

Causes of groundwater level and chemistry changes in an urban area; a case study of Warsaw, Poland

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ABSTRACT:

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The presented studies focus on changes in groundwater levels and chemistry, and the identification of important factors influencing these changes on short- and long-term scales in urban areas. The results may be useful for rational and sustainable groundwater planning and management in cities. The studies concerned three aquifers: (1) the shallow Quaternary aquifer, (2) the deep Quaternary aquifer, and (3) the Oligocene aquifer in the capital city of Warsaw (Poland). The spatial variability of groundwater recharge was determined and its changes in time were characterized. The characteristics of groundwater levels were based on long-term monitoring series. The results indicate that urban development has caused overall reduction in infiltration recharge (from 54 to 51 mm/year), which is particularly clear in the city suburbs and in its centre, where land development has significantly densified during the last 30 years. Studies of groundwater levels indicate variable long-term trends. However, for the shallowest aquifer, the trends indicate a gradual decrease of the groundwater levels. In the case of the much deeper Oligocene aquifer, groundwater table rise is observed since the 1970s (averagely c. 20 m), which is related with excessive pumping. Based on the studied results, the groundwater chemistry in the subsurface aquifer indicates strong anthropogenic influence, which is reflected in multi-ionic hydrogeochemical types and the occurrence of chemical tracers typical of human activity. The Oligocene aquifer is characterized by a chemical composition indicating the influence of geogenic factors.

Key words: Urban area; Quaternary aquifers; Oligocene aquifer; Groundwater level changes; Infiltration; Groundwater chemistry; Warsaw.

INTRODUCTION

Urbanization is the dominant global phenomenon of our times. Urban areas represent a specific environment for groundwater occurrence due to the distinct properties of this space. Anthropogenic features include variable land use resulting from the occurrence of zones playing different functions, i.e., residential, industrial, transportation, recreational and cultural. By paying very low attention or even

its lack to environmental conditions in urban design, intense urban development has led to ecological crisis in many agglomerations (Wust *et al.* 2002). All large cities should possess a diagnosis of environmental conditions, which would allow for shaping their sustainable development. Groundwater chemistry is the product of pervading impact between pollutants supplied by infiltrating precipitation, soil mineral composition and soil matrix of the aquifer, as well as groundwater dynamics. Moreover, results

of hydrological studies in urban areas indicate that the urbanization process, although favouring the reduction of water loss by evaporation, causes decrease of effective infiltration. Due to these conditions, sustainable management of water in urban areas can be considered a global issue (Vázquez-Suñé *et al.* 2010; Krogulec and Zabłocki 2015; Dochartaigh *et al.* 2017; Foster 2020). A reliable inventory of groundwater quantity and quality, as well as the determination of the reasons for changes in groundwater quality and levels are needed for rational and responsible water use. Manifestations of improper groundwater management policy include the development of a phenomenon known as urban drought, the occurrence of the so-called urban floods (results of rapid weather phenomena related to climate change), or, for deeper aquifers, the development of regional depression cones resulting from their exploitation.

This analysis was based on investigations conducted in the capital city of Warsaw with a surface area of 517.2 km² and 1.794 million residents (Kozłowska *et al.* 2021). In Warsaw, the main sources of the water supply network are surface intakes contributing to 96% of water used by the waterworks system; only 4% are represented by groundwater. Water for the Warsaw agglomeration is supplied by the Central System Waterworks, comprising the Central Water Treatment Plant which uses water from underneath the Vistula River and five groundwater intakes (Radość, Falenica, Powsin, Stara Miłosna, Wesola), and the Northern Water Treatment Plant which treats water from Zegrze Lake. The waterworks produce 350,000 m³ of water daily and the daily use is about 137 dm³ per resident (Koczowas 2021; <https://mpwik.com.pl>).

METHODS OF GROUNDWATER STUDIES IN URBAN AREAS

Cities are characterized by a set of specific features, therefore they require the application of a dedicated study methodology, with the aim of determining the spatial variability of groundwater recharge in subsurface aquifers and the characteristics of recharge changes in time; determining the characteristics of groundwater levels along with analysis of long-term monitoring series; and performing data analysis to show the characteristics of groundwater chemistry, particularly those related with subsurface Quaternary deposits.

Groundwater monitoring is performed in Poland as part of the National Environmental Monitoring in a monitoring network comprising about 1290 sites

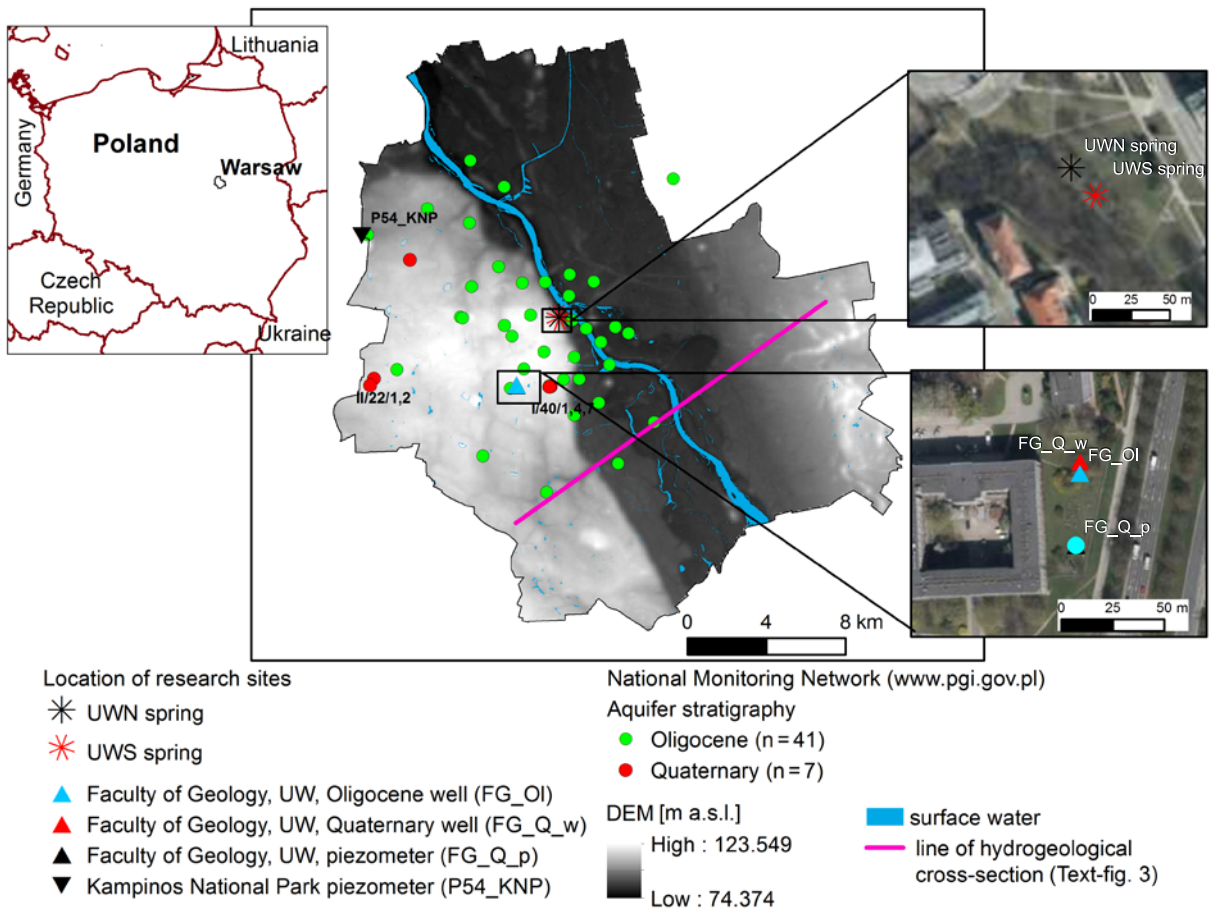
(wells, piezometers, springs), fulfilling the criteria in accordance with the requirements of the Water Framework Directive (2000). Over 70% of the monitoring sites include hydrogeological stations supervised by the Polish Geological Institute-National Research Institute in the frame of the activities of the Polish Hydrogeological Survey. The remaining monitoring sites are owned by communal centres and communities (in the case of potable water intakes), as well as companies and private parties (<http://mjwp.gios.gov.pl>).

The test site, representative for urban areas, is the Warsaw agglomeration. As of March 2022, there were 48 monitoring sites in Warsaw, of which 11 were actively pumped. Only 2 of them belonged to the network of the Monitoring of the Chemical State of groundwater, exploiting the Miocene and Oligocene aquifers, respectively. The most recent analyses of the chemical composition of water from the Quaternary aquifers reported by the Chief Inspectorate of Environmental Protection (<http://mjwp.gios.gov.pl/>) from Warsaw are from 2021 and refer to one drilled well, sampled twice during the year. Previous monitoring studies in the city took place in 2019 and were restricted to the sampling of 4 drilled wells. Monitoring of groundwater quality in Warsaw is therefore considered as insufficient for a reliable assessment of chemical water transformation in time and for recognizing local and global causes of changes in groundwater chemistry from shallow groundwater aquifers in urban areas. For a broader recognition of groundwater chemistry, studies of two springs (UWN and UWS) located at the foot of the central part of the Warsaw escarpment (Text-fig. 1) have been conducted.

Monitoring, performed since 1993 in the Survey Station of the Faculty of Geology, University of Warsaw (Text-fig. 1), included groundwater levels and chemistry from the Oligocene aquifer (FG_OL) and two Quaternary aquifers (FG_Q_w, FG_Q_p).

For groundwater level analysis in the city the following data were used: from the Survey Station of the Faculty of Geology, University of Warsaw, from a piezometer (P54_KNP), which is the part of the Kampinos National Park monitoring network, and from water quantity monitoring conducted by the Polish Geological Institute-National Research Institute (PGI-NRI), (www.pgi.gov.pl). In total, the analysis was performed for 50 sites, including: 9 sites pumping groundwater from the Quaternary aquifers (2 from the shallow aquifer, 7 from the deeper aquifer); and 41 sites pumping groundwater from the Oligocene aquifer.

Due to different monitoring intervals for par-



Text-fig. 1. Location of the studied wells and piezometers against the DEM of the Warsaw area. Insets show the position of the University springs (top right) and the wells and piezometers of the Survey Station of the Faculty of Geology (bottom right).

ticular sites, the data are presented as annual average values for particular hydrogeological years for the period from 1987 to 2021 (statistical analysis in STATISTICA 10).

