sandstones and locally conglomerates, which are a permeable medium with fracture porosity and an average potential discharge of wells in the range 10–30 m$^3$/h (locally up to 100 m$^3$/h). They are interbedded with clays, claystones and mudstones. The Upper Triassic succession is composed mainly of mudstones and claystones with thin interbeds of sandstones, which do not meet the criteria for being a main aquifer (potential discharge $Q_p$<10 m$^3$/h).

In the Palaeozoic core of the Świętokrzyskie Mts, in the S part of the Kamienna River drainage basin, there are the Devonian, Silurian, Ordovician and Cambrian multi-aquifer formations. Only the upper and middle parts of the Devonian multi-aquifer are of usable quality. They are represen-

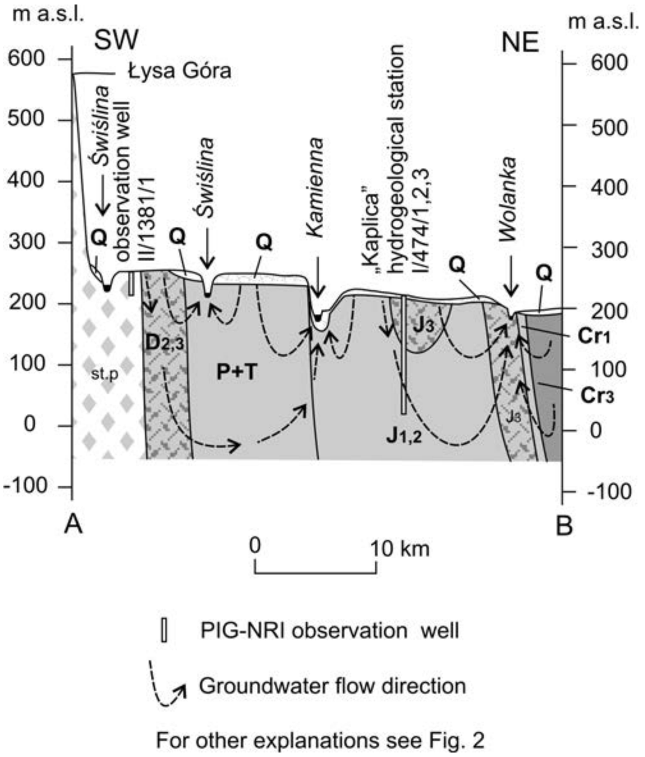

**Fig. 3.** Simplified geological cross-section, supplemented with some hydrogeological data given on

ted by Frasnian, Eifelian and Givetian limestones occurring in a WNW–ESE-oriented syncline. This is a permeable fractured-karstic medium with a potential discharge of wells in the range 50–70 m$^3$/h. The lower part of the Devonian multi-aquifer formation and older formations (Silurian, Ordovician and Cambrian) are composed of generally impermeable rocks and/or permeable clays, claystones, quartz sandstones and mudstones. Water-bearing deposits occur only locally in the topmost, weathered parts, attaining a thickness of about several metres (Wróblewska and Herman, 1997b; Wróblewska and Prażak, 2002b; Prażak, 2012).

Owing to the varied lithology of the water-bearing layers, often even within the same multiaquifer formation, the hydraulic contacts between them are usually discontinuous. The groundwater circulation is also complicated by folds and tectonic discontinuities in the study area. It is estimated that the zone of active groundwater exchange in the basin reaches a depth to about 250 m.

## METHODS AND MATERIALS

In the Kamienna River drainage basin, the water-table levels were measured by the IMGW in several hand-dug wells. The present work includes only data from eleven wells with continuous observations made in 1965–1983. Since 1979, measurements of the water table have been carried out in this area by the Polish Geological Institute in observation wells of the developing groundwater observation network. In 2005, this network was combined with the national groundwater-quality monitoring network, which operated since 1991, into the Groundwater Observation-Research Network (GORN) of the PGI-NRI, currently managed by the Institute. Within the study area, the network is represented by one hydrogeological station "Kaplica" (three observation points) and eleven stations with single observation points (Table 1) (Kazimierski, 2012). The observation points comprise hydrogeological-research wells and adapted drilled wells, measured at stabilized water tables after breaks in exploitation.

