Geological Quarterly, 2017, **61** (2): 384–395
DOI: http://dx.doi.org/10.7306/gq.1341

Evaluation of groundwater recharge in Poland using the infiltration coefficient method

Robert TARKA[1], Tomasz OLICHWER[1,] * and Stanisław STAŚKO[1]

[1] Wrocław University, Institute of Geological Sciences, M. Borna sq. 9, 50-204 Wrocław, Poland

Tarka, R., Olichwer, T., Staśko, S., 2017. Evaluation of groundwater recharge in Poland using the infiltration coefficient method. Geological Quarterly, **61** (2): 384–395, doi: 10.7306/gq.1341

Variable methods and results are reported on groundwater recharge in Poland. The evaluation of recharge on a small scale requires the use of a single method. In order to evaluate these outcomes and their distribution, the authors have decided to verify different approaches and select the infiltration coefficient by comparison. The article is an extension of the studies on groundwater recharge conducted by the authors. The main goal is to verify previously designed values of the infiltration coefficient based on groundwater runoff from additional river basins in Poland. Total groundwater recharge from precipitation in Poland was calculated at 34,118 km^3 per year, which equals 109.3 mm of water column. The obtained value is close to the average multi-year value of the groundwater runoff. Recharge constituted 18.6% of average precipitation in Poland, which was calculated at 588.5 mm. The estimated groundwater recharge value was verified referring to groundwater runoff from 37 river basins with known discharge rates in the years 1976–2005. Differences in mean groundwater runoff for the entire area (37 river basins) obtained by the infiltration coefficient method and by the use of Wundt's method amounts to only 0.7%. Despite the simplified calculation methods, the results obtained on a small scale are more accurate than other calculations, which are based on data pertaining to precipitation, soil type, land use, topography of the area, and depth to the groundwater.

Key words: groundwater recharge, infiltration coefficient, Poland.

INTRODUCTION

The article is an extension of the studies on groundwater recharge described by Staśko et al. (2012). At that stage, soil maps at a scale of 1:500,000 were selected to estimate groundwater recharge by the infiltration coefficient method for regional evaluation. Based on measured value of groundwater runoff and rock types, the infiltration coefficient (recharge rate) was defined for selected soil types. Next, in designated 15 test river basins from Lower Silesia (SW Poland), the recharge rate was calculated as a groundwater-related runoff associated with the catchment area.

The main goal of this paper is to verify previously designed values of the infiltration coefficient based on groundwater runoff from additional river basins of Poland. In total, 37 river basins, with a long-term and uniform river flow database, have been evaluated. Result of the previous study allows more correct evaluation of the recharge value associated with the precipitation distribution in the same way for the whole country. The results have been compared with selected outcomes from numerical modelling and reported values in Poland and other countries.

Groundwater recharge is an indicator of groundwater resources. It has a direct impact on the size of groundwater renewable resources and, to a large extent, determines the degree of groundwater vulnerability to contamination. Due to the high variability of physical and climatic conditions in Poland, many different methods have been employed in order to assess the recharge of particular river basins. However, the evaluation of recharge on a smaller scale, such as that of the whole country or large river basins, requires the use of a single method. For this reason, the authors have decided to assess groundwater recharge in a general scale for the whole area of Poland using the infiltration coefficient method.

While developing the methods of evaluating groundwater recharge, it is necessary to include processes occurring in the unsaturated and saturated zones and take into account areal and linear recharge, as well as recharge in preferential zones. They also comprise methods of evaluating groundwater runoff as the final stage of recharge. These methods can be divided into several groups: water balance, lysimeter, isotope tracking, numerical modelling, heat transfer, groundwater table fluctuation, and river hydrograph separation. The benefits and drawbacks of each of these techniques are analysed by Pazdro and Kozerski (1990), de Vries and Simmers (2002), Scanlon et al. (2002), and Brodie and Hostetler (2005).

Water balance methods require not only the knowledge of the changeability of precipitation, but also the evaluation of evapotranspiration, which adds to difficulties. Lysimeter methods are expensive experiments that allow for precise calculations in shallow zones. Isotope and heat transfer methods are more reliable on a local, rather than a regional scale. The groundwater table fluctuation method, despite numerous and

* Corresponding author, e-mail: tomasz.olichwer@uwr.edu.pl

Received: March 21, 2016; accepted: July 26, 2016; first published online: January 20, 2017

lengthy observations, relies heavily on the assumption that the parameters of aquifers are constant. Numerical modelling tests, based on the theory of water-bearing systems, are a useful tool when conducting experiments on a regional scale. Separation of river hydrographs illustrates the final result of effective infiltration and recharge along with its regional variability and is considered the most representative on a regional scale.

The majority of these techniques have been used in Poland, especially the water balance method. The isotope technique has also been implemented, albeit to a smaller extent (e.g., Pleczyński, 1981). The method most frequently employed when documenting groundwater resources is the water balance and effective infiltration method, which is mainly based on the permeability of surface formations (Pazdro and Kozerski, 1990; Paczyński, 1995). This method does not take into account the water capacity of rock formations. Methods based on the results of long-term pumping tests and the increasingly popular results of numerical modelling dominate in cartographic records.

An efficient way of evaluating the groundwater renewable resources is determining effective infiltration by means of the infiltration coefficient. This approach assumes that a portion of precipitation reaches aquifers and then is discharged through subterranean outlets into springs, rivers, lakes or the sea. The volume of water seeping to water-bearing layers is defined by means of an effective infiltration coefficient showing the ratio of effectively infiltrated water table to the arithmetic mean of annual rainfall measured over a number of years. The result is given either in percentage or decimal fractions. In Poland, the infiltration coefficient method was generally used in lowlands (Pazdro and Kozerski, 1990). However, attempts were also made to employ this method in uplands (Tarka, 2001) and mountainous areas (Duda et al., 2006).

STUDY AREA

The study is located in the eastern part of the North European Plain, dominated by lowlands markedly sloping down from south-east to north-west, with an average elevation of 173 m (Fig. 1). Lowlands (<300 m above sea level) take up around 91.3% of the total area of Poland, with highlands (between 300 m and 500 m) and mountainous areas (above 500 metres above sea level) constituting, respectively, 5.6% and 3.1% of the total area (Kondracki, 1994) . The average annual rainfall for the whole country is around 600 mm, although precipitation depends strongly on the elevation. For lowlands and highlands, for example, the figures range from 450 to 750 mm, while in mountainous areas, precipitation as high as 1200–1500 mm can be expected (Kondracki, 1994). The rainfall peaks during the summer months.