Assessment of groundwater infiltration in Warsaw was performed using the infiltration method, with relevant indexes characterizing overall natural and anthropogenic elements that influence infiltration, particularly in areas with strong anthropogenic pressure (de Vries and Simmers 2002; Schwartz 2006; Healy and Scanlon 2010; Duda *et al.* 2011). Infiltration recharge (R) was determined according to the formula:

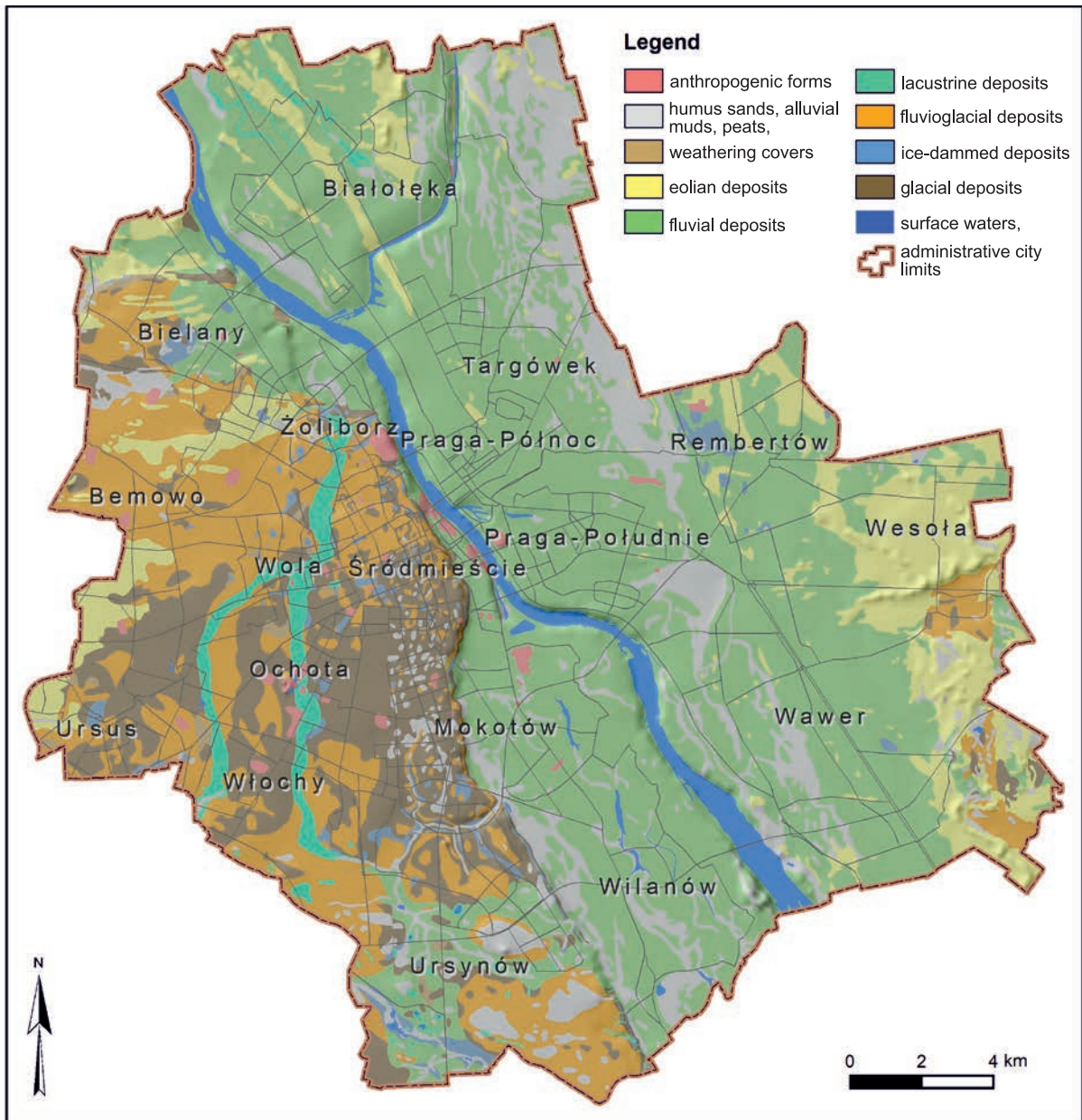
$$R = P \cdot \alpha \cdot \beta \cdot \gamma$$

where: P – annual precipitation [mm/year]; α – infiltration coefficient depending on the lithology of sub-surface deposits [-]; β – coefficient depending on the type of land cover and land use [-]; γ – coefficient depending on land slope [-].

HYDROGEOLOGICAL CONDITIONS IN WARSAW

Geological setting

The capital city of Warsaw is located in the central part of the Mazovian Basin, a Mesozoic structure filled with Paleogene and Neogene deposits under a Quaternary cover. The Paleogene succession begins with marine clastic rocks mostly of Oligocene age (Nowak and Uberna 1976). Directly under the city, these deposits form a 40–60 m thick continuous layer. In the middle Oligocene, brackish sediments began to transition gradually into continental strata (lacustrine-marshy and alluvial). They are typically muddy-sandy and sandy, with local occurrences of thin brown coal seams. These sediments terminate the Paleogene succession in the Mazovian Basin. Neogene strata representing the lower and middle Miocene overlay these sediments. They start



Text-fig. 2. Genetic types of deposits in the subsurface of Warsaw, based on information layers of the Detailed Geological Map of Poland (Morawski 1978; Sarnacka 1979).

with gravels passing into sands with a characteristic brown tint. Lenses of brown coal often occur in the sands. The succession is terminated with coaly muds and clays. In Warsaw, the thickness of these deposits does not exceed 60 m. Deposits representing the Pliocene (clays, locally loams and sands) occur above. In the Mazovian Basin these deposits reach a large thickness of averagely 50–70 m, locally up to 150 m (Baraniecka 1976, 1979, 1995).

Deposits of the Quaternary aquifers are characterized by large facies variability, with a clear contrast between the left-bank and right-bank parts of the city (Text-fig. 2). The right-bank districts are located in the Vistula River valley on the surface of Pleistocene and Holocene accumulation terraces. In this part of the city, the Quaternary succession is dominated by alluvial sand and gravel sediments formed during the Eemian Interglacial and the Vistulian Glaciation.

Older sediments of glacial origin from the South-Polish and Middle-Polish glaciations are preserved in depressions within the top of the clays of the Poznań Formation. The thickness of Quaternary deposits in the Vistula River valley is variable and reaches from several to over 110 m. This variability results from glaciotectionic deformations of the top of the Pliocene clays. The left-bank part of the city is situated on a post-glacial plateau, formed during the subsequent advances and retreats of the Scandinavian ice-sheet. The oldest Pleistocene deposits were formed here during the South-Polish glaciations. Glacial deposits from the Middle-Polish glaciations occur above. Two levels of glacial tills from that time, accompanied by ice-dammed and fluvio-glacial deposits can be drilled under the city. The lower till forms a horizon characterized by a wide distribution and thickness up to 30 m. The upper till is distinctly discontinuous and occurs in form of patches locally exposed to the surface. In the Eemian Interglacial a large ribbon lake of glacial origin formed (Żoliborz Lake). During the Last Glaciation, the area of Warsaw was located in the periglacial zone. Accumulation terraces were formed at that time in the Vistula River valley. Dune processes were initiated by the end of the Pleistocene. As a result, fields of aeolian sands were formed on the ancient terrace surfaces, with well-developed parabolic dunes. During the Holocene, the contemporary lower and higher floodplain were formed in the Vistula River valley; diluvial covers developed within the Warsaw escarpment and the depressions were filled with alluvial muds and peats (Morawski 1978; Sarnacka 1979).

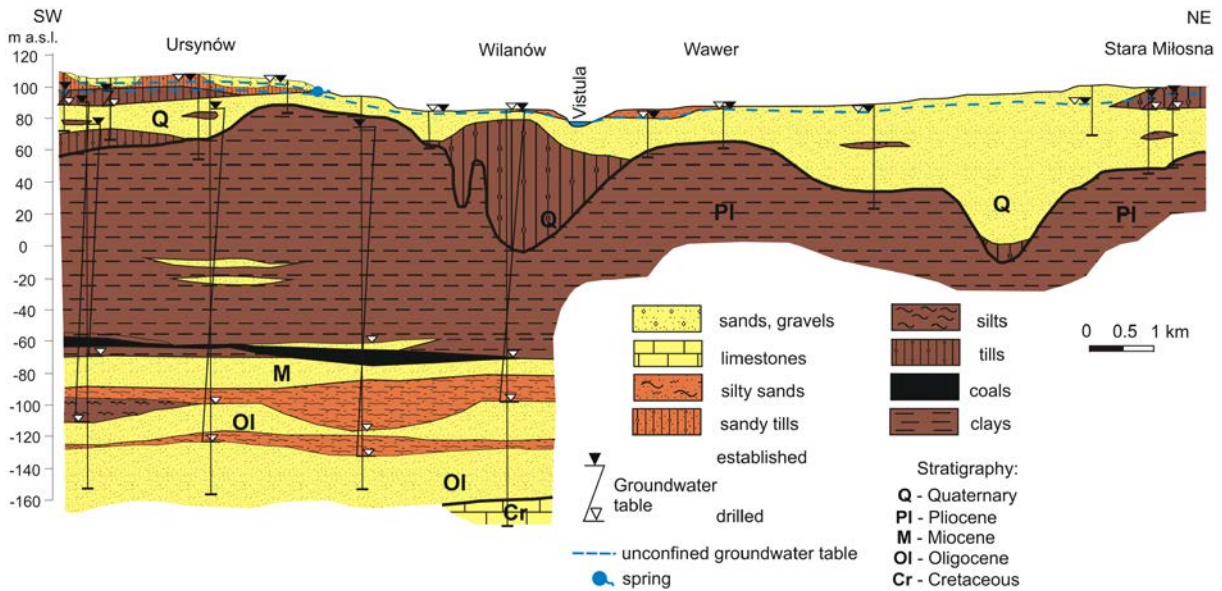
Hydrogeological conditions

The hydrogeological conditions in the area are distinctly bipartite, resulting from the geological setting and geomorphology of the area (Text-fig. 3). The groundwater table of the shallow aquifer occurs in Quaternary strata, and its depth, degree of isolation and threats result from its location within the glacial plateau (most of left-bank Warsaw) or in the Vistula River valley (the entire right-bank Warsaw). The aquifer in Pleistocene and Holocene fluvial sediments, formed during several sedimentary cycles, is composed of strata of the oldest cycle of the Mazovian Interglacial. It is represented by an up to 10 m thick layer of gravels and sands. The conductivity of these sediments determined on the basis of archival test pumpings is about 40 m/d (Cygański 1997a, b). Sediments of the two subsequent cycles comprise the Mazovian and Eemian Interglacial. They include fluvial sands with gravels with a total thickness of about 25 m. The con-

ductivity reaches from 26 to 37 m/d (Cygański 1997a, b). Peat intercalations are locally present in the top of the Eemian sediments. Earlier accumulation terraces of the Vistula River occur above (Praga, Kampinos, Otwock terraces), formed during the Last Glaciation. They include fluvial sands and gravels with permeability parameters similar to those characterizing the Eemian sediments. Holocene Vistula River floodplains are composed of fluvial sands with the flood facies in the topmost part. The conductivity of the Holocene sands was determined using column and field tests and ranged from 15 to 24 m/d (Krogulec *et al.* 2020). The subsurface aquifer is strongly variable. Water-bearing sediments within the plateau include sands and clayey sands in the form of thin weathering covers on glacial tills or within them, and sands, fine sands and gravels within the fluvio-glacial plain forms (Kubiczek 2006). Water-bearing sediments of the Vistula valley include alluvial muds on sands, sands and gravels, and sands and gravels within earlier accumulation terraces, locally peats on sands within ox-bow lakes and dune sands, and alluvial muds and peats on sands in the north-western part of the area (Hulboj 2006). The thickness of the subsurface aquifer is from 2 m in the plateau to over 40 m in the Vistula River valley. Beyond areas of glacial till occurrence on the surface and exposures of the Pliocene basement, the aquifer is considered as continuous. It is in direct hydraulic connection with surface waters. The thickness of the aquifer is variable and exceeds 40 m only locally. In its direct basement occur poorly permeable Pliocene deposits. They include variegated clays with interbeddings of silts and fine sands, reaching a thickness of up to 160 m. The conductivity of the clays in the vicinity of Warsaw reaches values in the range of 10^{-6} – 10^{-5} m/d (Kaczyński 2002). The top of the Pliocene is strongly undulated due to the presence of numerous forms of erosional and glaciotectionic origin.

