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Managing aquifer recharge

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Groundwater recharge is an important issue considering water management and water quality protection from land surface. Groundwater recharge assessment methods could be divide into several groups: water balance, lysimeter, isotopic techniques, numerical modeling, heat transport or water level fluctuations or hydrograph separation method. Water balance methods despite knowledge on precipitation distribution require assessment of evapotranspiration what creates difficulties. Lysimeter measurements are expensive point field experiment and allow precise calculations in shallow zones. Isotopic techniques like heat transport provide good results in local scale and does not include regional variations. Method of water level fluctuation despite having long series of observation needs assumption the constancy of parameters aquifers. For regional evaluation of special important are numerical modeling methods, based on the flow system analysis, as well as the method of hydrograph separation what illustrating the final effect of the effective infiltration and covering the whole study area (Brodie, Hostetler, 2005). An overview of process and techniques could be found in many papers summarized for example in Pleczyński (1981), Pazdro and Kozerski (1990), de Vries and Simmers (2002), and Scanlon et al (2002).

In Poland, most of these methods are applied and especially water balance (for example Pleczyński, 1981). In groundwater resources documenting process the most appropriate and recommended are method of water balance and effective infiltrate based mainly on permeability of surface rocks (Paczyński, 1995, Instruction) associated with methods of long-term pumping tests results and more popular numerical modeling.

Poland, located in moderate climatic condition, receives low annual amount of atmospheric precipitation as average equals 600 mm. Only in southern part within Carpathian and Sudeten Mountains rainfall up to 1200-1400 mm is reported. According to normal evaluated value of the effective infiltration only 18.2 % of this amount renew country groundwater resources (Pazdro, Kozerski, 1990). However a significant spatial and temporal variability is observed.

Evaluation of groundwater recharge has been calculated during Groundwater vulnerability map of Poland elaboration (Duda et al., 2007). Considering the amount of water entering shallow groundwater system two methods of recharge has been tested. Effective infiltration method has been selected and next base flow analysis used as a verification method. In first method infiltration coefficient of annual rainfall has been assigned for different soil types based on moisture capacity and permeability of top soil detailed maps.

EFFECTIVE INFILTRATION METHOD

One of the basic methods of assessing renewable groundwater resources (equals groundwater recharge) is the designation of the amount of water to the top soil through a effective infiltrate. This method assumes that part of precipitation infiltrating actually to aquifers, and finally flow to the rivers, lakes or the sea. The quantity of water entering into the aquifers called effective infiltration is expressed as water column height in relation to average annual rainfall in long term condition. Calculation of recharge in the area can be performed based on geological maps. On such map class of infiltration area is designed in first stage. There are several classification of top soils on the basis of which such division is made. They include proposal by: Pazdro and Kozerski (1990), Paczyński (1995), Schneidera i Züschang'a (vide Załuski 1973), Singh (2003), Wright et al. (1982) and Daly (1994).

In Pazdro and Kozerski (1990) approach effective infiltration in range 0.05–0.3 has been assumed as permeability (or stsrativity) for different types of rock. Similar approach adopts Wright et al. (1982) but value indicators are higher. For example it 0.2 for poorly permeable clay rocks, 0.5 to 0.8 for sand clay soils and high permeable sand and gravel. In turn, Daly (1994) proposes infiltration 0.3 for thick clay sediments, and 0.6 for thin clay layers and 0.9 for thin permeable soils developed on carbonate karstic rocks. Both of these examples use values infiltrate concern areas of Ireland, where high average precipitation (from 750 mm for areas area to 1600 mm) and evaporation (500–575 mm) are reported.

In Poland in general this method has been used to lowland terrains and was adopted by Pazdro and Paczyński (poz. cit). However, it was also adapted this method for foreland of mountain (Tarka, 2001) or mountainous terrains (Duda et al., 2006).

For example, for the purposes of modeling research in the catchment of the River Raba in Carpathian flisch sandstone series 0.11 effective infiltration and 0.165 and flisch series of mudstone shale. (Duda et al., 2006).

To design value of infiltration, also map of top soil could be applied, because soil type and genesis is function of geological build up and climatic conditions. Hence there is a direct relationship between rock properties development and granular soil types. This relationship was applied when creating an elaborate layers of information to the Groundwater vulnerability map on pollution from land surface in scale 1: 500,000 (Table 1).