**Table 1**

Index of SOBWP survey points in Kamienna River drainage basin

| GORN survey point | | Aquifer stratigraphy | Screened at depth | | Year of the observation start |
|---|---|---|---|---|---|
| | | | from | to | |
| I/47/1 | Hydrogeological station Kaplica | Upper Jurassic | 55.0 | 90.0 | 1983 |
| I/47/2* | | Middle Jurassic | 102.0 | 149.0 | 1983 |
| I/47/3* | | Middle Jurassic | 158.8 | 198.0 | 1983 |
| II/339/1 | | Upper Jurassic | 18.3 | 24.1 | 1989 |
| II/385/1 | | Middle Devonian | 32.0 | 35.0 | 1979 |
| II/485/1 | | Lower Triassic | 28.9 | 53.0 | 1986 |
| II/492/1 | | Upper Jurassic | 37.0 | 47.0 | 1986 |
| II/1375/1 | | Quaternary | 7.1 | 9.8 | 2005 |
| II/1376/1 | | Middle Devonian | 16.7 | 22.0 | 2005 |
| II/1379/1 | | Quaternary | 20.2 | 26.2 | 2005 |
| II/1381/1 | | Silurian | 23.0 | 30.0 | 2005 |
| II/1382/1 | | Quaternary | 10.0 | 14.0 | 2005 |
| II/1384/1 | | Upper Jurassic | 60.0 | 122.0 | 2005 |
| II/1403/1 | | Upper Cretaceous | 26.5 | 32.5 | 2007 |

* – observation points neglected in research drain deeper aquifers

Groundwater observation points of the IMiGW and of the GORN monitor groundwater levels of the first aquifer. An exception is Station No. II/485/1, in which the water-bearing layer is monitored at a depth of 20–55 m and the groundwater is confined by overlying shales. The observation wells and piezometers monitor water-bearing strata that vary in lithology and stratigraphy: Quaternary, Upper Cretaceous, Upper and Middle Jurassic, Lower Triassic, Middle Devonian, Silurian and Ordovician. Hand-dug wells monitor groundwater levels in the Quaternary deposits (sands, tills, loess and deluvial sediments) or the top parts of the older deposits of undetermined, geological sections. Geological sections of the GORN PGI-NRI observations wells are well documented (Fig. 3). Observation points of the “Kaplica” hydrogeological station monitor the following three water-bearing layers located at different depths, but remaining in hydraulic connection (Fig. 4): I/474/1 Upper Jurassic limestones (7.5–93.0 m), I/474/2 Middle Jurassic – Callovian sandstones (93.0–150.0 m), I/474/3 Bajocian sandstones interbedded with clays and shales (150.0–200.0 m).

Observation points are located in areas with different hydrodynamic conditions in terms of recharge, retention dynamics and groundwater flow directions, that is, in recharge areas, transit flow zones and groundwater drainage areas (Fig. 4).

In the outer and inner watershed zones of the study area, the aquifers are recharged by the effective infiltration of rainwater. The thickness of the vadose zone commonly exceeds 1 m. The water table is subjected to seasonal and multi-year fluctuations, controlled by the discharge rate. Groundwater outflow occurs towards the outside of the watershed. However, the flow rate towards the neighbouring drainage basins may vary, depending on the hydraulic head of the groundwater. In the recharge area and the transit flow zones, the aquifers are also recharged by effective infiltration of rainwater, even if the thickness of the vadose zone exceeds 1 m, and the groundwater table is subjected to seasonal and multi-year fluctuations, controlled by the varying discharge rate. Drainage zones include areas in river valleys and wetlands, practically devoid of any effective recharge of deeper aquifers. The groundwater flow occurs towards shallower aquifers, drained directly by surface waters and by evaporation in the areas of shallow occurrence of the water table.

In the deeper aquifers, owing to internal pressure, resulting from the variability of filtration parameters, the stabilized water table is not dependent on surface water levels. In some cases, it may even stabilize above them, as in the case of flowing wells. For these reasons, all the river valleys, including upper terraces, where the depth to the water table can exceed 1 m, should be considered as drainage zones of deeper-situated aquifers.