Within the plateau, below the subsurface aquifer at depths of 5–15 m or 15–50 m occurs the main deeper Quaternary aquifer with a confined groundwater table stabilizing at a depth of 7–10 m. The sandy gravel sediments forming this aquifer are 10–20 m thick; in the Vistula valley it is connected with the subsurface aquifer, and manifestations of its occurrence are springs located at the foot of the Warsaw escarpment (Cygański 1997a, b). Locally, the spatial range of this aquifer may be restricted by the presence of elevations of the Pliocene basement or the presence of Quaternary silty sands with poorer filtration parameters.

Below the Quaternary sediments, aquifers were observed within the Pliocene, Miocene and Oligocene, of which the first two ones occur locally in



Text-fig. 3. Hydrogeological cross-section across the Vistula River valley between Ursynów and Stara Miłosna (line of cross-section shown in Text-fig. 1).

the form of lenses, and the third is of regional significance (Macioszczyk T. and Michalak 1974; Macioszczyk T. 1985, 1996; Cygański 1997a, b). The Oligocene aquifer in the Mazovian Basin covers an area of c. 51,000 km² and is the largest artesian basin in Poland (Kleczkowski 1990). It is composed of fine and medium or silty sands with glauconite, with a typical thickness of 20 m, occurring at depths of 160 m in the basin margins to 233 m in the central part of the basin (Warsaw area).

CHARACTERISTICS OF GROUNDWATER RECHARGE CHANGES IN TIME IN WARSAW

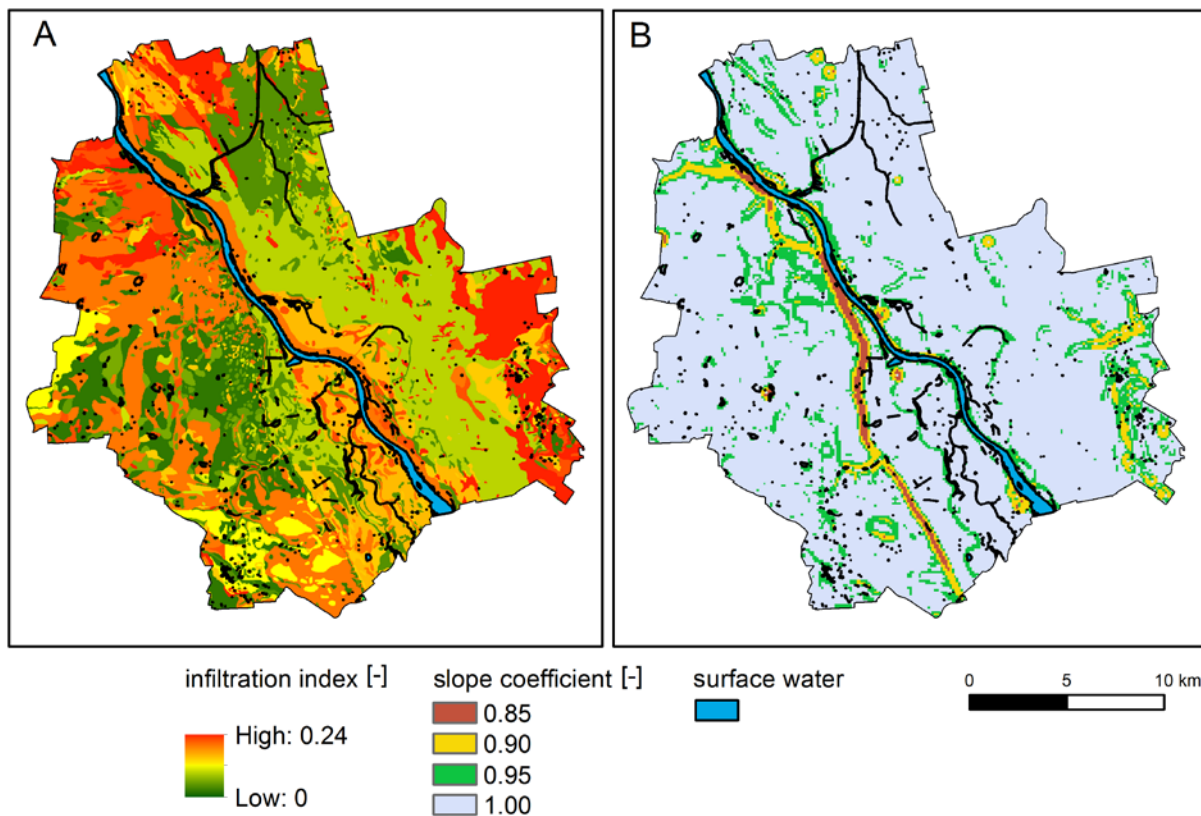
Infiltration recharge is usually identified with the magnitude of renewable resources. Groundwater recharge in areas under strong anthropogenic pressure, such as urban areas, includes the following three sources (Kowalczyk 2003): 1) infiltration recharge from precipitation, 2) recharge from waters infiltrating from surface water bodies, and 3) artificial recharge from broken-down water and sewage systems, and dispersed waste water discharge.

The basic sources of groundwater recharge include precipitation and surface water bodies. This volume may be significantly diminished due to proceeding insulation of the area resulting from urbanization. The presence of built-up areas and increase

of the surface of impermeable zones on the cost of exposed and biologically active areas significantly influences the dynamics of surface flow and the process of its generation (McGrane 2016), and thus has direct impact on infiltration through increase of surface runoff (Dunne and Leopold 1978; Arnold and Gibbons 1996). On the other hand, a complex network supplying water for communal and industrial needs and discharging sewage may generate additional, artificial recharge sources (Lerner 2002; Kowalczyk 2003; McGrane 2016).

According to the information for 2020 (Koczowaś 2021), the volume of losses resulting from the differences between water produced by municipal water plants and the water sold was about 13.2% of the total produced water. The loss has been gradually reduced from 2006 when it reached 15.7%.

There are also no data on the losses from the sanitary and combined sewage system (length in 2020–2905 km), and the storm water system (434.4 km). In this case the problem with assessing this volume results from excessive amounts of rainwater and meltwater piped by the storm water and combined systems in relation to sewage produced by the network users. In 2019 this excess reached 58394.8 thousand m³, which comprises 33% of the total volume of purified sewage. Beside meteoric water, this amount covers also groundwater drained by the sewage system, whose share was assessed in 2019 at averagely



Text-fig. 4. Infiltration index based on subsurface lithology (A) and slope coefficient estimated from DEM (B) within Warsaw city limits.

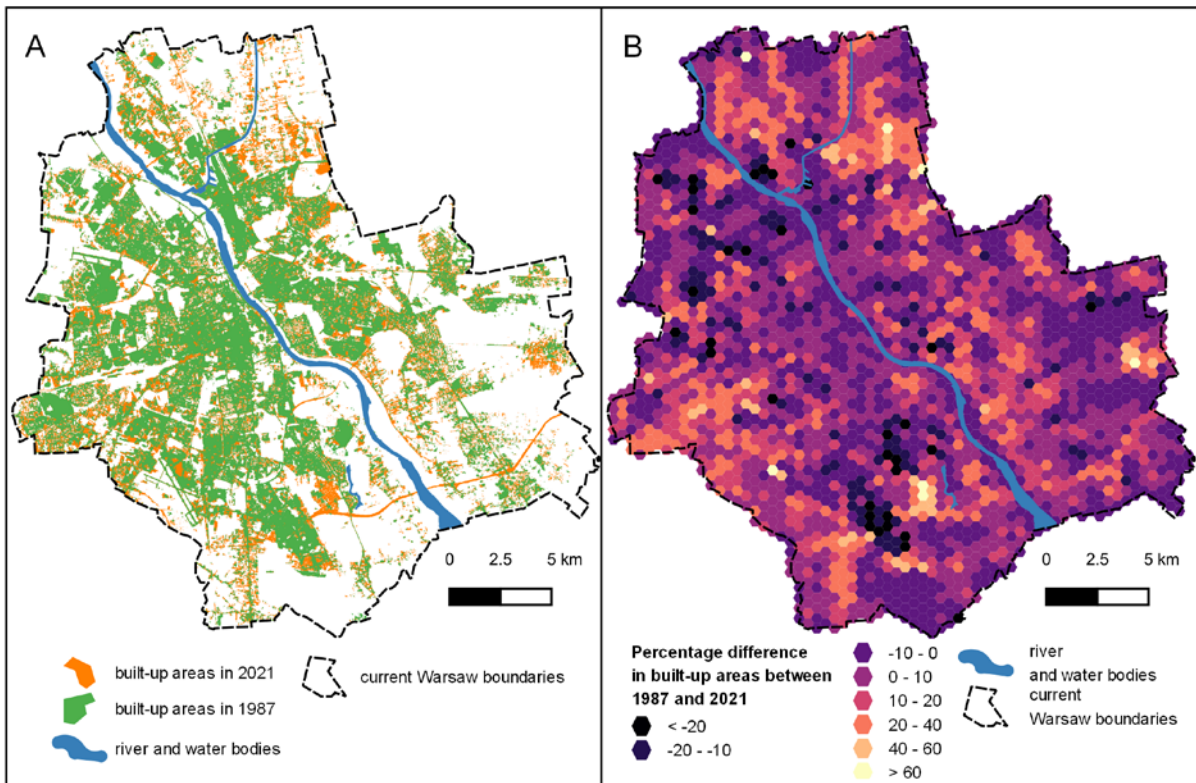
22% of the total volume of purified sewage, which may exceed the volume of water lost on the leaking sections of the network. Due to lack of data on the water loss caused by leaks in the water and sewage systems, these aspects were not included in the profit account of the city water balance.

One of the basic components of the formula for infiltration recharge is the volume of precipitation for Warsaw, equal to 539 mm/year as the average value from 1967–2021 based on monthly precipitation data from the synoptic station Warszawa-Okęcie (<https://danepubliczne.imgw.pl>). The constant value of precipitation was accepted for the entire city to ensure comparison of the calculated results of effective infiltration using the presented method.

Spatial distribution of the infiltration index α was obtained based on the lithological units from the Detailed geological map of Poland at the scale of 1:50,000 (Sarnacka 1974, 1976, 1979; Morawski 1978). The assumed values were referred to the classification of Pazdro and Kozerski (1990), but were changed in accordance with the thickness of the vadose zone and the degree of isolation of the succes-

sion by sealing deposits. Ultimately, the attained values were from 0.02 for the finest fractions to 0.24 for coarse and aeolian sediments (Text-fig. 4A, Table 1). In the left-bank area of Warsaw, the plateau is covered by glacial till ($\alpha = 0.02$, 9% of the surface area), and fluvio-glacial and ice-dammed sands ($\alpha = 0.2$, 7.5% of the surface area). The floodplains include fluvial sands ($\alpha = 0.2$) and silty-clayey alluvial muds (heavy; $\alpha = 0.16$). The higher Vistula terraces are composed of sands with gravel, usually covered by organic deposits of variable thickness ($\alpha = 0.09$, 12% of the surface area), and sandy loams (light alluvial muds) and varved clays with a coefficient $\alpha = 0.04$. The uppermost terrace is covered with aeolian sands ($\alpha = 0.24$) forming covers or dunes (Text-fig. 2).