Table 1. Characteristic protection properties of soil (Witczak et al., 2003; Duda et al., 2004) modified.

Protection ability of soil	Soil category	Granular group (according to soil classification)	Infiltration coefficient [%]	Field water capacity as volume [a)]	t_{g1m} Mean residence time in 1m soil profile [years]
Very low	Very light	Sand: loose, loose dusty, poorly loam and dusty	30 (27*)	0.12	1.2
Low	Light	Sand: loam light, strong, dusty and dusty sand	20	0.17	1.7
Medium	Medium	Clay light and dust loam	13(20*)	0.24	2.4
Good	Heavy	Clay: average and dusty, heavy and silt particles	8	0.36	3.6

(27*) modified value.

Application of soil or geological maps, as the experience is very similar to its assessment of renewable groundwater resources (Tarka, 2001). For example, for the eastern and central parts of North Sudetes Syncline, where Cretaceous rocks are the main the main geological formation, comparison of renewable groundwater resources has been discussed based on an analysis of geological maps 1: 50 000 (Szałamacha, Milewicz, 1988) and soil maps 1:300 000 (Musierowicz et al., 1960) i 1:500 000 (Pawlak et al., 1997).

Obtained results indicated effective infiltration as 134.7 and 116.8 mm respectively despite application of different layers of land cover (Tarka, 2010).

Evaluation of groundwater recharge with effective infiltration method required assessment of the average annual precipitation for calculated fields. Then designated surfaces area of the classes representing different infiltration values is calculated in the precipitation region. On this basis calculated weighted value of infiltration is designed for each precipitation area as follow:

$$\alpha_r = \frac{\sum_{i=1}^{n} \alpha_i \cdot A_i}{\sum_{i=1}^{n} A_i} \qquad (1)$$

where: α_r — average effeective infiltration for selected area of precipitation r, α_i — infiltration coefficient for i — selected soil region in precipiatation area, A_i — surface area i-soil type [L^2] in precipitation arrea r.

The total infifltaration is the sum of the recharge evaluated for individual regions:

$$R = \frac{\sum_{r=1}^{m} \alpha_r \cdot P_r \cdot A_r}{A} \qquad (2)$$

where : P_r — average precipiatation amount in precipitation region r [L], A — surface area of study region [L^2], m — number of selected precipiataion regions.

At the construction of the map of groundwater recharge, for Lower Silesia region, in order to select clases of infiltartion the numerical map of soil in the scale 1:500 000 performed by the Institute of Soil Sciences and Plant Cultivation in Puławy (Musierowicz et al., 1960) has been used. In the first stage we accepted clases of the infiltration for individual soil types in compliance with Table 1 and with orders to the Map of the groundwaters vulnerability to pollution in the scale 1:500 000 (Witczak et al., 2003; Duda et al., 2004). Calculations were performed for 15 catchments (basin) with different surface area and the height of the position and the geological buil-up (Fig. 1). Tested area covers surface almost 17000 km2.

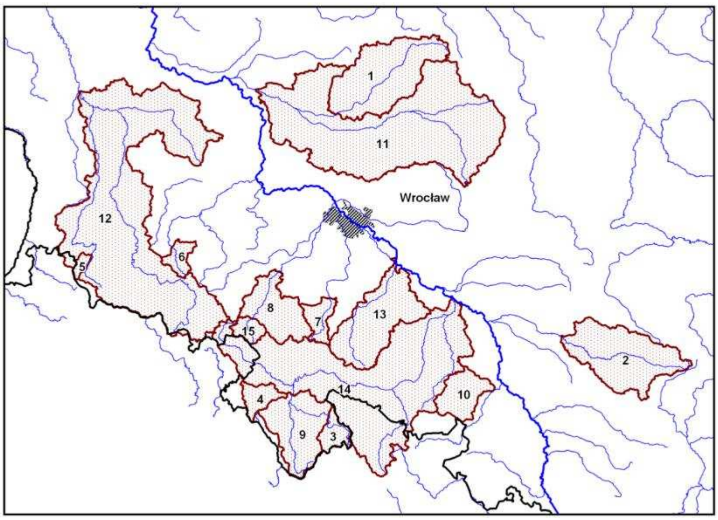

Figure 1. Localization of tested catchmentt areas in Lower Silesia region (number according Table 2.).

Precipitation were accepted on the basis of the Atlas of the climate of Poland (Lorenc, 2005). The estimated value of infiltartion has been verified based on measuerd values of groundwater base flow in basins.