Among the GORN observation points, in the watershed zone, there are the three points of the “Kaplica” hydrogeological station (II/474/1, II/474/2 and II/474/3); in the drainage zone, four observation points in the Kamienna River valley, monitoring of water from near-surface aquifers (I/339/1, I/1375/1, I/1379/1 and I/1382/1); and the remaining seven observation points are located in the recharge area and transit flow zones (Figs 1, 3). It should be noted that none of the observation points lies within the area, affected by groundwater extraction or mine dewatering.

First, the scope of the data and the nature of retention changes within the basin were analysed. For this purpose, the average annual groundwater levels from all monitoring points were plotted on a single graph and at the same scale. The points include the IMGW rainfall stations and the first-order and second-order stations of PGI-NRI (Fig. 5). In the case of the “Kaplica” hydrogeological station, only one observation point, No. I/474/1, is plotted. This is a well monitoring water from the uppermost aquifer of the Upper Jurassic limestones. The graph provides some basic data; groundwater levels are given below the ground surface:

a) The water table occurs at depths of about 1 m to almost 55 metres; in one GORN observation point (confined aquifer), it stabilizes approximately 2 m above the surface;

b) In the IMGW observation points, the unconfined water table was monitored in 1965–1983;

c) There is only one point of the groundwater observation network, in which the observation sequence coincides with the observation sequence from the IMGW groundwater points, over a four-year period;

d) Water table measurements at the “Kaplica” hydro-g eological station of the groundwater observation-research network (three wells) started in 1983. It was the last year of measurements at the IMGW observation points;

e) The observation periods of the GORN piezometers and observation wells are different: 33 years (1979–2011) for 1 point; 29 years (1983–2011) for 3 points; 26 years (1986–2011) for 2 points; 23 years (1989–2011) for 1 point; 7 years (2005–2011) for 6 points and 5 years (2007–2011) for 1 point.

## RETENTION CHANGES IN THE KAMIENNA RIVER DRAINAGE BASIN

Long-term changes of water retention in the territory of Poland show a clear cyclicity, documented by the multi-annual observations in 193 observation wells of the IMGW (Institute of Meteorology and Water Management) and 193 observation points of the GORN (Groundwater Observation-Research Network). The individual cycles of retention changes have been determined, as a result of research by the National Hydrogeological Survey. Depending on the region, their boundaries (Fig. 6) vary from 2 to 6 years (Herbich *et al.*, 2009). Four cycles have been identified (see Fig. 6), spanning the following periods:

– Cycle A ended in 1951–1955 and was observed only at the IMiGW points;

– Cycle B started in 1951–1955 and ended in 1975–1981;

– Cycle C started in 1975–1981 and ended in 1999–2000;

– Cycle D started in 1999–2000 and still continues.

In the Kamienna River drainage basin, two complete cycles and two incomplete cycles of multi-year groundwater storage changes (Table 2) were identified at most of the