The Sudetes and Carpathians dominate the landscape of southern Poland. The erosive and accumulative activity of Pleistocene glaciers and ice sheets during the Quaternary period had a significant impact on the geological structure of surface layers in central and northern Poland. Four glacials interspersed with interglacials have lead to the accumulation of compact glacial drifts such as sand, gravel or clay, whose thickness reaches 150–200 m in some places (Stankowski, 1996). These deposits contain about 75% of renewable groundwater resources of Poland (Fig. 2). Groundwater in Quaternary deposits occurs in several layers, whose number and thickness increases from the south to the north of Poland. The water is accumulated in porous material such as sand and clay sediments, which are the most common aquifers in central and northern Poland. The occurrence of groundwater in the highlands and the West Tatra Montains is strictly connected to the formation of

Fig. 1. General overview map of Poland

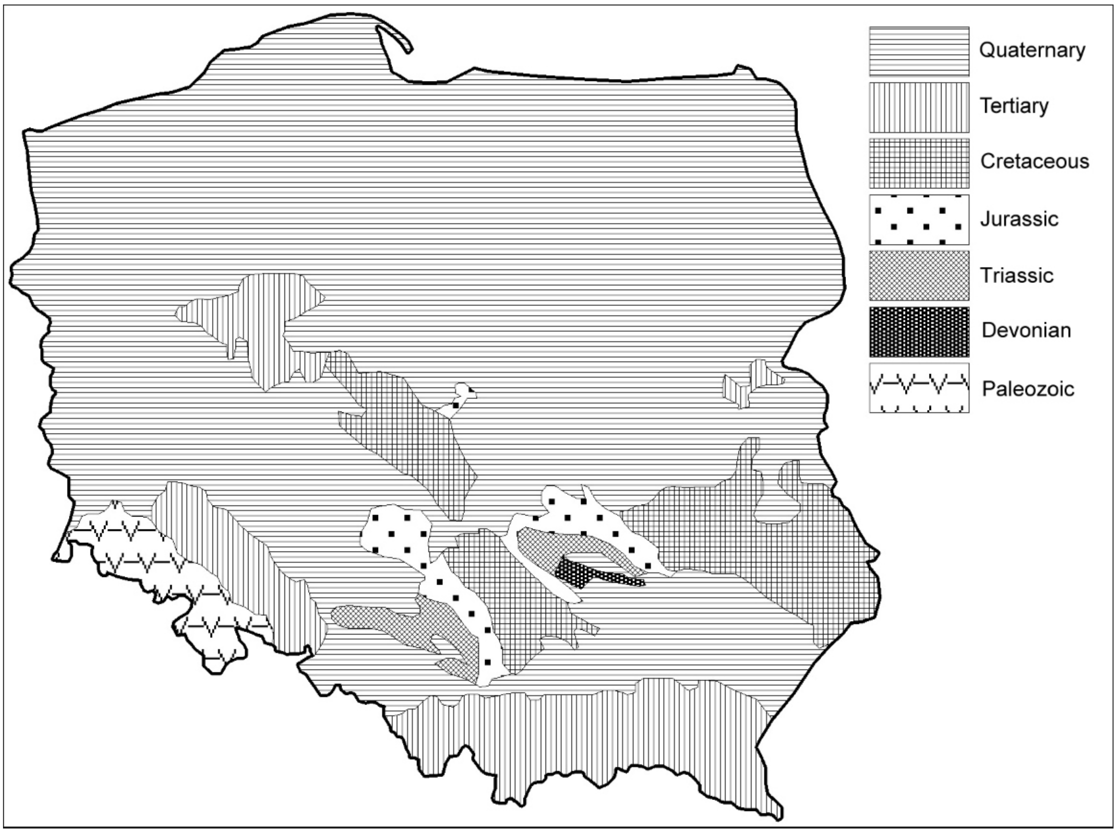

Fig. 2. A schematic map of the first aquifer formation in Poland (after Paczyński, 1995)

fracture-karstic reservoirs by carbonate structures. In the Sudetes area, groundwater is mostly linked with fractured crystalline formations and their granular weathering cover.

The groundwater table usually occurs within the uppermost aquifer that can be found at varying depths depending on the location. In carbonate-rich highlands, these aquifers usually lie at depths of 10–50 m. In the Carpathians, Sudetes and in terminal moraine areas of the lake district in northern Poland, they can be found at depths of up to 20 m. In the central lowlands and Forecarpathian Vallies, the depth, at which these aquifers are located, usually does not exceed 5 m (Paczyński and Sadurski, 2007).

In order to evaluate the groundwater recharge map of Poland, 37 river basins from all over Poland have been selected. The river basins 1–15 are located in Lower Silesia (test area – stage II). Next 22 river basins (16–37, test area – stage III) have been selected from the remaining part of Poland (Table 1 and Fig. 3).

A more detailed hydrogeological description of the 37 river basins and the verification of the calculations of groundwater recharge are illustrated in Table 1. The river basins (Fig. 3) differ between each other in their surface areas and locations relative to physical, geographical and hydrogeological units, and cover a total area of 50,737 km^2.

METHODS AND MATERIALS

An efficient way of evaluating the renewable groundwater resources is determining effective infiltration by means of the infiltration coefficient. This approach assumes that a portion of precipitation reaches aquifers and then is discharged through subterranean outlets into springs, rivers, lakes or the sea. The volume of water seeping to water-bearing layers is defined by means of an infiltration coefficient method.

The infiltration of precipitation in an area can be computed by referring to geological or soil maps. Thus, the test areas have to be identified on the map and assigned to separate infiltration classes. There are several classifications used for the assigning, e.g. classifications by Paczyński (1972), Schneider and Züschang (Załuski, 1973), Wright et al. (1982), Pazdro and Kozerski (1990), Daly (1994), Singh (2003), Voudouris et al. (2007) and Ali Rahmani et al. (2016). In these classifications the infiltration coefficient of very good permeable rocks (fluvioglacial and aeolian sands and gravel, fractured and karst rocks) ranges from 0.3 to 0.5, and for good and medium permeable deposits (sands and gravel in terminal moraines, glacial sands and gravel, sands and muds, alluvial fill terraces, diluvial sands, peat, silty sands) it is 0.2–0.25. The lowest figures <0.1 are typical for tills, loams, stagnant-river/lake muds, diluvial clays, non-fractured clay rocks, phyllites, limestones, sandstones, shales and hard rocks. The infiltration coefficient value is associated not only with the permeability of the soil/rock in the unsaturated zone, but also with the climatic zonation. For example, Ali Rahmani et al. (2016) reported these values for the semi-arid condition.