Identification of changes in land use and land cover in Warsaw was accomplished using data from the Earth surface classification software Corine Land Cover, collected between 1990 and 2018 and enriched with analysis of satellite images. In order to recognize built-up zones in Warsaw and changes of their surface area in time, satellite data from the Landsat and Sentinel 2 missions were used. The spa-



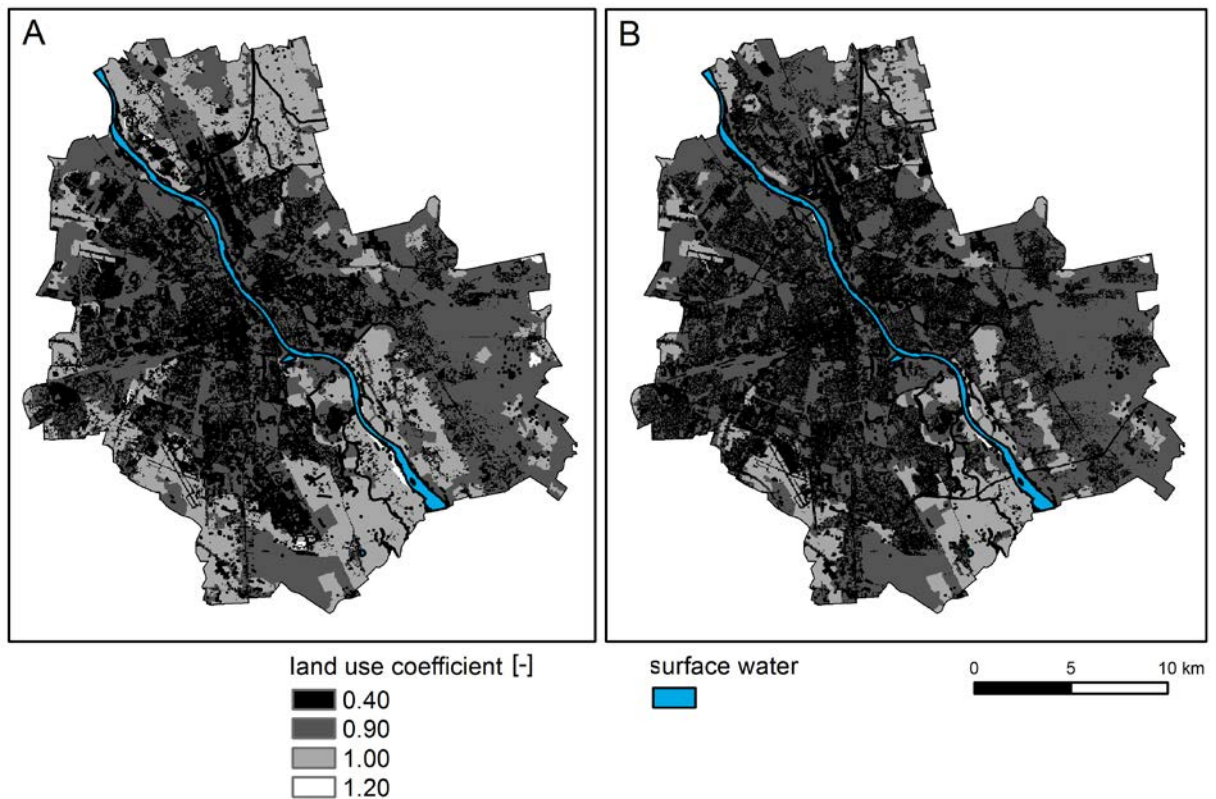
Text-fig. 5. Spatial distribution of built-up areas within the current Warsaw city limits in 1987 and 2021 (A) and differences in the percentage contribution of the built-up surface between 1987 and 2021 (B); cluster average 500 m.

tial resolution of the acquired images is 30 m (the size of a single pixel), which allows for regional and local-scale observations. Revisits of the registering device over the analysed area take place approximately every 16 days (Loveland and Dwyer 2012). The observation platforms of the Sentinel 2 mission acquire images since 2015. Compared to the images obtained by the Landsat satellite scanners, the spatial resolution is much higher and reaches 10 m, allowing for a better precision of identification. Application of twin components (Sentinel 2A and Sentinel 2B) significantly shortens the revisit interval to 5 days (Gascon *et al.* 2017). Both Landsat and Sentinel 2 missions provide images of the surface in many ranges of the electromagnetic spectrum, which allow for land surface classification. The radiation ranges registered in the spectral channels in both programs largely correspond to one another, which allows for a mutual analysis. An additional asset of the observation programs is that the generated data with documentation are open-access.

To determine the coefficient depending on the land cover and land use (β), two datasets were used.

They depicted the surface of Warsaw in its current administrative city limits in the period preceding the political changes of 1989, and the current land use and land cover. The first dataset was registered on 15.07.1987 by Landsat 5, and the second – on 21.06.2021 by Sentinel 2B. Classification of satellite images included sets of spectral channels acquired in the optical range of the electromagnetic spectrum (radiation reflected from the surface), in the visible radiation range near infrared (*NIR*). Moreover, images registered in the middle of the vegetation season were used. This was induced by the need to unify the spectral response in poorly urbanized areas used for farming. Classification prepared for intervals beyond the vegetation period would have caused error increase resulting from large complexity and similarity of the spectral response between urban areas and farmlands devoid of vegetation (Li *et al.* 2017).

After radiometric and atmospheric correction of the images, the Normalized Differential Vegetation Index (*NDVI*) was calculated, which is the quotient of the difference and sum of electromagnetic radiation in the *NIR* and red range. It attains values from -1 to 1.



Text-fig. 6. Land use coefficient within Warsaw city limits as of 1987 (A) and 2021 (B).

In the case of classification of areas using the NDVI, areas with values below about 0.3 are considered to be deprived of vegetation and either the cover is sparse or in poor condition. Higher values usually describe areas completely covered by vegetation (Tomaszewska *et al.* 2011). The *NDVI* value calculated for both data-sets was further classified, with 0.3 as the boundary value between built-up areas and those covered by vegetation. It should be emphasized that the pixels attaining values smaller than this boundary value do not necessarily record areas completely devoid of vegetation. This is linked with the spatial resolution of the satellite images. The signal registered in a single pixel is the resultant of components reaching from different objects, which at lower image resolution (30×30 m of the Landsat data) may result in the deteriorated precision of the classification.

According to the classification, in 1987 built-up areas in Warsaw covered 157.5 km², and in 2021 – 188.7 km² (Text-fig. 5A). Significant surface area increase is observed in the city suburbs. Built-up zones in these regions cover from 20% to even 60% larger surface area than in 1987 (Text-fig. 5B). Attention is drawn onto zones with decreased building density

(negative percent values). On one hand this is linked with the closing-down of numerous industrial enterprises, demolition of industrial buildings and remediation of industrial areas, and on the other hand – with the spatial resolution of data from 2021, allowing the distinguishing of green areas between the buildings and in residential areas.

Determined spatial ranges of the built-up areas were attributed to values of recharge reduction coefficient β taking into account the percentage contribution of impermeable surface from the resources of the Institute of Geodesy and Cartography (<http://www.igik.edu.pl/en/corine-hrl>). Coefficients for non-built-up areas were attributed to Corine Land Cover (CLC) classes at level 3 after Duda *et al.* (2011) in order to deal with areas smaller than 25 ha. In 1987, about 31% of present day Warsaw was classified as built-up areas, for which the contribution of impermeable surfaces was determined at 60% and the coefficient value at $\beta=0.4$. Among the non-built-up areas there dominated forests and midland wetlands linked to the ox-bow lakes of the Vistula River, situated on subsequent terraces 42.5%, followed by non-farming green areas, arable soils, permanent crops, variable

Lithology	Infiltration index
surface water	0.00
clays, loams, glacial tills	0.02
sandy loams, humus sands on glacial till	0.04
fluvioglacial and ice-dammed loams, glacial tills on sands	0.05
peaty alluvial muds	0.09
sandy eluvia and silts, glacial till residual deposits	0.10
sands and muds of kame, fluvial and eluvial-aeolian origin	0.12
peats, peats on fluvial sand, loams, sands on glacial tills and clays	0.15
silty-sandy alluvial muds	0.16
light alluvial muds	0.18
sands and alluvial muds, fluvial, lacustrine and fluvioglacial sands	0.20
sands and gravels of fluvial, fluvioglacial and residual origin	0.22
aeolian sands, fluvial and fluvioglacial gravels with sands	0.24
Slope [°]	Slope coefficient
<0.5	1.00
0.5–1	0.95
1–2	0.90
2–4	0.85

Table 1. Values of coefficients for particular subsurface lithologies (after Sarnacka 1974, 1976, 1979; Morawski 1978) and slopes (GUGiK, www.gugik.gov.pl).

farmlands, meadows and areas with variable natural vegetation c. 26%. The smallest group was represented by exposed surfaces with poor vegetation or without vegetation, areas covered by open pits and waste dumps c. 0.5%. In 2021, built-up areas contributed to 37%, forests (and wetlands) to 48%, non-farming green areas and farmlands to 14%, and exposed areas and dumps to 0.1% (Text-fig. 6).

The method assumes that recharge depends also on land slope. Based on DEM resources of GUGiK (www.gugik.gov.pl), slope values were calculated for raster size 30×30 m, and then the coefficient value was attributed based on the degree of slope from 1 to 0.85 (Table 1). Flat areas with slope up to 0.5° cover 83% of the surface area, 13% is represented by land with slope up to 1°, mainly dune and denudation valley slopes within the plateaus, open pits and other forms of human activity. About 4.6% are slopes in the range of 1–2° related with the northern and southern part of the Warsaw escarpment and higher dunes in the eastern part. Slopes exceeding 2° and below 4° represent 1% of the surface area in the central part of the city within the Warsaw escarpment, which occasionally exceeds 20 m in height (Text-fig. 4B).