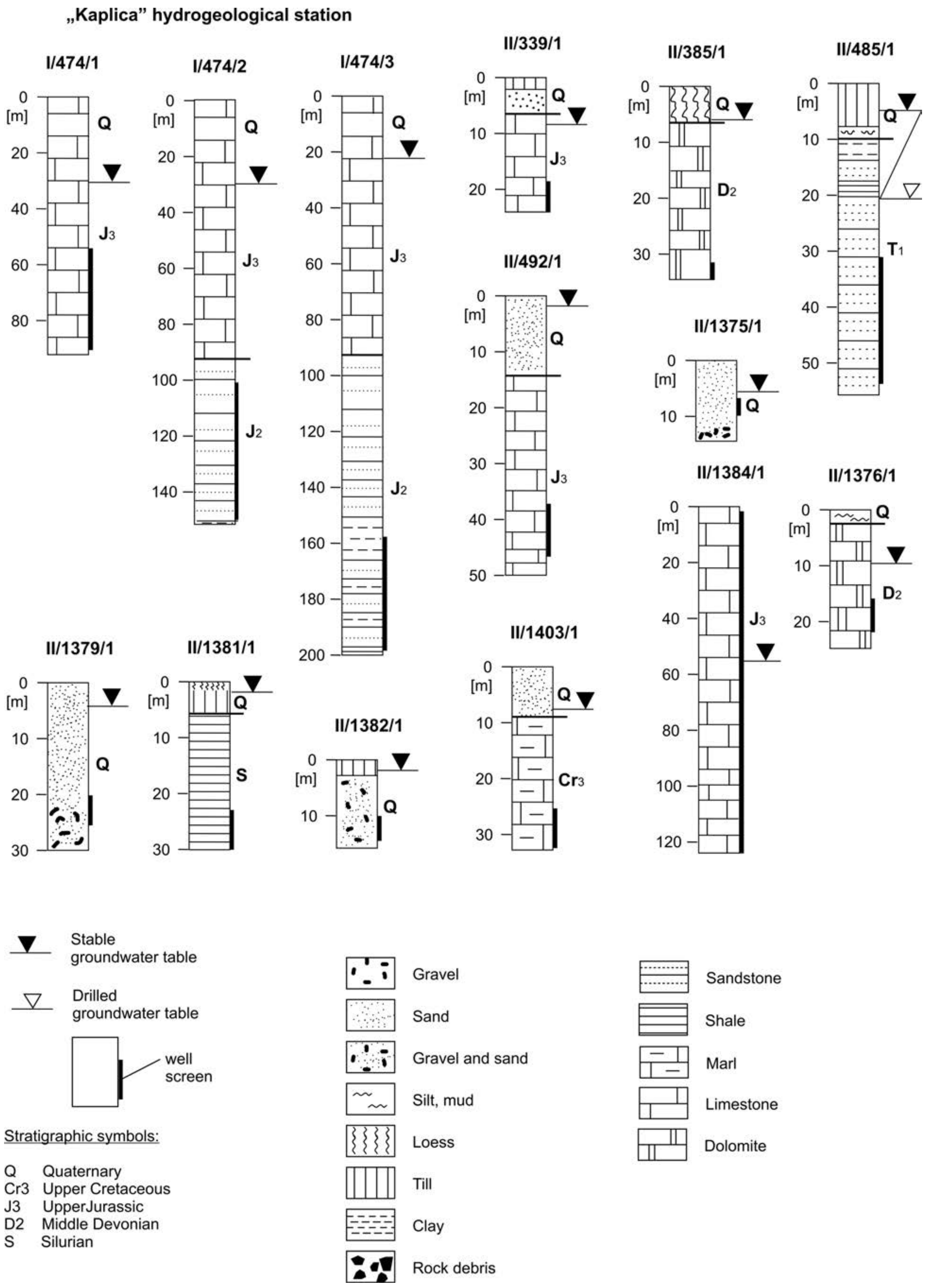

**Fig. 4.** Geological sections of GORN piezometers and observation wells in Kamienna River drainage basin

observation points, with an accuracy of ± 1 year. The cycles are bounded by maximum levels. Long sequences of observations of the water table were performed for the observation point (I/474/1) at the "Kaplica" station and for one point (II/385/1) of the Sieradowice groundwater monitoring station. At the remaining observation points, the measurements lasted for a shorter period, allowing only for confirmation of the timing of the occurrence of the maximum groundwater tables in the last cycle.

**Table 2**

Multi-year cycles of groundwater srorage changes in Kamienna River drainage basin

| Cycle | Beginning of cycle [year] | End of cycle [year] | Duration [years] |
|---|---|---|---|
| B | ?1965 | 1981 | ? |
| C | 1982 | 2002 | 21 |
| D | 2003 | ? | ? |

Cycle B started before 1965 and continued until 1981. Cycle C covered the period 1982–2002, and the current cycle D has continued since 2003. Determination of the end of cycle B, based on groundwater table data at the IMGW points (hand-dug wells), is not very clear, owing to the small amplitudes of the water table fluctuations However, it is observed in most of the posts. A complete cycle C can be traced in observation well No. II/385/1 at Sieradowice, which monitors the fractured-karstic rock medium (Middle Devonian dolomites). This cycle is almost complete at observation point No. I/474/1 of the "Kaplica" hydrogeological station, which also monitors the fractured-karstic rock medium (Upper Jurassic limestones). The Sieradowice observation point is located within the recharge and transit zones, whereas the "Kaplica" hydrogeological station is situated in the watershed zone. The maximum, minimum and average values of groundwater table levels observed at these points in the individual hydrological years (XI–X) are presented on the graphs, with the boundaries of individual