The lithological maps and knowledge of precipitation levels is necessary to calculate effective infiltration. Large-scale geological maps, which depict various types of surface cover, are useful when creating lithological maps. When conducting research on a smaller scale or whole country, lithological maps must be generalized or substituted with other available sources, such as small-scale geological maps. Soil maps are also suitable for determining the infiltration coefficient, since the type

Table 1

Hydrogeological characteristics of the river basins

No.	River/gauge	Surface area [km^2]	Precipi-tation [mm]	Type of aquifer	Aquifer stratigraphy	Depth to groundwater table/type of groundwater flow
1	Orla/Korzeńsko	1141	525	porous	Quaternary	0–10/confined, unconfined
2	Barycz/Osetno	4589	533	porous	Quaternary	2–10/confined, unconfined
3	Mała Panew/Staniszcze Wlk.	1068	637	porous, frac-tured-karstic	Quaternary, Triassic	5–15/confined, unconfined
4	Biała/Dobra	358	625	porous	Quaternary, Paleogene	0–10/confined, unconfined
5	Biała Lądecka/Lądek Zdrój	161	846	fractured	Paleozoic	5–30/confined, unconfined
6	Bystrzyca Dusznica/Szalejów Dln.	174	742	porous-fractured	Cretaceous	5–40/confined, unconfined
7	Nysa Kłodzka/Kłodzko	1060	622	porous, porous-fractured, fractured	Quaternary, Creta-ceous, Paleozoic	0–40/confined, unconfined
8	Nysa Kłodzka/Skorogoszcz	3927	614	porous, porous-fractured, fractured	Quaternary, Paleogene, Creta-ceous, Triassic, Permian, Paleozoic	0–40/confined, unconfined
9	Oława/Oława	961	577	porous, fractured	Quaternary, Paleo-zoic	0–40/confined, unconfined
10	Ślęza/Białobierze	186	575	porous	Quaternary, Paleogene	0–10/confined, unconfined
11	Bystrzyca/Jugowice	120	622	fractured	Paleozoic	5–30/confined, unconfined
12	Bystrzyca/Krasków	678	585	porous	Quaternary, Paleogene	0–10/confined, unconfined
13	Kaczawa/Świerzawa	136	575	fractured, fractured-karstic	Paleozoic	5–30/confined, unconfined
14	Czarny Potok/Mirsk	51	725	fractured	Paleozoic	5–30/confined, unconfined
15	Bóbr/Żagań	4258	605	porous, po-rous-fractured, frac-tured	Quaternary, Creta-ceous, Paleozoic	0–40/confined, unconfined
16	Gwda/Piła	4697	605	porous	Quaternary	2–10/confined, unconfined
17	Drawa/Drawsko Pomorskie	609	673	porous	Quaternary	2–10/confined, unconfined
18	Ina/Goleniów	2127	573	porous	Quaternary	2–10/confined, unconfined
19	Słupia/Słupsk	1428	674	porous	Quaternary	5–15/confined, unconfined
20	Warta/Działoszyn	4092	608	fractured-karstic, porous-fractured	Jurassic	5–20/confined, unconfined
21	Prosna/Mirków	1249	579	porous	Quaternary	5–15/confined, unconfined
22	Noteć/Pakość	2174	525	porous	Quaternary	2–20/confined, unconfined
23	Reda/Wejherowo	393	670	porous	Quaternary	5–10/confined, unconfined
24	Bukowa/Ruda Jastkowska	650	581	porous	Quaternary	5–0/confined, unconfined
25	Pisa/ptaki	355	615	porous	Quaternary	5–10/confined, unconfined
26	Liwiec/Łochów	246	525	porous	Quaternary	20/confined,
27	Biała/Grybów	205	736	porous-fractured	Paleogene	8–20/confined
28	Skawa/Jordanów	98	950	porous-fractured	Paleogene, Creta-ceous	8–20/confined
29	Łososia/Piekiełko	154	810	porous-fractured	Paleogene	8–20/confined
30	Skrwa/Parzeń	154	525	porous	Quaternary	5–10/confined, unconfined
31	Kamienica/Nowy Sącz	237	698	porous-fractured	Paleogene	8–20/confined
32	Świder/Wólka Mlądzka	835	525	porous	Quaternary	5–10/confined, unconfined
33	Orzyc/Krasnosielsk	1275	568	porous	Quaternary, Paleogene	8–20/confined
34	Brzozówka/Karpowicze	650	575	porous	Quaternary	5–10/confined, unconfined
35	Nurzec/Boćki	546	525	porous	Quaternary	5–10/confined, unconfined
36	Wierzyca/Bożepole Szlacheckie	404	588	porous	Quaternary	5–10/confined, unconfined
37	Pilica/Przedbórz	2457	605	karstic-fractured	Triassic	0–5/unconfined