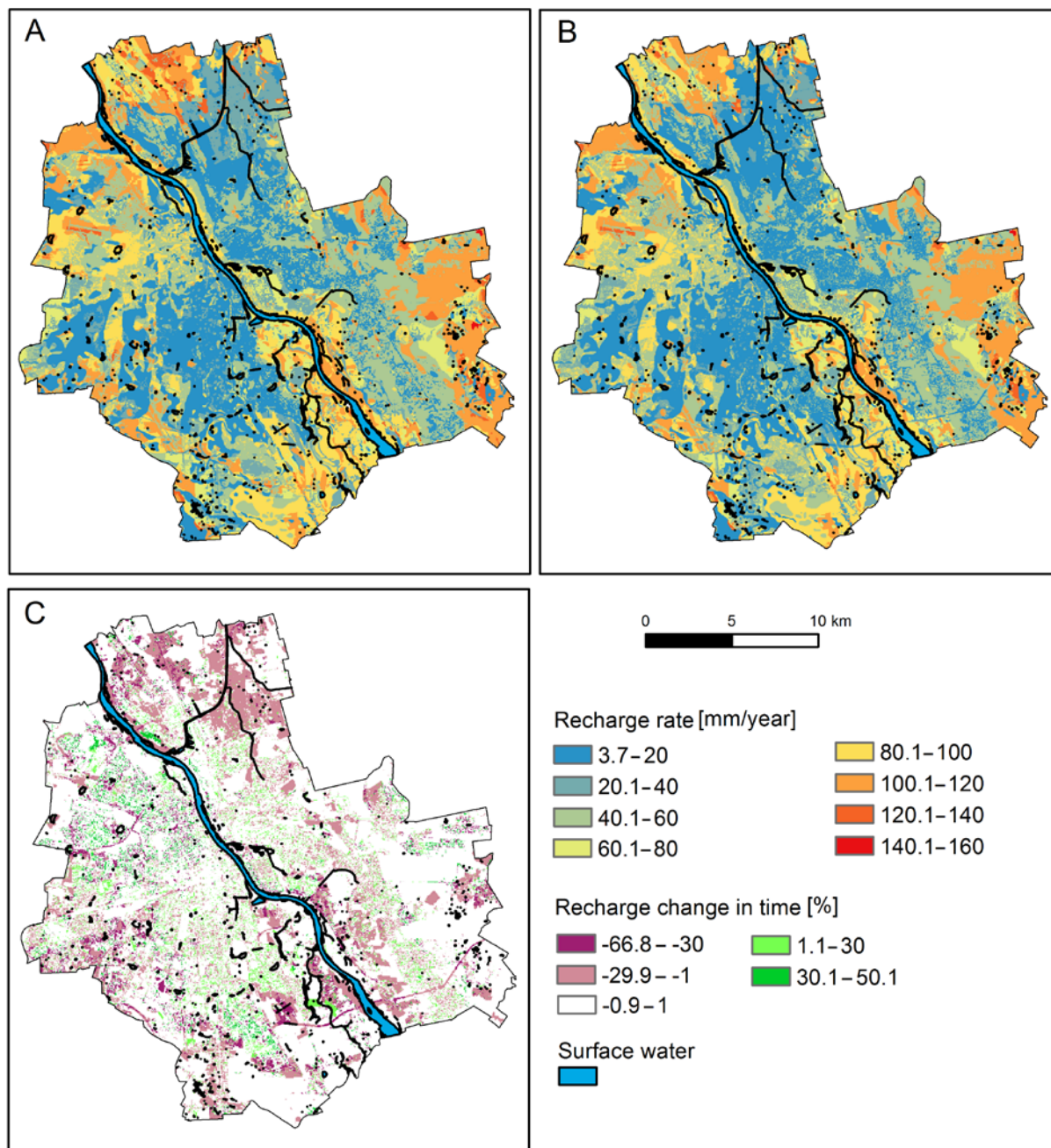
Following the calculations, maps of infiltration recharge for 1987 and 2021, and a difference map were prepared (Text-fig. 7). The average recharge slightly changed from 54 mm/year in 1987 to 51 mm/year in 2021. In both maps, in 1987 and 2021, recharge is represented by three most abundant classes. The first, where recharge does not exceed 20 mm/

year, was defined for the central part of Warsaw on 27% of its surface in 1987 and 31% in 2021. The second class of recharge in the range of the average value between 40 to 60 mm/year is situated in right-bank Warsaw, which contributes to 24.8% in 1987 and 25.1% in 2021. The third class is represented by recharge values of 100–120 mm/year, which contributes to 14.9% in 1987 and 13.3% in 2021.

The difference map indicates change of infiltration recharge in the study area between 1987 and 2021, which is in agreement with earlier analyses using the Sen slope method (Krogulec *et al.* 2020). Decrease of recharge refers to 93% of the surface area, including 21% of the built-up zone, whereas recharge increase was noted for c. 7% of the surface. The changes refer to decrease of recharge averagely by 16%, max. up to 66%, and increase averagely by 20%, max. up to 50%. The largest changes are linked to suburb areas, where new housing estates developed in 1987–2021: Białołęka in the north, Ursus in the west, Wilanów and Ursynów in the south, and Gołław, Wawer and Wesoła in the south-east.

CHARACTERISTICS OF GROUNDWATER LEVELS AND ASSESSMENT OF THEIR CHANGES IN TIME

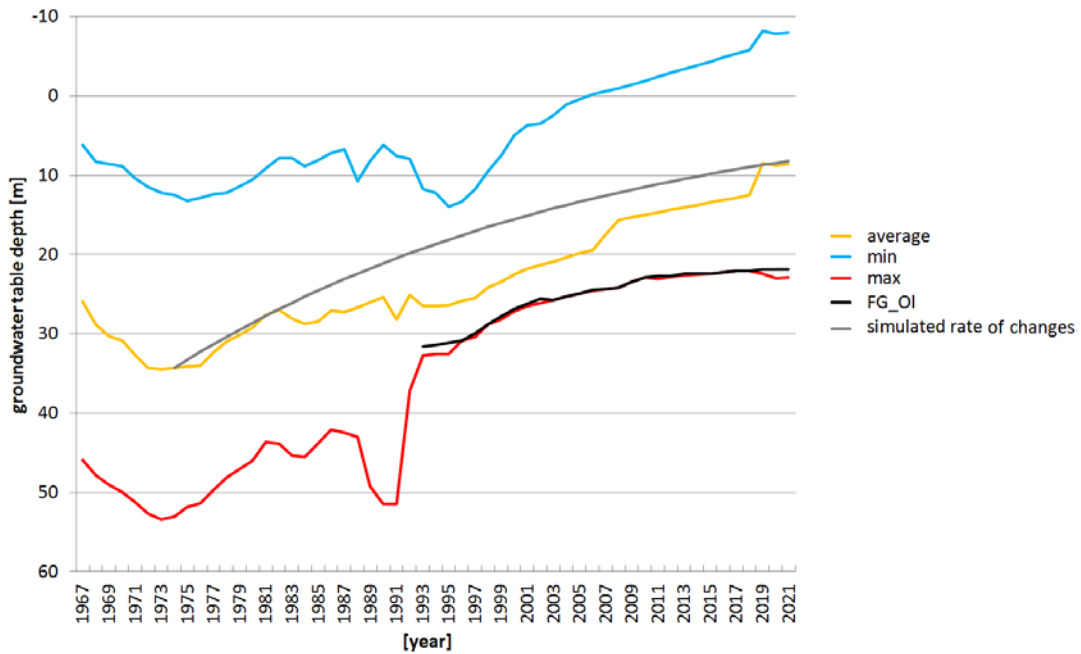
Analysis of the variability of groundwater levels for data from 50 points was performed for the Oligocene and both Quaternary aquifers.



Text-fig. 7. Recharge rate and its change within Warsaw city limits. A – recharge estimated for 1987; B – recharge estimated for 2021; C – recharge change in time between 2021 and 1987.

The distribution of piezometric pressures of the groundwater table in the Oligocene deposits clearly changed with regard to the primary observations, which is due to the intense exploitation of groundwater from this aquifer. Before the period of intense pumping, i.e., in the 1900s, the groundwater table stabilized in Warsaw at depths c. 20 m above the average

water level in the Vistula River (Łodziński 1976). Lack of restrictions for the pumping of groundwater in the 1960s and 1970s (pumping 50–60 thousand m^3/d) resulted in the maximum depth of the cone depression exceeding 50 m below the land surface (Kowalczyk and Nowicki 2007). Data from 41 sites drawing water from the Oligocene show a similar



Text-fig. 8. Potentiometric surface depth in the Oligocene aquifer in Warsaw (n = 41; FG_Ol; for location of piezometer see Text-fig. 1).

trend of changes in the values of annual means at a 1 year interval (Text-fig. 8). Since 1973–1974, a rising groundwater table trend is observed, with the exception of the turnover between the 1980s and 1990s, when a distinct fall of the groundwater table was caused again by excessive pumping. Restricted pumping of groundwater from the Oligocene aquifer by industry, according to the regulations contained in the Regulations of the Warsaw Voivode of 11th June 1993, allowed for the further reconstruction of piezometric pressures (Bażyński 1996). In 2018–2021, artesian conditions were observed in 4 sites located within the Vistula valley at low elevations, which confirms the rebound of the resources of this aquifer after long-term excessive pumping. The process of

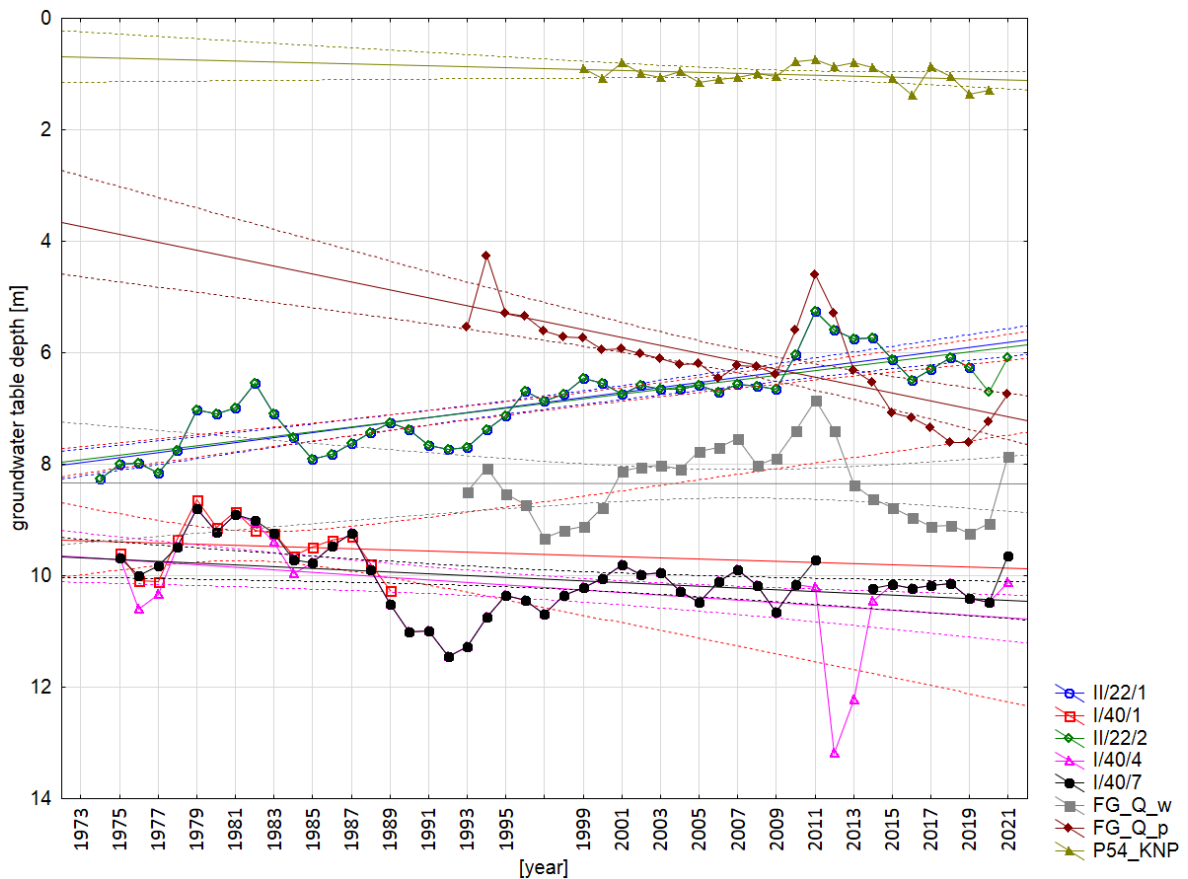
groundwater table reconstruction was characterized by variable dynamics, and in the last 40 years was as follows: 0.51 m during 1973–1983; 0.36 m during 1983–1993; 0.62 m during 1993–2003; 0.35 m during 2003–2013; and 0.34 m during 2013–2021; it should be assumed that it did not stop and its rate of change (ROC) is 3%. The rate of changes was calculated based on the average annual values of depth from all sites, according to the formula:

$$ROC = \left(\left(\frac{H_N}{H_1} \right)^{\frac{1}{N}} \right) - 1$$

where: H – average annual values of depth; H₁ – at first year, H_N – at the last year of the observations; N – number of observation years.