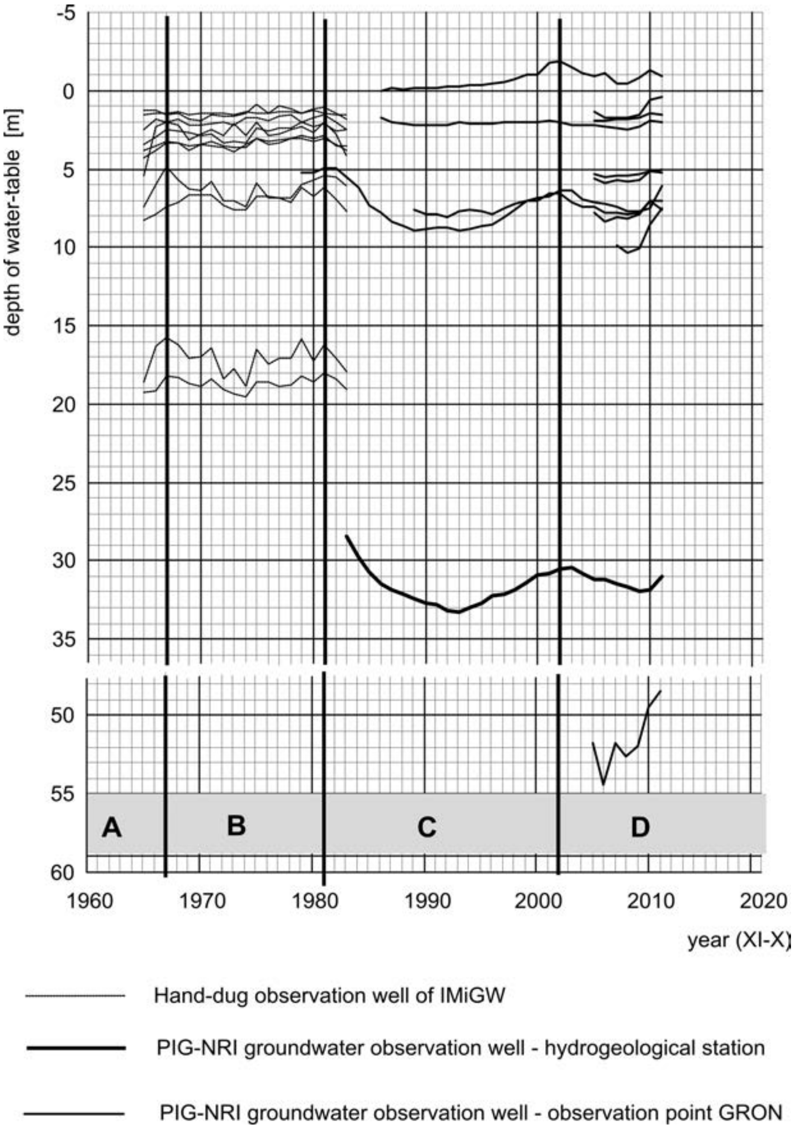

**Fig. 5.** Water-table levels for period 1965–2011 at observation points located in Kamienna River drainage basin (annual averages)

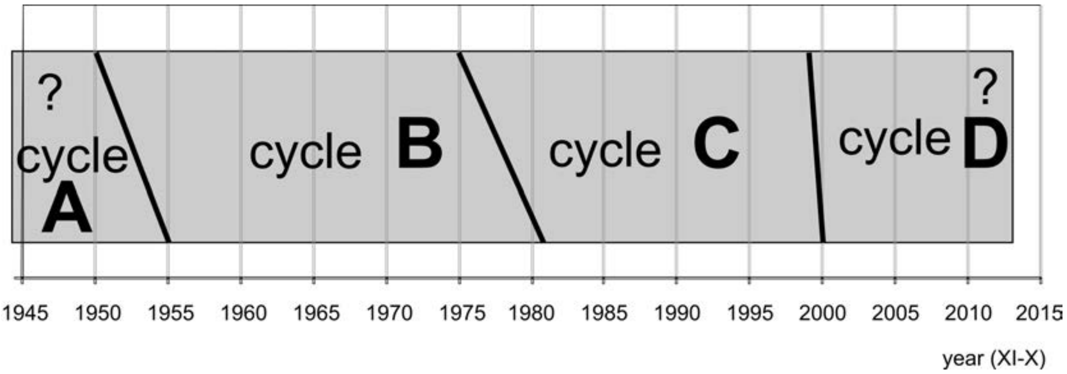

**Fig. 6.** Multi-year cycles of groundwater storage changes in Poland (after Herbich *et al.*, 2009)

cycles marked (Fig. 7). The hydrological year is defined on the basis of the course of events of the water runoff cycle of surface and ground waters and lasts in Poland from November 1st to October 31th (Dowgiałło *et al.*, 2002). October is the month of the most frequent lowest flow rates in rivers and the lowest groundwater storage rates.