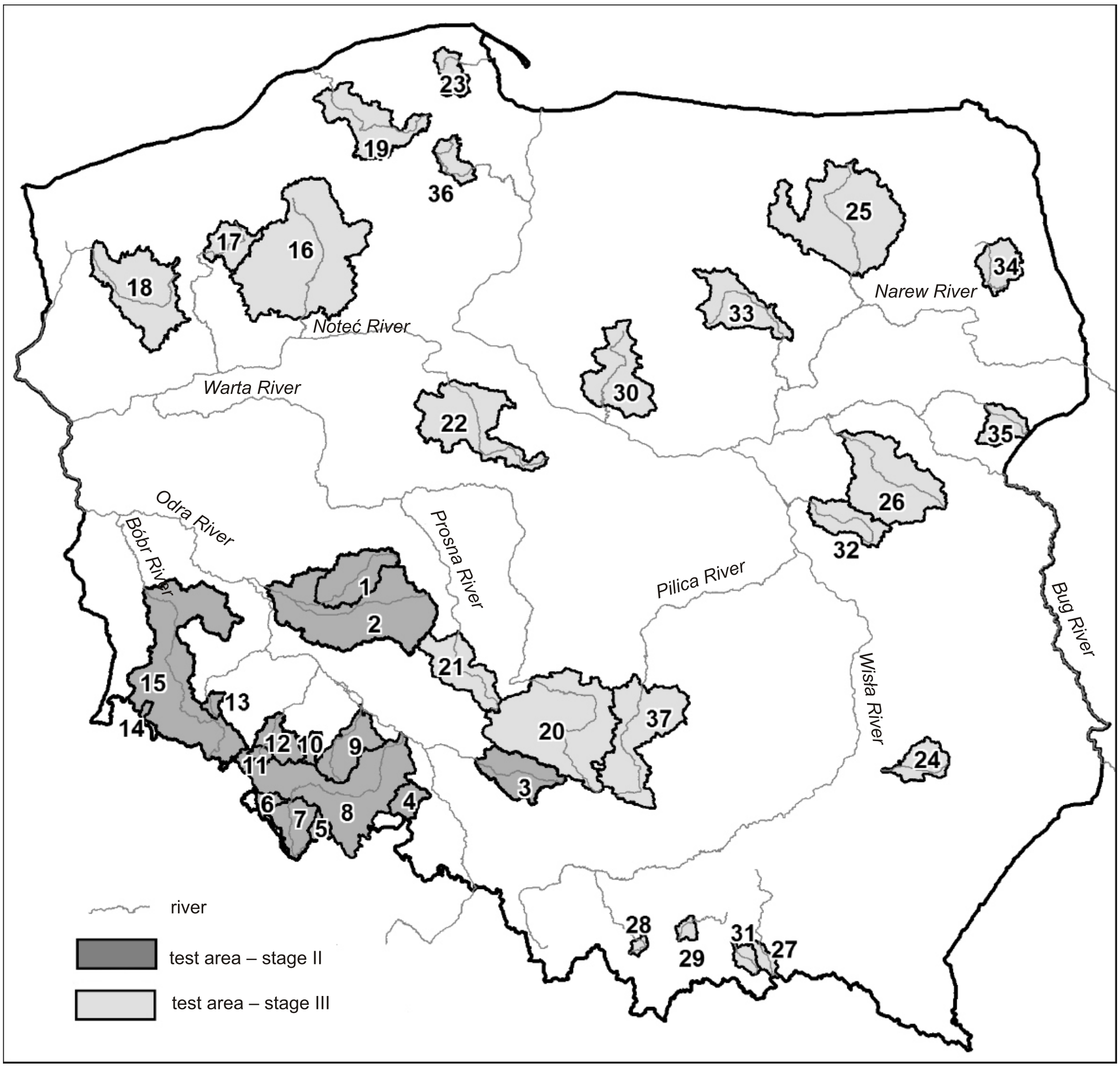

Fig. 3. Location of river basins (numbers as in Table 1)

and category of soil reflects the geological structure and climatic conditions. There is also a direct correlation between the lithological form and the grain-size group of the co-occurring soil. This correlation was relied upon in the process of drawing up guidelines for data compilation for "The map of groundwater vulnerability to pollution in Poland'' at a scale of 1:500,000 (Duda et al., 2011).

The assessment of groundwater renewable resources by means of the infiltration coefficient method requires the division of a given area into regions with varying average annual precipitation levels. They can be selected, for example, by looking at isohyets. Next, the area of each class reflecting infiltration coefficients in a given precipitation zone must be defined. This forms a basis for calculating the weighted mean [1] of the infiltration coefficient for each precipitation area.

$$ {}_r = \frac{\sum_{i=1}^{n} {}_i \, A_i}{\sum_{i=1}^{n} A_i} \qquad [1] $$

where: ${}_r$ – the average infiltration coefficient for precipitation zone (effective fraction), r, ${}_i$ – the infiltration coefficient for the i-lithological configuration within the precipitation zone, A_i – the surface of the i-lithological configuration [L^2] in precipitation zone r.

The aggregate recharge [2] is the sum of recharge values calculated for each precipitation area:

$$ R = \frac{\sum_{r=1}^{m} {}_r \, P_r \, A_r}{A} \qquad [2] $$

where: R – groundwater recharge, P_r – the average annual rainfall in precipitation area r [L], A – the area under study [L^2], m – the number of selected precipitation zones.

This method for determining groundwater recharge has been used to calculate the total recharge in Poland by authors.

It is worth mentioning that groundwater recharge depends not only on the amount of precipitation, but also on air temperature, depth to the groundwater table, and plant cover. Hence, when making calculations, e.g. for mountainous areas, infiltration coefficients should include the relationships with climatic conditions affecting the percentage increase in infiltration. An example is the methods used to estimate an effective infiltration in the framework of the Hydrogeolgical Map of Poland 1:50,000 (Herbich et al., 2008) and the map of groundwater vulnerability to pollution in Poland 1:500,000 (Duda et al., 2011). Intensity of groundwater recharging by infiltration was evaluated by superposition of current information pertaining to precipitation, soil type, land use, topography of the area, and depth to groundwater.

The groundwater recharge for Poland has been estimated in three stages. Stage I – selection of methods, stage II – test of the methods in Lower Silesia and compilation of a map of groundwater recharge for the whole of Poland, stage III – checking the map in particular 22 areas.

The selection of methodology to determine the groundwater recharge on a general scale has been done in first step. The creation of a comprehensive map of groundwater recharge in Poland in general scale required the identification of particular infiltration classes. This was done through the use of the infiltration coefficient method and with the help of a numerical soil map (a scale of 1:500,000), created by the Institute of Soil Science and Plant Cultivation in Puławy. Precipitation was determined according to the “Polish Climate Atlas” (Lorenc, 2005).

During the first stage, infiltration coefficients for given soil class (Table 2) were determined according to the principles used in the construction of the soil profile’s protective layer of map of groundwater vulnerability to pollution in Poland (Duda et al., 2011; Table 2).

In the second stage, verification of the methods has been evaluated based on selected rivers with long-term measurements in Lower Silesia (SW Poland), where, as a result, a positive correlation was approved (Staśko et al., 2012). Recharge values were first calculated for the test areas which covered river basins near the upper and central Odra River basin. Calculations have been made for 15 river basins (test area – stage II; Fig. 3), differing from each other in surface area and location relative to physical, geographical and hydrogeological units, and covered in aggregate an area of 17,000 km^2. The recharge was assessed according to the previously described method [formulas 1 and 2]. The estimated groundwater recharge value was verified referring to groundwater runoff from the river basins under study. Wundt’s method (Wundt, 1953; Jokiel, 1994) was applied to calculate groundwater runoff from the catchments during the years 1976–2005. According to Wundt (1953) the mean monthly low water runoff yield corresponds for long observation periods to the groundwater runoff of a catchment area and consequently to the groundwater recharge. However, the recharge figures obtained through the use of the infiltration coefficient were incompatible to these of the groundwater runoff from the areas under study. In order to correct this, both the figure for the infiltration coefficient and soil classes had to be modified. Results of several analyses prompted the decision to change the infiltration coefficient for “very light soil” from 27 to 30%. It was also agreed that forest areas (Ls) with low soil thickness, previously classified as “medium soil”, should in fact fall into the “light soil” category. This resulted in the infiltration coefficient values for these areas having to be changed from 13 to 20%.