Variable	Units	Mean	Standard deviation	Precipitation	Pearson's correlation coefficient R							
					II/22/1	II/22/2	I/40/1	I/40/4	I/40/7	FG_Q_p	FG_Q_w	P54_KNP
Precipitation	mm/year	550	102	1.00	-0.26	-0.26	-0.17	-0.14	-0.31	-0.44	-0.51	-0.61
II/22/1	m b.g.s.	6.37	0.38	-0.26	1.00	1.00	0.56	-0.23	0.24	0.18	0.12	0.36
II/22/2		6.37	0.38	-0.26	1.00	1.00	1.00	-0.23	0.24	0.18	0.12	0.36
I/40/1		9.47	0.46	-0.17	0.56	1.00	1.00	0.97	0.95	-	-	-
I/40/4		10.19	0.21	-0.14	-0.23	-0.23	0.97	1.00	0.84	0.20	0.11	0.23
I/40/7		10.15	0.23	-0.31	0.24	0.24	0.95	0.84	1.00	0.47	0.33	0.45
FG_Q_p		6.37	0.74	-0.44	0.18	0.18	-	0.20	0.47	1.00	0.75	0.63
FG_Q_w		8.27	0.69	-0.51	0.12	0.12	-	0.11	0.33	0.75	1.00	0.42
P54_KNP		1.01	0.17	-0.61	0.36	0.36	-	0.23	0.45	0.63	0.42	1.00

Table 2. Basic statistical analysis of precipitation and depth of the groundwater table in Quaternary aquifers. Statistically significant values are in bold.



Text-fig. 9. Line plot of annual groundwater table depth with linear fitting and 95% confidence intervals for wells within Warsaw city limits (for location of wells and piezometers see Text-fig. 1).

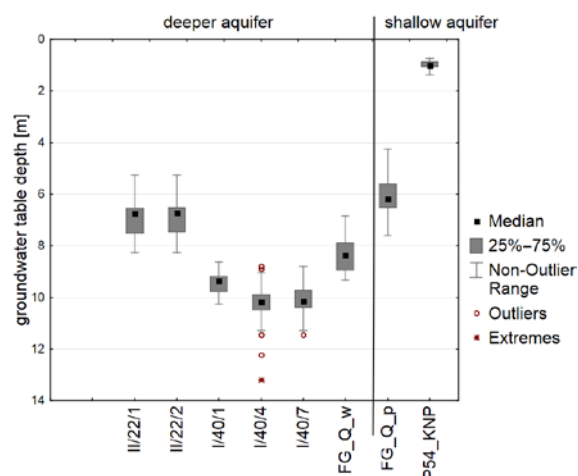
Based on these trends, the predicted average groundwater table depth in the next 10 years will be 6.32 m.

Analysis of the monitoring series from 9 sites referring to the position of the groundwater table in two Quaternary aquifers (the shallow Quaternary aquifer and the deeper Quaternary aquifer) allowed an indication of the change trends (Text-fig. 9). Linear trends along with their 95% confidence intervals were determined for each depth dataset. All types of changes in time can be observed.

Sites monitoring the shallow aquifer show decreasing trends of groundwater levels. A slow but gradual decrease of the groundwater table was already known from other parts of Warsaw, i.e., in the Las Bielański nature reserve, where surface flows have gradually disappeared since the 1980s (Mikołajków 2003), and in 2022 the groundwater table in the presently dried-up stream channel occurred at the depth of 2.1–4.7 m. Such changes clearly indicate that measures should be undertaken to protect

groundwater resources, particularly with regard to the shallow aquifer.

The statistical analysis of data on the groundwater level from wells drawing groundwater from the Quaternary aquifers was also focused on verifying the correlation with precipitation in particular monitoring sites (Table 2). There is lack of linear correlation with precipitation for all monitoring sites taking into account annual averages. In the piezometer of the Survey Station of the Faculty of Geology (FG_Q_p) and piezometer P54_KNP, this correlation is negative and statistically significant, which points to lack of a simple relationship between precipitation (infiltration impulse) and groundwater levels, but in an annual cycle. This is also confirmed by the interpretation of monthly results (Krogulec *et al.* 2020). The correlation of -0.51 (-0.61) is, however, not strong enough to consider other factors shaping groundwater levels as insignificant. Moreover, regression analysis confirms the lack of a relationship between the groundwater table depth and the inde-



Text-fig. 10. Box plot of multiple variables for average annual depths in 1987–2021 at the sites pumping groundwater from the Quaternary aquifers (for location of wells and piezometers see Text-fig. 1).

pendent variable represented by precipitation. The standardized regression coefficient was not obtained in any of the cases.

A characteristic feature of the data from the Quaternary aquifers is the similar average annual amplitude (Text-fig. 10). In the long term interval it does not exceed 2 m for any of the sites. The average groundwater table depths in the study interval are from c. 1 m near the Warsaw city limits with the KNP, where marshy areas occur in the wide Vistula valley, to about 10 m in the Mokotów district in the central part of the plateau.

The information on the flow rate of the springs is an important breakthrough in the changing infiltration recharge regime associated with the city development. The Warsaw springs located at the foot of the Warsaw escarpment (University springs) began to be observed in the 14th century, when the first mentions of water flows within the Old Town appeared. In the 1960s, the southern University spring (UWS) had a constant discharge of 9.0–11.0 dm³/min (Czarnecka 1963), then according to Mysiak and Nejfled (1975), in the beginning of the 1970s, the flow rate of this spring decreased to 3.8–4.2 dm³/min, whereas measurements in 1995–1996 (after reconstruction of the casing) pointed to increase of the average discharge to 7.5 dm³/min. Surveys performed in 1997–2004 point to decrease of the discharge of both springs to an average range of 0.6–1.02 dm³/min (Niewiarowicz 2007). This interval covers the construction of the first underground line, when between 2000 and 2002 the discharge from both springs disappeared

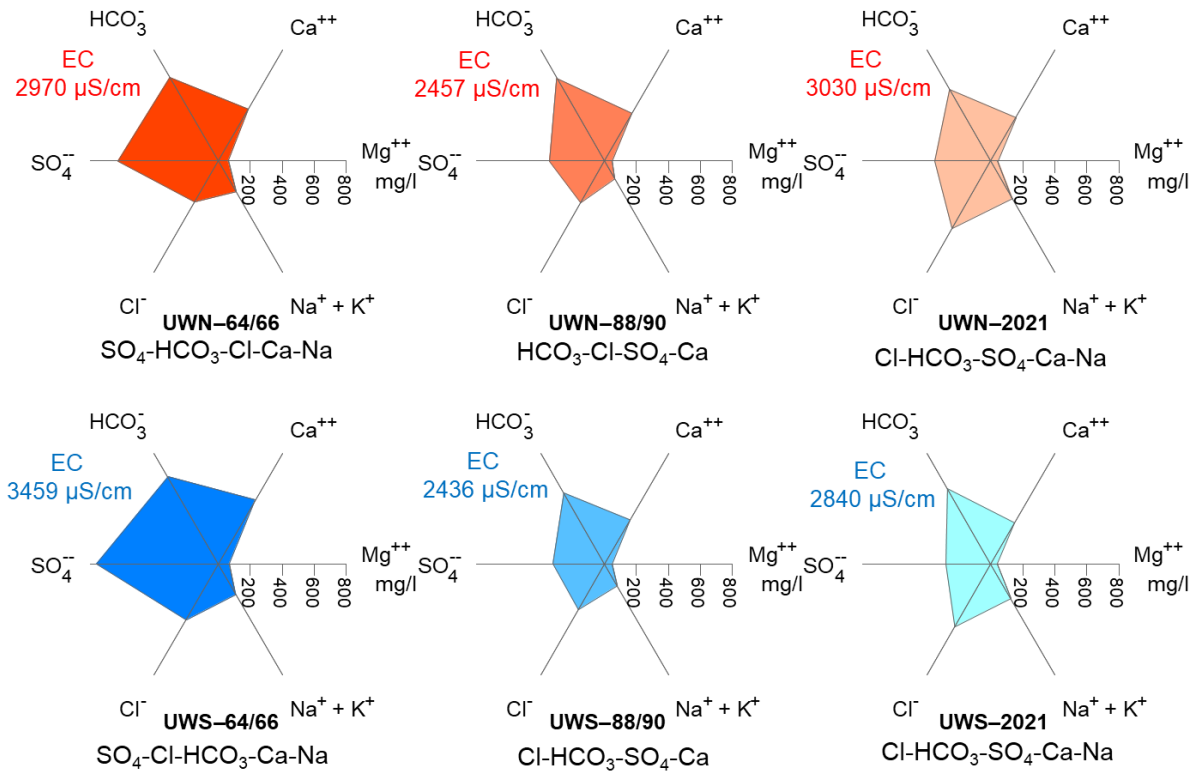
completely (Dziedziczak 2006). Our measurements conducted in 2022 showed an average discharge of 2.01 dm³/min and 3.83 dm³/min at UWN and UWS springs, respectively.

CHARACTERISTICS OF GROUNDWATER QUALITY AND ASSESSMENT OF ITS CHANGE IN TIME

The chemical composition of shallow groundwater in Warsaw is influenced by anthropogenic factors (Pich and Płochniewski 1968; Chrzanowski *et al.* 1972; Macioszczyk A. *et al.* 1991; Kużawa and Gutry-Korycka 2003). Stationary chemical studies of the springs were conducted: in 1836–1843 by Pusch (1844); in 1880 by Leppert (Kużawa and Gutry-Korycka 2003); in 1960 by Czarnecka (1963); in 1964–1966 by Pich and Płochniewski (1968); and later by Mysiak and Nejfled (1975), Macioszczyk A. *et al.* (1991), and Dziedziczak (2006).

The thermal regime of the University springs was also subject to distinct transformations in time. In 1841–1844, when Pusch (1844) analysed the water temperature in five Warsaw springs, the average water temperature in the University springs was 8.7°C (max. 9.8°C in August, min. 6.9°C in March). Till the 1990s, the average temperature increased by about 1–2°C: for UWS averagely 9.7°C (max. 11.8°C, min. 7.8°C), for UWN averagely 10.7°C (max. 12.1°C, min. 5.7°C) (Kużawa and Gutry-Korycka 2003). The most recent readings from 2021 point to a further temperature increase, with the maximum noted water temperatures in July at 17.1°C for UWS and 17.3°C for UWN.

The groundwater chemistry in the University springs significantly differs not only from the chemical composition of the remaining Warsaw springs but also from the groundwater of the shallow aquifer in other parts of the city. A fully documented viable for balancing chemical analysis of water can be found in the report of Pich and Płochniewski (1968), in which the chemical type of groundwater was determined: UWN as SO₄-HCO₃-Cl-Ca-Na, and UWS as SO₄-Cl-HCO₃-Ca-Na (Text-fig. 11). In 1964–1966, mineralization expressed as the average value of electrical conductivity (EC) was 2,970 μS/cm (UWN) and 3,459 μS/cm (UWS). The average concentrations of sulphates were at the level of: 644 mg/dm³ for UWN and 754 mg/dm³ for UWS. Additionally, such values allow the assignation of the waters to exposure class XA2, i.e., environments with high aggression towards concrete (PN-EN 206+A2:2021-08). In



Text-fig. 11. Changes of the chemical composition of water from the University springs in particular study intervals (UWN – northern spring, UWS – southern spring; for location of springs see Text-fig. 1).