The characteristic parameters of the water table in cycle C are shown in Table 3.

The best documented cycle C began in 1982 and lasted 21 years until through 2002. The lowest water table occurred in the middle of the cycle, in 1988–1995. With the amplitude of this cycle attaining 5 m in the fractured-karstic rock media, the groundwater balance in the cycle was negative. Water-table levels in the observation points at the end of the cycle were lower by 1.40 m in Sieradowice and by 1.94 m in "Kaplica", compared with the initial ones.

## DISCUSSION

Multi-year cycles of groundwater storage changes are a joint effect of changes in climatic conditions, mainly amount and distribution of rainfall in time (including snow cover), depth and duration of frozen ground, humidity and evapotranspiration and hydrogeological conditions in the immediate proximity to the observation wells. In the Kamienna River drainage basin, they appeared to have been relatively reliably identifiable and are confirmed at most observation points. The multi-year amplitudes of cycle B, observed in shallow hand-dug wells, monitoring the Quaternary porous aquifer, generally do not exceed 2 m. Greater amplitudes, up to 4.85 m, are observed in cycle C in the Upper Jurassic and Middle Devonian fractured-karstic aquifers. At the observation points monitoring of groundwater from the dominant Middle Jurassic and Lower Triassic fractured-porous aquifers, the measuring sequences are too short and do not allow determination of the amplitude of fluctuations of the water table within the whole cycle. Such considerable differences in the amplitudes of individual multi-year cycles in the pore aquifers of cycle B and in the fractured-karstic aquifers of cycle C are mainly due to differences in the active porosity of the rocks. The active porosity coefficients for porous aquifers commonly varies from 0.1 to 0.3, while for fractured-karstic aquifers, its value does not exceed 0.05. All the groundwater observation points of the IMGW and the GORN are located outside the cones of depression of major groundwater intakes. The changes in retention observed in these intakes are natural.

The above-presented analysis of the results of water table observations shows that the changes in groundwater resources in the Kamienna River drainage basin in the multi-year retention cycles are relatively small. If we take, as a measure, the amount of water in the saturated zone of active exchange of fresh groundwater, then the magnitude of the changes falls within the range of 1 to 3% of the total amount of groundwater stored in the aquifers.

**Table 3**

Basic parameters of water-table changes in cycle C (1982–2002) from GORN observation points in Devonian and Jurassic fractured-karstic aquifers

| Characteristic parameters of cycle C | | Sieradowice II/385/1 (D2) | Kaplica I/474/1 (J3) |
|---|---|---|---|
| Beginning of cycle | | 1982 | 1982-* |
| End of cycle | | 2002 | 2002-2003 |
| Duration | | 21 | 21-22 |
| Maximum water level | Depth of water table | 4.92 | 28.47 |
| Minimum water level | | 8.93 | 33.32 |
| Amplitude | | 4.01 | 4.85 |
| Initial water level | | 4.92 | 28.47 |
| Final water level | | 6.32 | 30.42 |
| Cycle balance | | -1.40 | -1.94 |
| Cycle balance - % of cycle amplitude | | -35% | -40% |

* – by analogy to observation point at Sieradowice

## IMPORTANCE OF MULTI-YEAR GROUNDWATER STORAGE CHANGES FOR WATER MANAGEMENT

Knowledge of long-term changes in groundwater storage conditions in aquifers is necessary for the assessment of their renewable resources, as well as for the prediction of resources in the context of potential climate changes.