The final result of the second stage is a map of groundwater recharge for the whole of Poland.

In the third stage the reliability of the map was checked in particular 22 areas (test area – stage III). Detailed calculations were made for 22 river basins (whole Poland) with measured river flows in the years 1976–2005 (Fig. 3). Wundt’s method was applied to calculate groundwater runoff from the catchments.

Additional two statistical indicators have been applied to evaluate precision of the designed value of recharge and groundwater runoff. The first means the quotient of the module of the difference among the calculated values with the infiltration method (R) and the groundwater runoff (Qg) and groundwater runoff expressed in % [100 %(R-Qg)·/Qg]. This value is expressed as AV (absolute variability). The second one, specific difference (SD), is a quotient of the difference among the calculated recharge values evaluated by an infiltration method and groundwater runoff and the area of the river basin [(R-Qg)/A. It is expressed in l/s~km^2.

RESULTS AND DISCUSSION

Results of groundwater recharge acquired based on the revised infiltration coefficients (stage II – Methods) for the 15 river basins (Lower Silesia) were compared with the groundwater runoff recorded in these basins. Infiltration values calculated based

Table 2

Protective capacities of soil (*vide* Duda et al., 2011)

Soil protective capacity	Soil category	Soil type acc. to grain size group	Infiltration coefficient [%]	Water capacity [a] [-]	tg1m approximate time of water exchange in 1 m of soil profile [b] [years]
Very weak	very light	gravel soils, loose sands, slightly clayey sands, rocky soils, skeletal soils, sandy soils	30 (27*)	0.12	1.2
Weak	light	clayey sands, slightly clayey and clayey sands, Neogene rendzina soils, Jurassic rendzina soils, old-formation rendzinas, gypsum rendzina soils, sandy alluvial soils, muck and muck-like soils	20	0.17	1.7
Medium	medium	slightly clayey soils, silt soils, loess and loess-like soils, clay soils, powdery soils, Cretaceous rendzina soils, alluvial soils	13 (20*)	0.24	2.4
Good	heavy	clay: medium and powdery, heavy and powdery, silt loam, peat, silts and bog soils	8	0.36	3.6

a – average water capacity (natural volume of soil moisture); b – approximate time of water exchange was calculated for the average effective infiltration equal to 100 mm per year and based on the piston displacement model; (27*) value modified by authors

Table 3

Comparison of evaluated effective infiltration and groundwater runoff in selected river basins of Lower Silesia (test area – stage II)

No.	River	Gauge	Calculated infiltration [m^3/s]	Groundwater runoff [m^3/s]	Differences [m^3/s]	Absolute variability [%]	Infiltration coefficient [%]
1	Orla	Korzeńsko	3.08	1.76	1.32	75.0	16.2
2	Barycz	Osetno	15.54	7.52	8.02	106.6	20.0
3	Mała Panew	Staniszcze Wlk.	4.78	4.03	0.75	18.6	22.1
4	Biała	Dobra	1.16	0.68	0.48	70.6	16.3
5	Biała Lądecka	Lądek Zdrój	0.97	2.03	–1.36	67.0	20.2
6	Bystrzyca Dusznicka	Szalejów Dln.	0.67	1.3	–0.63	48.5	18.9
7	Nysa Kłodzka	Kłodzko	3.78	6.82	–3.04	44.6	18.1
8	Nysa Kłodzka	Skorogoszcz	15	17.31	–2.31	13.3	19.6
9	Oława	Oława	2.09	2.51	–0.42	16.7	11.9
10	Ślęza	Białobierze	0.52	0.24	0.28	116.7	15.3
11	Bystrzyca	Jugowice	0.46	0.52	–0.06	11.5	19.3
12	Bystrzyca	Krasków	2.17	1.61	0.56	34.8	17.3
13	Kaczawa	Świerzawa	0.4	0.6	–0.20	33.3	16.1
14	Czarny Potok	Mirsk	0.24	0.35	–0.11	31.4	20.3
15	Bóbr	Żagań	16.41	23.14	–6.73	29.1	20.1

on the infiltration coefficient method and those obtained usingWundt's method differ from each other by anywhere between –0.06 m^3/s and 8.02 m^3/s (Table 3). These discrepancies are a result of imprecise estimations of precipitation levels, which, in the uppermost regions of the Sudetes, are significantly higher than what the rates used for calculations might suggest. The Barycz River basin also appears to behave in an unusual manner, probably due to changes in its natural environment and the influence of pond management on runoff conditions.

The mean precipitation level in the tested area equalled 587 mm, while the average recharge, calculated through the infiltration coefficient method, was 109 mm. This means that recharge constituted 18.5% of precipitation. Calculations based on groundwater runoff yielded a similar result: 108 mm. In the whole Lower Silesia test area, the difference between recharge values calculated through the use of the infiltration coefficient and those based on groundwater runoff is only 0.7% (Staśko et al., 2012). This means that the values of groundwater recharge can be considered reliable on a regional scale.

The compatibility of groundwater runoff determined using the infiltration coefficient method in 15 river basins allowed for the creation of a map of groundwater recharge that would cover the whole area of Poland. Table 4 shows the portion of the area of Poland taken up by particular classes of infiltration. Figures obtained for particular calculated fields ranged from 42 to 229.5 mm. Figure 4 shows the results of these calculations in the form of a groundwater recharge map where each colour represents a different 25 millimetre bracket.

Based on the constructed map, the total groundwater recharge from precipitation in Poland was calculated at 34.118 km^3 per year, which equals 109.3 mm of water column. The recharge constituted 18.6% of average precipitation in Poland, which was calculated at 588.5 mm. This value does not differ much from the other sources (Jokiel, 1994; Duda et al., 2011). In the framework of the map of groundwater vulnerability to pollution in Poland 1:500,000, the total groundwater recharge was estimated at 31.515 km^3/year, which equals 102.2 mm (Duda et al., 2011).

In the third stage the resultant map of groundwater recharge was verified for areas of chosen river basins in Poland. Detailed calculations were made for 22 river basins (test area – stage III; Fig. 3) with known discharge rates in the years 1976–2005. The authors tried to verify the precision of the estimation of the recharge based on earlier 15 test river basins (test area – stage II). The recharge values obtained for 22 basins from the test area has been compared with the values of the groundwater runoff adequate to the catchment. Differences in the values of groundwater runoff and calculated recharge vary from 0.07 to 5.15 m^3/s, at the mean value – 0.18 m^3/s. This dependence shows similar differentiation as in the test area – stage II (Fig. 5).