Parameter	Units	University springs					
		UWN			UWS		
		study intervals			study intervals		
		1964–1966	1988–1990	2021	1964–1966	1988–1990	2021
HCO ₃ ⁻	mg/dm ³	606.5	598.5	517.0	628.5	509.5	543.0
Cl ⁻		295.5	298.0	485.5	401.5	329.5	450.5
SO ₄ ²⁻		628.5	344.0	350.0	764.0	351.0	281.0
Ca ²⁺		377.0	346.5	313.0	462.0	317.0	296.5
Mg ²⁺		62.0	49.0	42.95	67.5	47.5	38.8
Na ⁺		190.0	84.5	224.0	180.0	112.5	200.5
K ⁺		31.0	42.5	45.7	40.0	45.0	47.1
EC	µS/cm	2970	2457	3030	3459	2436	2840
pH	–	*	*	6.49	*	*	6.86

Table 3. Variability of average concentration values for the main ions, EC and pH values for the University springs in particular study intervals. Asterisks denote lack of specific data. Data for 1964–1966 and 1988–1990 taken from Pich and Płochniewski (1968), and Niewiarowicz (2007).

1988–1990, a distinct decrease in the concentrations of sulphates, chlorides and sodium was observed in water from the University springs. In turn, the most recent unpublished analyses performed in three surveys in 2021 point to a renewed increase in concentration of the same pollution indicators. The chemical type of both springs has also changed: from HCO₃-Cl-SO₄-Ca and Cl-HCO₃-SO₄-Ca to Cl-HCO₃-SO₄-Ca-Na. Text-fig. 11 and Table 3 present the variability

of water chemistry from the University springs in three study intervals.

A distinct decrease of pH of groundwater should also be noted. Studies from the 1960s and 1980s show that pH was close to neutral, the value 7.24 was noted in 2007 for the southern spring (Niewiarowicz 2007), whereas according to the most recent analyses from 2021, the pH varies in the range of 6.4–6.59 for UWN and 6.64–7.08 for UWS. At present, the waters should

Parameter	Units	FG_Q_p			FG_Q_w		
		1993–1999	2000–2009	2010–2019	1993–1999	2000–2009	2010–2019
HCO ₃ ⁻	mg/dm ³	449.17	498.89	471.26	413.57	384.05	388.49
Cl ⁻		92.35	84.11	85.60	103.47	119.77	100.55
SO ₄ ²⁻		169.68	106.32	194.25	256.74	129.02	273.25
Ca ²⁺		205.28	183.80	163.55	211.13	169.70	215.47
Mg ²⁺		24.02	16.62	20.36	27.18	20.95	27.44
Na ⁺		51.52	51.60	46.29	47.85	52.69	44.52
K ⁺		1.32	2.35	2.57	2.80	2.78	2.33
NH ₄ ⁺		0.06	3.58	3.85	0.11	0.09	0.10
Mn ²⁺		0.06	0.04	0.52	0.48	0.54	0.55
Fe ²⁺		0.23	0.15	3.45	4.17	3.24	3.85
EC	μS/cm	1223	1208	1189	1168	1217	1131
pH	–	7.33	7.53	7.39	7.09	7.11	7.14

Table 4. Variability of average concentration values for the main ions, EC and pH for the Quaternary aquifers tested in the Survey Station of the Faculty of Geology in 1993–2019.

be classified as weak acidic, which may cause their high aggressive behaviour with regard to concrete.

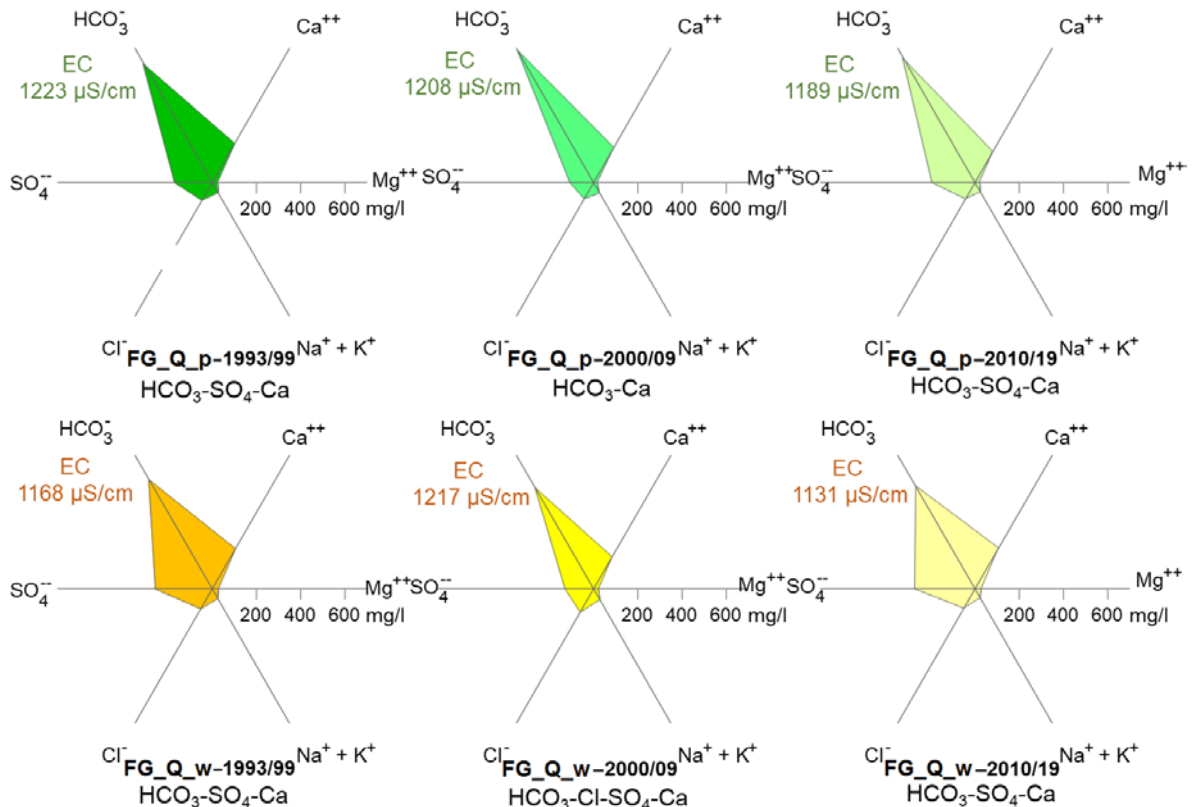
The chemical composition of shallow groundwater is monitored in the Survey Station of the Faculty of Geology, in the Ochota district. High-density housing from the 1950s dominates (in the direction of groundwater inflow) and a large green area – the Pole Mokotowskie – occurs to the east. In the closest vicinity, the development in the Ochota University Campus became much denser during the last 10 years, which resulted in the average surface runoff coefficient for the area being about 0.7 (based on Database of Topographic Objects, BDOT10k; <https://bdot10k.geoport.gov.pl>). This has a significant impact on shaping the infiltration recharge in the area. Factors influencing recharge increase include waterworks infrastructure with hydrants subject to periodical control and water discharge from the water system, as well as the shifting of snow cover from pavements and streets onto green areas. Groundwater chemistry near the Station is mostly influenced by the presence of an important traffic-way of the city, which is the source of dust pollution, heavy metals, hydrocarbons and products of winter road maintenance.

Results of chemical analyses of the two Quaternary aquifers were grouped for the following intervals: 1993–1999, 2000–2009 and 2010–2019 (Text-fig. 12, Table 4). The hydrogeochemical types of groundwater from the two aquifers are similar, with HCO₃-SO₄-Ca as the dominating type; in one interval HCO₃-SO₄-Cl-Ca and HCO₃-Ca types were also noted. A similar hydrogeochemical type confirms the relatively poor isolation of the deeper aquifer determined at about 15 m and the possible percolation through poorly permeable sediments. In all cases, the presence of SO₄²⁻ at the level of 106–273 mg/dm³

points to stable anthropogenic pressure, as indicated also by high concentrations of Na⁺ (in the range of 44–52 mg/dm³), significantly exceeding the range of the hydrogeochemical background for groundwater of the Quaternary aquifers (up to 10 mg/dm³ after Macioszczyk A. and Dobrzyński 2002). For the analysed intervals, there was no significant change in time for any of the components or physical-chemical features (Table 4). The performed analyses indicate that the anthropogenic factor plays a significant role in shaping the chemistry of water from the two aquifers (Kadzikiewicz-Schoeneich *et al.* 2005; Małecki *et al.* 2007; Małecki 2013).

The chemical composition of the water from Oligocene aquifer has been the subject of research since the 1920s, while the more detailed studies that form the theses that are still valid today, come from the 1970s (Macioszczyk A. 1979). The total mineralization of the water from Oligocene aquifer in the Warsaw region is about 400–900 mg/dm³. The dominant and common hydrogeochemical type is HCO₃-Na, less often types HCO₃-Na-Ca, HCO₃-Ca-Na or HCO₃-Cl-Na. Their characteristic features are: the SO₄²⁻ ion content in the amount of more than 20% meq, a constant temperature of approx. 9°C, no bacteriological contamination, excess amounts of iron, manganese and ammonium ions, and locally increased turbidity (Macioszczyk A. and Płochniewski 1996).

Changes in the water chemistry of the Oligocene aquifer caused by intensive exploitation relate to two quality parameters: salinity associated with the ascension of salt waters from the Mesozoic formations and the increase in colour of the water as a result of water inflow from the Miocene aquifer. The analysed changes in chloride concentrations did not



Text-fig. 12. Changes of the chemical composition of groundwater from the Quaternary aquifers observed in the Survey Station of the Faculty of Geology (for location of well and piezometers see Text-fig. 1).

indicate a clear trend of salinity changes as a result of exploitation (Macioszczyk A. and Płochniewski 1996), currently, during the groundwater table increase, such trends were not also noted (Porowska and Małecki 2009).

Groundwater drawing the Oligocene aquifer at the University of Warsaw Survey Station (FG_OL, Text-fig. 1) was the subject of research in 1991–2007 (Porowska and Małecki 2009). A stable hydrochemical composition of the $\text{HCO}_3\text{-Cl-Na-Ca}$ type was observed, and total mineralization varied in the range from 542.5 to 640.6 mg/dm^3 , on average 578.6 mg/dm^3 , pH from 6.90 to 7.52, with a mean of 7.43.

The regional diversification of water chemistry indicates the long duration of the processes shaping the water chemistry, and on the other hand, it may indicate the disappearance of natural ascension processes. The presence of an organic substance, reducing conditions and low sulphate concentrations points in the active process of sulphate reduction. Studies of the isotopic composition of oxygen (d^{18}O), deuter (dD) and carbon (^{14}C) indicate water typical of the glacial period (Porowska and Małecki 2009).