In determining regional renewable groundwater resources, retention changes are usually within the limits of

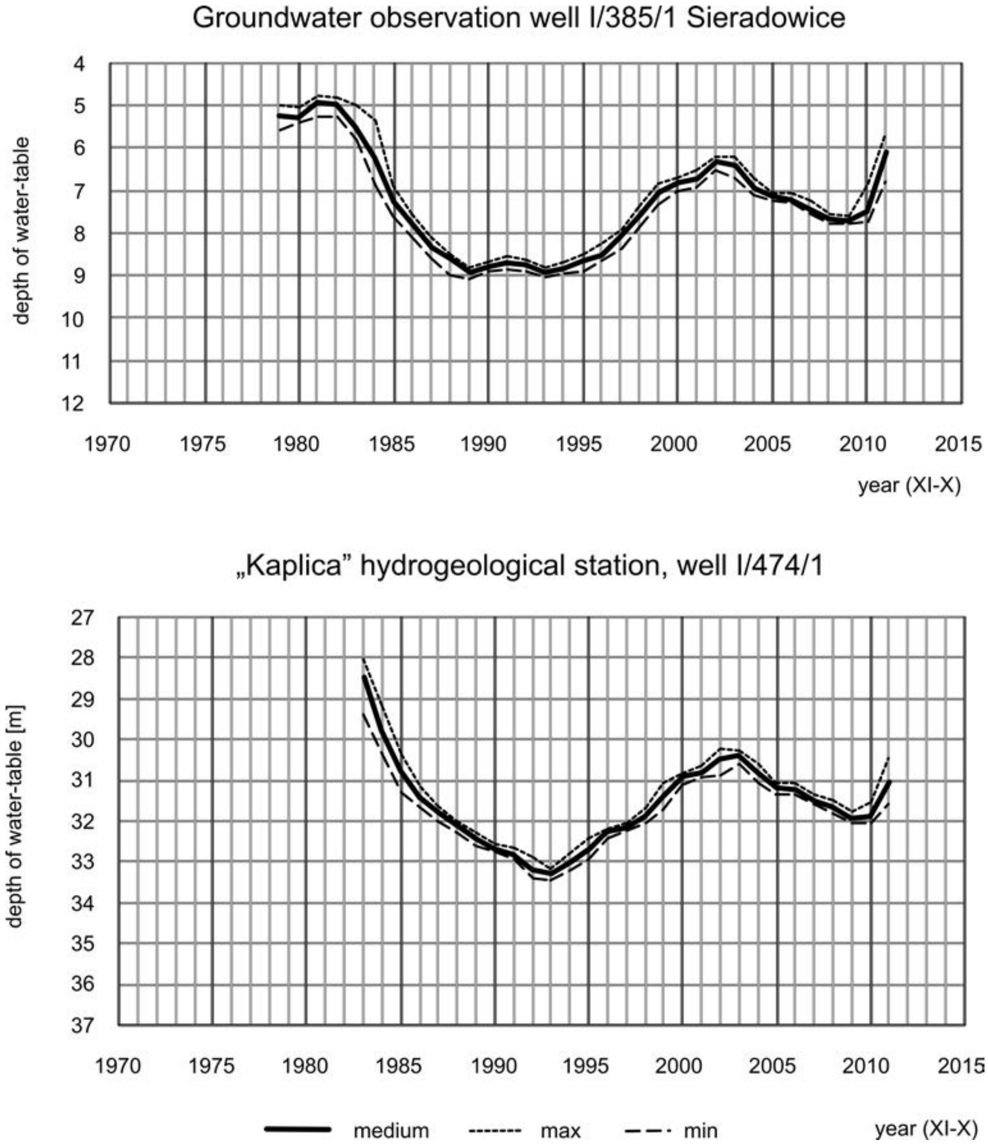

**Fig. 7.** Multi-year cycles of groundwater storage changes in fractured-karstic aquifers of Kamienna River drainage basin

error of the calculation methods. The calculation of groundwater recharge is based on the multi-year average precipitation, which roughly corresponds to the average retention. Groundwater storage changes also affect the exploitable resources of groundwater intakes. This is particularly important in the case of hand-dug wells and shallow drilled wells. Their operating efficiency also depends on the water column in the well. In formal reports of the groundwater resources, there is always the information that "the resources have been established as of the date...". However, any information about the state of retained groundwater at the date of assessment and about the possible reduction of resources at low groundwater storage during post-drought periods is given very rarely.