In relation to the groundwater runoff, the absolute value of the difference between groundwater runoff and recharge (AV) ranges from 0.4 to 80.65% (Table 5), at the arithmetic mean 36.18% and the geometric mean 23.39%. In this way for 22 test river basins (test area – stage III) it is obtained the greater compatibility between the groundwater runoff and the calculated recharge than for the test area, where the average value of the deviation was 40.90% and the geometrical mean 28.46%. This confirms that constructed map of infiltration is respectable for the estimation of the groundwater recharge when evaluating in a small scale. The calculated effective infiltration values are higher that the measured values of the groundwater runoff in 10 cases. These are basins located in the upper courses of rivers, which

Table 4

Infiltration classes in Poland

Conditions of infiltration	Infiltration coefficient [%]	Area [km^2]	Percentage of total area of Poland
		3,444.80 (surface waters)	1.10
Poor	8	37,073.50	11.88
Medium	13	93,047.85	29.82
Good	20	74,096.07	23.74
Very good	27	104,421.81	33.46
	Total area	312,075.04	100

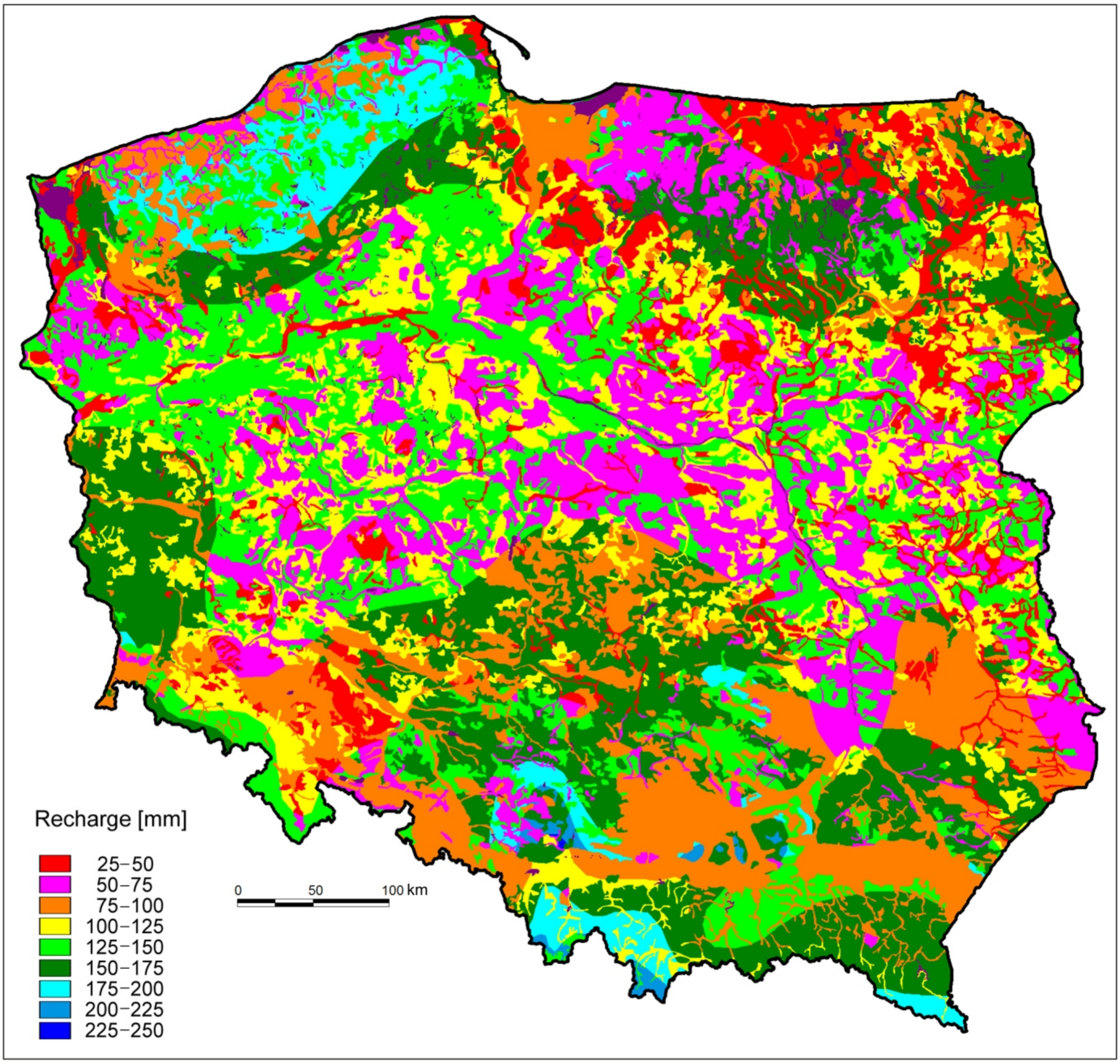

Fig. 4. Map of groundwater recharge in Poland, based on the infiltration coefficient method

could be explained by the prevalence of the deeper component of the water circulation (recharge area) in this part of the system. In catchments situated in lower river course according to the flow systems theory appear the aggregated groundwater resources. This explains why the calculated values are lower than the measured ones in this case. The final results for all the 37 river basins (test areas – stages II and III) are presented in Table 6.

As a consequence, in larger catchments with high values of reported runoff the discrepancies between evaluated recharge rates could be larger. Due to the size of the deviation of the calculated recharge and groundwater runoff reference to the magnitude of the catchment obtaining the specific difference (SD). In the test area –stage II (22 river basins), the specific difference varies from –3.48 to 2.54 l/s km^2 (Table 6), at the arithmetic mean 0.04 l/s km^2. Analysis of Figure 6 shows that specific differences have a similar value regardless of the area of the river basin. For the 70% of all 37 analysed catchments this value is lower from 1.5 l/s km^2. There is a lack of clear relationship between the specific difference and the groundwater runoff (Fig. 6).

GROUNWATER RECHARGE ESTIMATION

The groundwater recharge values for 22 river basins (test area – stage III) range from 93.1 mm (Ina River basin) to 179.3 mm (Skawa River basin) in the Carpathians. The average groundwater recharge was calculated at 125.7 mm, while the figure obtained through groundwater runoff was 129.6 mm (Table 5).

The average value of recharge rate for all 37 river basins (total area over 50,000 km^2) is 120.5 mm. The mean value of the infiltration coefficient is 19.73%.