IDENTIFICATION OF FACTORS INFLUENCING CHANGES IN TIME OF THE GROUNDWATER LEVELS AND CHEMISTRY IN AN URBAN AREA – DISCUSSION OF THE RESULTS

The cumulative operation of numerous elements which are mutually dependent and should be discussed jointly can be observed in urban areas (Table 5). Changes of groundwater levels and chemistry result both from the progressive global climate change as well as local changes related with urban infrastructure. Variability resulting from natural conditions (spatial variability of the geological setting and hydrogeological conditions) is overprinted by anthropogenic factors (land levelling related with urban development, formation of embankments and tunnels), which not only change the primary landscape but also the hydrographic network. In Warsaw, significant impact on the terrain morphology can be observed in the plateau escarpment, the Warsaw escarpment, on almost its entire length, in the form of: dumping of communal waste from the 16th century (up to 11

Groundwater resources	Impact	Groundwater chemistry	Impact
increased areas of paved and sealed surfaces	–	cumulative influence of pollution of various origin and age: industrial, communal, road maintenance, silt	–
construction drainage: permanent and periodical	–		
land morphology transformations	–/+	removal or violation of the soil cover	–
densification of subsurface soil layers	–		
changes of climate factors: precipitation magnitude and intensity, wind force and direction, temperature	–		
changes of the hydrodynamic system due to deep foundation construction	+/-	leakage in waterworks and sewage infrastructure	+/-
transformation of the hydrographic network	–		
groundwater intake	–		
surface water intake by infiltration intakes	–	changes of the morphology (in the past, superstructure of slopes with waste)	–
leakage in waterworks and sewage infrastructure	+/-		
application of retention-attenuation devices	+		
removal or violation of the soil cover	+		

Table 5. Potential factors with positive (+) and negative (–) impact on the changes of groundwater resources and chemistry in Warsaw.

distinguished layers) or rubble during and after the Second World War (Meyza 1999; Frankowski and Wysokiński 2000). Thick embankments (after the torn down development of the Warsaw Ghetto) also occur in the city centre, in the Muranów district. Around Warsaw, at present within the city boundary, there occur terrain transformations related with the Warsaw Fortress, which consist of rings of forts, embankments and ditches that protected outlying areas and transport routes (Pałubska 2014).

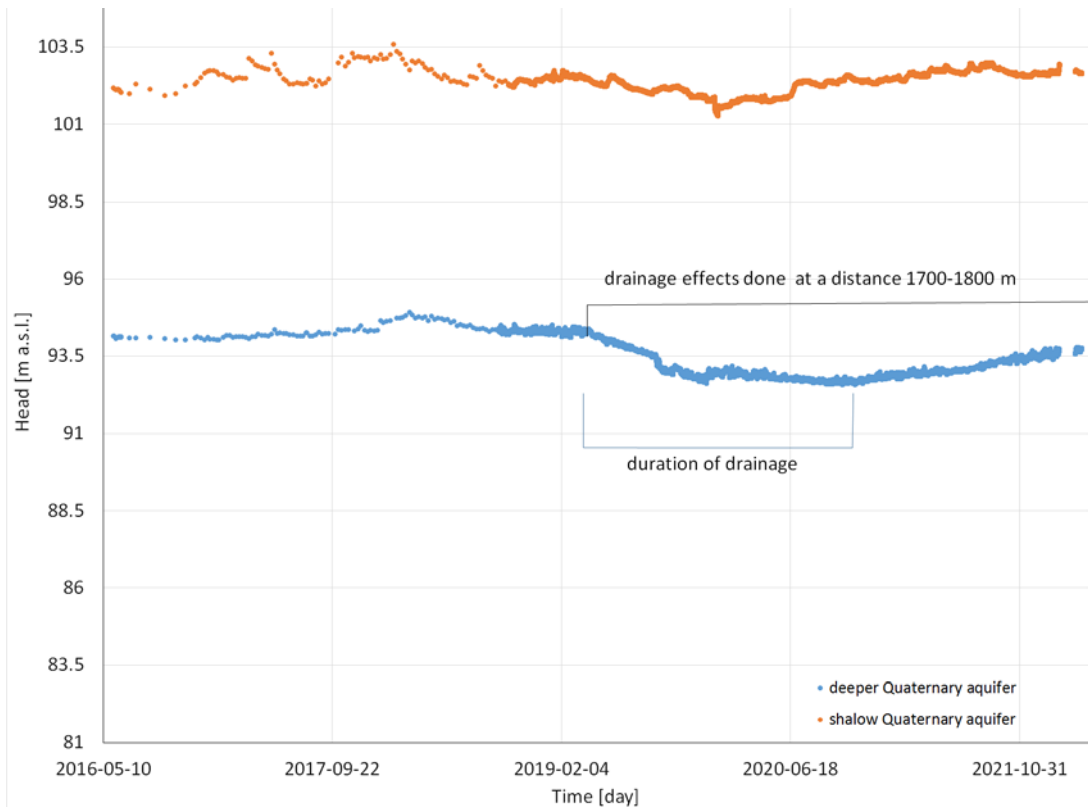
Beside transformations of the terrain morphology, an important role in shaping the groundwater resources is played by the degree of isolation of the aquifer through application of hardened surfaces (pavements, streets) and the location of subsequent constructions. In both cases, water discharge from these areas takes place into the combined sewage system. The effects of changes in the infiltration conditions and aquifer recharge in the city should be thus discussed with regard to the diminishing of the contribution of this component in the water balance. Calculations indicate that in Warsaw the average value of the surface runoff coefficient is 0.44, reaching even 0.69 for the plateau above the UWS and UWN springs (based on Database of Topographic Objects BDOT10k, <https://bdot10k.geoportal.gov.pl>).

Recharge changes are difficult to depict in time and space in the scale of the entire city. It has been shown that local hydrodynamic conditions in urban areas can be modified due to construction drainage, which periodically changes the groundwater table. Such a case has been observed in southern Warsaw, in the Ursynów district, where two Quaternary aquifers occur in contact with one another. The shallow aquifer is linked with sandy fluvio-glacial sediments, within which occurs an unconfined groundwater ta-

ble. The deeper aquifer occurs in sandy fluvio-glacial deposits under a layer of sandy glacial tills, which attains thicknesses from 4.5 to 8 m in the area; depending on the locality, its groundwater table is unconfined or confined. Measurements indicate that construction drainage caused decrease of groundwater tables in both aquifers (Text-fig. 13). The subsurface aquifer is not treated as a capacious groundwater aquifer of economic significance, although it represents a transitional element between the infiltrating precipitation and the deeper useful aquifers (Kowalczyk 2005). Its role in water circulation, as the main source of recharge of hydrogeological systems in plateaus has been confirmed in this case study, and the restriction of the percolation to the deeper aquifer may be observed for a few years after the investment is accomplished on a distance of a few kilometres.

A similar example showing the influence of a construction investment requiring drainage on the periodical decrease of the groundwater table is documented by measurements performed in the Wola district by Godlewski *et al.* (2019). Some objects requiring drainage during the construction stage change the hydrodynamic system only for a short time, but the construction of high-rise objects with deep foundations permanently alters the structure of the groundwater stream (Opęchowski and Krogulec 2019). In the scale of all investments in the city this factor is impossible to estimate, but it has significant local impact on the groundwater table depth. A counterbalance for the decreasing water volume in the water balance of an urban area is the contribution of water flowing from the leaking water-sewage system, estimated in Warsaw at 13.2–15.7%.

Urban development has enforced changes in the river network in the city, with strong impact on



Text-fig. 13. Changes of groundwater table level due to construction drainage (location in the Ursynów district).

the course of streams (2nd range) flowing into the Vistula. Parts of the streams do not exist anymore, some have lost their natural character and flow in channels or have been canalized. In the case of Rudawka, and the Bielański and Służewiecki (formerly: Sadurka) streams, the streams have changed their routes, and in some stretches they have been isolated from natural conditions, flowing in covered channels (Mikołajków 2003). The Nowomiejski stream was canalized already in the 18th century, and its valley was turned into the Old Town moat. Similar transformations have been accomplished in the case of other tributaries of the Vistula in Warsaw and its vicinity (Galera *et al.* 2010).

The consequence of changing hydrodynamic conditions is the change of hydrogeochemical conditions. Removal of the subsurface layer, particularly within the soil profile during construction excavations causes increased threat posed on groundwater with regard to potential pollution from the land surface (decreasing the thickness or complete removal of the aeration zone).

The degree of complexity in the identification of factors influencing changes of groundwater levels

and chemistry in time increases after taking into account anthropogenic factors, such as: uneven water intake resulting from increased water demand during the summer, unexpected breakdowns (e.g., damage of the Rudawka channel in 2021 due to construction works and flooding of neighbouring areas), and the degree of urbanization and industrialization reflected in the quality of atmospheric air and precipitation chemistry. Climate factors are also important issues, not only with regard to increasingly frequent periods of droughts and floods, but also due to the fact that urban development changes natural wind directions and causes thermal change (higher temperatures result in more intense evaporation and thus potentially lower infiltration). The hardest to assess is the impact of local, usually short-term drainage which violates the settled hydrodynamic conditions, overprinted by other anthropogenic elements.

Urban management pursues a low groundwater table and low soil humidity, because higher levels and large humidity of the vadose zone may lead to flooding of basements and underground levels of buildings (high humidity, fungal attacks), which result in dewatering methods that not only decrease

the groundwater table but also drain the subsurface soil layers through: wells, horizontal drains, ditches, or casings around buildings. Enlarged renewability of hydrogeological systems may largely depend on the augmented applicability of soakaway crates for attenuation and infiltration, whose implementation in cities results from purely economic aspects – there are no further possibilities for increasing the capacity of the combined sewage system or introduction of storm water sewage systems for newly constructed objects.

SUMMARY

This paper analyses the influence of geogenic and anthropogenic factors shaping groundwater levels and chemistry in an urban area. Separate treatment and analysis of particular factors seems impossible, therefore the cumulative impact should be discussed. The spatial and temporal analysis of groundwater levels and chemistry at the same angle and resolution for the entire city is also difficult. Cities are characterized by a set of specific features, therefore they require the application of a dedicated methodology for solving the research problem.

1. The magnitude of infiltration recharge has been spatially presented for 1987 and 2021. The comparison points to decrease of recharge on 93% of the surface (including 21% of built-up areas), whereas increase of recharge was observed on c. 7% of the surface area. The largest changes are linked with the city suburbs, where in 1987–2021 new residential settlements have been constructed.

2. Analysis of a long-term observation series of groundwater levels has shown that the groundwater table of the deeper Quaternary aquifer gradually decreases in the central part of Warsaw. A similar trend was observed in sites monitoring the shallow aquifer in different parts of the city. Reconstruction of piezometric pressures was observed only within the Oligocene aquifer in constrained pumping conditions.

3. The groundwater chemistry of the subsurface aquifer points to strong anthropogenic pressure, which is manifested in the multi-ionic hydrogeochemical types (e.g., $\text{SO}_4\text{-Cl-HCO}_3\text{-Ca-Na}$) and presence of chemical tracers typical for human activity. This is particularly evident in the city centre, where anthropopression displays high spatial and temporal variability. The pressure is also apparent in the deeper Quaternary aquifer, where the dominating hydrogeochemical type is $\text{HCO}_3\text{-SO}_4\text{-Ca}$.

4. Groundwater chemistry of the Oligocene aquifer of regional importance is characterized by a chemical composition pointing to the activity of geogenic factors, although some of them have been indirectly induced in the past by human activity as a result of excessive pumping. The specific hydrogeochemical type is $\text{HCO}_3\text{-Na}$, which shows spatial variability but almost no temporal variability.

5. Analysis of datasets containing long-term measurement series has emphasized the role of groundwater resources, helps in planning sustainable water management and to a certain degree allows the prediction of the effects of irrational water management or the inadequate direction of urban infrastructure development.

6. With regard to monitoring it seems indispensable to expand the monitoring network in the city and perform detailed analyses resulting from the need to solve specific research problems, which requires individualized analyses referred to real, recognized hydrogeological conditions.

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