Within the boundaries of the study area, groundwater is extracted mainly by deep wells that screen the older aquifers. Large, multi-hole intakes with groundwater discharge rates of about 100 $m^3$/h are located only in the areas of Skarżysko-Kamienna and Ostrowiec Świętokrzyski. Rural water supply systems and small industrial plants usually procure water from individual wells with discharge rates of about several $m^3$/h. Water extraction from wells of individual users is relatively low. Almost all wells of municipal water-supply systems of major towns and rural water-supply systems are commonly more than 50 m deep; some are even 100 m deep. Some shallow wells that screen Quaternary aquifers are located in river valleys, where the retention changes in porous media are smallest and generally do not exceed 1.5 m. Thus, it can be concluded that long-term retention changes in this drainage basin in practice do not significantly affect their discharge rates.

A particular issue is the prediction of groundwater storage changes under conditions of possible climate change. In this case, the continuity of observations of the water-table levels, reflecting the response of the aquifer system to the changes, is extremely important. The results of long-term observations will be necessary for prediction of groundwater resources to reduce the possible loss in the water supply.

Determination of relationships between groundwater recharge by precipitation, the state of the retained groundwater, and groundwater discharge in the drainage basin requires longer observation sequences, particularly in the fractured-porous and porous rock media. In one of these observation points (II/385/1), observations started in cycle B, continuing through the full cycle C and the current cycle D. At four of these points (I/474/1, II/339/1, II/485/1, II/492/1) observations started in cycle C, and the full cycle of multi-year changes will be completed after the end of the current cycle D. At the remaining seven points (II/1375/1, II/ 1376/1, II/1379/1, II/1381/1, II/1382/1, II/1384/1, II/ 1404/1) started only in the middle of the current cycle D, and the full cycle of changes will be completed after the end of another cycle E. Assuming that the state of retained groundwater near the observation point should be characterised by at least one full cycle of multi-year retention changes, a full assessment of their relationship to the groundwater recharge, groundwater runoff and anthropogenic drainage will be possible only in a few decades. However, the existing data are the basis for evaluation studies carried out by means of appropriate mathematical models (Asmuth, 2012). They will help us, at least in part, to answer the question about the future changes in the state of retained groundwater resources in the Kamienna River drainage basin in the context of possible global climate change. The answer to this question is needed to develop a long-term water-management strategy. Despite incomplete data and the limitations of the calculation methods, the modelling results will be the basis for assessing the sustainability of current sources and for the designation of new sources of water supply to the waterworks, agriculture and industry in case of predicted long-term drought.

## CONCLUSIONS

Changes to groundwater storage in the Kamienna River drainage basin have been monitored since 1965. The observation points changed with time. At the beginning, these were hand-dug wells, and then, starting from 1983, observations were carried out only in the hydrogeological parts of the groundwater observation-research network of PGI-NRI. From 1945 to the present day, four multi-year cycles of retention changes have been distinguished in Poland: A, B, C and D (Herbich *et al.*, 2009). In the Kamienna River drainage basin, observations of the water-table levels began in 1965, but there is only one fully documented, 21-year cycle C for the period 1982 to 2002. The amplitude of the changes in the water-table levels at the observation points, monitoring the fractured-karstic rock aquifers, is 4 to 5 m. The initial water table at the beginning of the cycle was higher by 1.40 to 1.94 m than at the end of it. However, complete cycles of retention changes have not yet been fully documented in the fractured-porous and porous aquifers that predominate in the basin. It will be possible only after several consecutive years of water-table observations.

In cases of low groundwater storage, the actual discharge rate for the safe yield of intakes may be lower than at the time of their assessment. This refers mainly to shallow wells. Multi-year changes in groundwater storage will also be among the basic data for the calculations carried out for water management, as well as for the prediction of resources in the case of potential global climate change. For this reason, it is important to conduct continuous measurements of the groundwater level at observation points within the groundwater monitoring network in Poland. On the basis of these results, it will be possible to evaluate the characteristic parameters of the current cycle D and subsequent cycles in all types of aquifer within this drainage basin.

At the current stage of research, the literature sources and references on groundwater storage changes in Poland are still scarce. This is mainly because of short observation sequences. The IMiGW finished their observations of groundwater table levels in 1983, and the observation sequences of most of the subsequently established observation points of the GORN are too short for the full characterisation of retention cycles. Therefore, any attempts at modelling estimates of resources can be based on multi-year retention changes and analyses of the relationships between the retention changes and the recharge of the aquifer system through the infiltration of atmospheric precipitation, as well as groundwater runoff, are still of a theoretical nature.

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