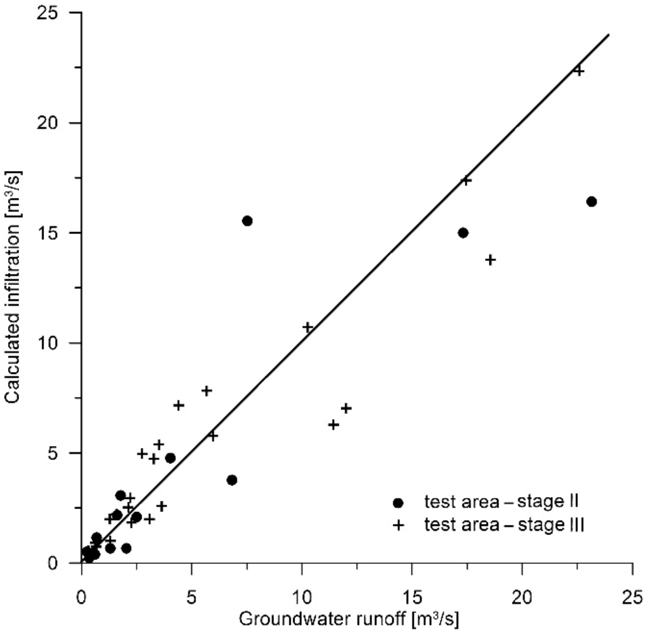

Fig. 5. The relationship between calculated infiltration (infiltration coeficient method) and groundwater runoff (Wundt method)

The results show conformity with research results in other countries. For example, lysimeter measurements of river and lake sediments show the wide range of the value from 1 to 3000 mm/year in Minnesota and Wisconsin, and from 12 to 122 mm/year in Nevada (*vide* Scanlon et al., 2002). Using the hydrograph separation method obtained recharge value from 127 to 635 mm/year for rivers basins of the eastern USA (Rutledge 1998, *vide* Scanlon et al., 2002). Uddameri and Kuchanur (2006), in turn, applying the modelling of the water balance show low magnitudes of the recharge in south Texas within the range from 0 to 15.2 mm/year. Applying isotope technique (tritium injection) it has been reported at the foot of the Himalayas that within a period of monsoonal rains the range of the infiltration 3–13% of precipitation (Israil et al., 2006). Research of recharge in India performed by means of indicatory methods showed values from 3–10% (20–50 mm) of annual precipitation in the Western Rajasthan to 12–20% (120–200 mm) in Uttar Pradesh, Punjab, and Haryana (Sukhija et al., 1996). The coastal areas of Pondicherry and Neyveli have an average recharge rate of about 15–25% (200–300 mm). In the basaltic and granitic-gneissic rocks the natural recharge rate has been evaluated as 3–15% (20–100 mm). In the Germany and the Netherlands with similar climatic conditions like in Poland, the groundwater recharge is 135 mm to average annual precipitation equal 859 mm (Zingk, 1988; Otto, 2001).

Additionally, results of the calculation have been compared with published data from numerical modelling evaluation and selected data published from Poland, Germany, USA, India and

Table 5

Comparison of infiltration values and groundwater runoff in the test area – stage III

No.	River	Gauge	Calculated infiltration [m^3/s]	Groundwater runoff [m^3/s]	Absolute variability [%]	Specific difference [$l/s \cdot km^2$]	Infiltration coefficient [%]
16	Gwda	Piła	22.34	22.58	1.1	–0.05	24.8
17	Drawa	Drawsko Pomorskie	2.59	3.64	28.8	–1.72	19.9
18	Ina	Goleniów	6.28	11.43	45.1	–2.42	16.2
19	Słupia	Słupsk	7.03	12	41.4	–3.48	23
20	Warta	Działoszyn	17.38	17.45	0.4	–0.02	22
21	Prosna	Mirków	4.97	2.75	80.7	1.78	21.7
22	Noteć	Pakość	7.16	4.41	62.4	1.26	19.8
23	Reda	Wejherowo	2	3.09	35.3	–2.77	23.9
24	Bukowa	Ruda Jastkowska	2.97	2.2	35.0	1.18	24.8
25	Pisa	Ptaki	13.77	18.55	25.8	–1.34	19.8
26	Liwiec	Lochów	7.82	5.68	37.7	0.87	19.1
27	Biała	Grybów	0.92	0.62	48.4	1.46	19.2
faul t28	Skawa	Jordanów	0.56	0.31	80.6	2.54	18.9
29	Łososina	Piekiełko	0.74	0.66	12.1	0.52	18.5
30	Skrwa	Parzeń	5.39	3.51	53.6	1.21	20.9
31	Kamienica	Nowy Sącz	1.01	1.3	22.3	–1.22	19.3
32	Świder	Wólka Młądzka	2.53	2.11	19.9	0.50	18.2
33	Orzyc	Krasnosielsk	4.74	3.28	44.5	1.14	20.6
34	Brzozówka	Karpowicze	2.22	1.58	40.5	0.98	18.7
35	Nurzec	Boćki	2	1.27	57.5	1.34	22
36	Wierzyca	Bożepole Szlacheckie	1.84	2.26	18.6	–1.04	24.3
37	Pilica	Przedbórz	10.71	10.26	4.4	0.18	22.7
Groundwater recharge [mm]			125.7	129.6			

Table 6

Statistical data of infiltration and groundwater runoff values in 37 chosen river basins

	Groundwater runoff [m^3/s]	Calculated infiltration [m^3/s]	Difference [m^3/s]	Absolute variability [%]	Specific difference [l/s·km^2]	Infiltration coefficient [%]
Min.	0.24	0.24	–6.73	0.40	–3.48	11.9
Max.	23.14	22.34	8.02	116.67	2.54	24.8
Mean	5.44	5.24	–0.20	40.91	–0.36	19.73
Geometric mean	2.70	2.78	–	28.46	–	19.53
Standard deviation	6.46	5.70	2.49	27.09	2.09	2.75
Mean deviation	5.02	4.43	1.60	21.00	1.61	2.06

Ghana (Table 7). Most of the calculated groundwater recharge values with numerical modelling techniques are in the range of 40–150 mm (12–25% of precipitation), especially in the low-lying part of the country (Table 7). The low value in central Poland (Dąbrowski et al., 2007) is associated with the lowest precipitation in the Mazovia region and the marsh zones (Krogulec and Zabłocki, 2015). As indicted in most modelling studies in the northern and central part of the country, the effective infiltration values are in the range of 90–160 mm, with some deviations in the lakelands. Exceptionally high values are reported as 15–43% of total precipitation for municipal terrains under deep mining impact (Kowalczyk, 2005). In the southern uplands and mountainous areas the reported values are 120–265 mm. Evaluation of the groundwater resources also indicates the effective infiltration of 18% (Herbich and Skrzypczyk, 2015).

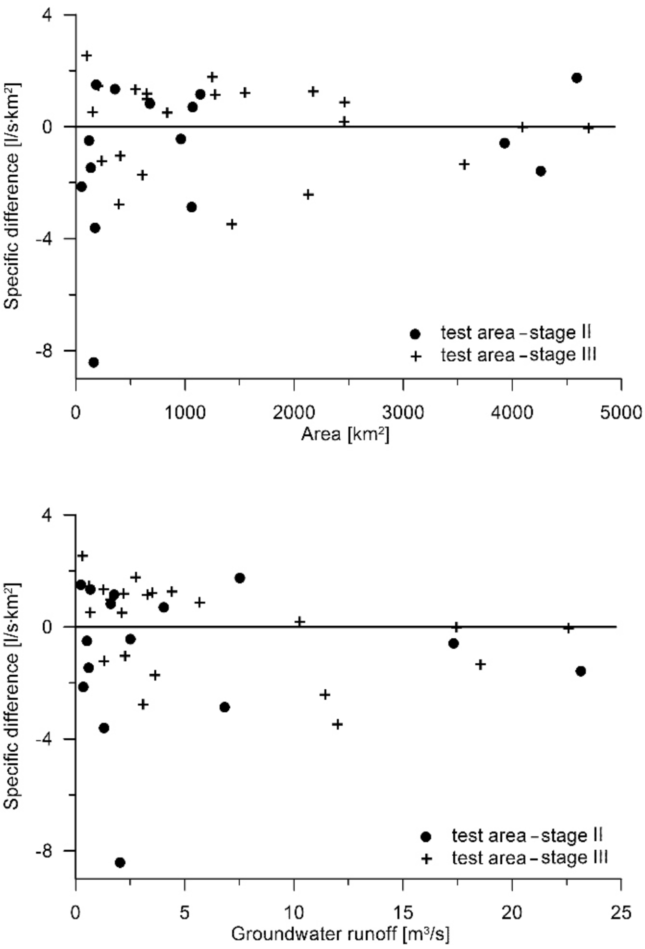

Fig. 6. Illustration of the specific differences between the calculated infiltration and groundwater runoff in 37 chosen river basins

CONCLUSIONS

Due to the high variability of physical and climatic conditions in Poland, many different methods have been employed to assess the groundwater recharge of particular river basins. However, the evaluation of recharge on a smaller scale, such as that of the whole country or large river basins, requires the use of a single method. Applying a modified version of the effective infiltration coefficient method for whole Poland has proven an efficient way of assessing the effective infiltration equivalent to groundwater recharge. The modification of infiltration coefficient values for light soil and forest areas allows a high compatibility of results with groundwater runoff measurements. Results of observations carried out in Lower Silesia and other parts of Poland show groundwater recharge rates ranging from 42 to 229.5 mm, constituting 16.2–24.8% of total precipitation. Assuming the average precipitation levels in Poland to be around 588.5 mm (183.43 km^3), the groundwater recharge constitutes 18.6% of precipitation (109.3 mm of water column). Finally, groundwater recharge in Poland after recalculating equals 34.118 km^3 per year. The obtained value is close to the average multi-year value of the groundwater runoff (Herbich and Skrzypczyk, 2015). Despite the simplified calculation methods the authors obtained results that are similar to other calculations, which are based on data pertaining to precipitation, soil type, land use, topography of the area, and depth to the groundwater. However, field observations and lysimeter measurements in mountainous areas indicate that, in reality, these figures are much higher and can reach 50%.

This study shows that the application of a simple scheme based on properties of the soil cover and the precipitation distribution are reliable for groundwater recharge evaluation on a small scale. This has also an important practical meaning. Conversely as reported some attempts of the regard in the analysis of the recharge the greater number of factors results not necessary in precise values of this parameter. For example, the map of groundwater vulnerability by Duda et al. (2011) illustrates that arbitrary introduction of the values of land use, topography, and depth to the groundwater did not provide better results. For the same of 22 river basins which are analysed in the cited work the outcomes showed average deviation of the calculated recharge value around –0.94 m^3/s, so passed five times higher than in the propos method. They also obtained a repeatedly higher value of the individual deviation, amounting to

Table 7

Values of the groundwater recharge/infiltration evaluated based on numerical modelling

Location	Precipitation [mm]	Aquifer: age and type of rock medium	Recharge [mm]	Infiltration [%]	Authors
Kaszuby Lake District	652	Quatern. sand. gravel	147	22.5	Jaworska-Szulc (2015)
Chełmińskie Lakeland	500–610	Quatern. sand, gravel	40–90	12	Pomianowska (1999)
Odra River valley		Quatern. sand, gravel	52–84	14	Gurwin (2000)
Wisła River valley	539	Quatern. sand, gravel marsh zones	29-105 50	5–19 9	Krogulec (2004); Krogulec and Zabłocki (2015)
Central Poland	616	Quatern. sand, gravel	37	6	Dąbrowski et al. (2007)
Odra River near Wrocław	600	Quatern. sand, gravel	116–160	19–26	Krawczyk et al. (2015)
Łódź Basin	600	Cretaceous, sandstone, limestone	144	24	Rodzoch and Pazio-Urbanowicz (2015)
Carpathian flysch, Tylicz region	848	Paleogene, sandstone, shale	179	21	Porwisz et al. (1999)
Sudetes Cretaceous basin	813	Cretaceous, sandstone	119–265	15–32	Korwin-Piotrowska et al. (2014)
Upper Silesia	779–864	Triassicl, imestone	39–155	5–19	Kowalczyk (2005)
Germany (Schleswig-Holstein region)	859	sand, sandstone, granite etc.	100–300	16	Zingk (1988); Otto (2001)
NW India (semi-arid regions)	500–1000	sand, gravel, sandstone	20–200	3–20	Sukhija et al. (1996)
USA (eastern states)	241–1618	sand, sandstone, limestone, basalt tuff	2.9–191	1–12	Rutledge (1998)
North Ghana (tropical areas)	900–1200	mudstones, siltstones, sandstones	81–252	0.9–21	Menash et al. (2014)

–0.68 l/s km^2. This proves that the accuracy of the average value of groundwater recharge decreases with increasing number of factors influencing the infiltration process.

Acknowledgements. The data presented in this study are a result of observations conducted as part of the statutory research carried out at the Institute of Geological Sciences, Wrocław University, within the framework of project 1017/S/ING/10, titled “The processes of recharge, flow and drainage of groundwater”. The authors express their profound gratitude to all the reviewers (B. Jaworska-Szulc and two anonymous reviewers) for their insightful comments and important suggestions.

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