The groundwater run-off from the catchment was evalualted by means of methods Wundt method (Jokiel, 1994) for periods 1976–2005, based on low monthly flows rates in selected rivers. In several cases were analysed smaller basins. In the first stage of calculations obtained results was not directly corresponding to the basin areas. In next the steppe values of effective infiltration has been corrected that change of categories of selected soil properties in the order are obtain the conformity with evaluated values of the groundwater base flow. As a result modification of the category of soil „very light" with 30% on 27% and to change classifying of forest-(Ls) areas from the category of average soil on light what provide effective infiltration value the change from 13% to 20%.

Received close results with both methods for 9 catchment. The difference among the appointed groundwater base flow and magnitudes of recharge amounts from 13% to almost 117%. Greater divergences appear in small mountainous basins (Fig. 1). It could be explained by under estiamation of rainfalls which in top-parties of Sudeten are higher than accepted to calculations. The difference appears in the Baryczy river basin (No. 11) are connected with the considerable degree of the transformation of the basin (the fishery pond). For remaining basins (No. 1, No. 7 and No. 10) it could be explain with the divergence among properties of soils and rocks represented in this scale and inter basin water exchange. Nevertheless for the all test-area the difference among the evaluated recharge with the method of the effective infiltration and the ground run-off method amounts only 0.7%.

With the method of the effective infiltration obtained results for whole region the average recharge in the amount of 109 mms for average annual precipitation equals 587 mms while the method of the groundwater base flow showed 108 mms. Recharge states so as average 18.5% of precipitation. It allows quite good conformity of results what permits this to accept obtained the map of effective infiltration as reliable in the regional scale.

Another example is groundwater modeling technique, as a recommended method when water resources are evaluated in regional scale. Results of such research showed low values in range 52-84 mm/year for Quaternary aquifer system (Gurwin, 2000). In central part of Poland where the lowest values of rainfall are recorded groundwater recharge values 11-80 mm has been reported by Dąbrowski et all (2007) for deeper Tertiary aquifer.

Special case is recharge in mountainous region of the Sudety Mountains (Staśko et al 2010). Recent study on recharge in small and medium mountainous hard rock catchment (7-160 km^2) in Sudeten Mountains in SW Poland characterized by moderate to cold mountainous climate with mean precipitation 1360 mm/y showed interesting results.

Table 2. Comparison of evaluated effective recharge and base flow in selected river basins of Lower Silesia.

Watershead number	River	Measuring point	Surface areas of subbasins	Surface area	Flow as average	Base flow	Groundwater run-off	Infiltration in subbasins	Infiltration in basin	Difference	Base flow IMGW*
			[km²]	[km²]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[%]	[m³/s]
						Wundt's method	Effective infiltration method				
1	Orla	Korzeńsko	1143.7	1143.7	4.42	1.76	—	3.08	3.08	75.0	1,25
11	Barycz	Osetno	3438.5	4582.2	12.22	7.52	7.52	12.46	15.54	106.6	8,19
2	Mała Panew	Staniszcze Wlk.	1066.6	1066.6	6.90	4.03	4.03	4.78	4.78	18.6	4,61
10	Biała	Dobra	357.6	357.6	1.13	0.68	0.68	1.16	1.16	70.6	—
3	Biała Lądecka	Lądek Zdrój	161.2	161.2	3.37	2.03	—	0.67	0.67	–67.0	3,06
4	Bystrzyca Dusznicka	Szalejów Dln.	173.9	173.9	2.26	1.30	—	0.67	0.67	–48.5	1,21
9	Nysa Kłodzka	Kłodzko	722.1	1057.2	12.93	6.82	—	2.44	3.78	–44.6	10,59
14		Skorogoszcz	3497.0	4554.2	33.89	17.31	17.31	11.22	15.00	–13.3	28,21
13	Oława	Oława	959.2	959.2	3.88	2.51	2.51	2.09	2.09	–16.7	2,65
7	Ślęza	Białobierze	186.1	186.1	0.48	0.24	0.24	0.52	0.52	116.7	0,30
15	Bystrzyca	Jugowice	120.6	120.6	1.33	0.52	—	0.46	0.46	–11.5	0,77
8		Krasków	555.4	676.1	4.32	1.61	1.61	1.71	2.17	34.8	2,83
6	Kaczawa	Świerzawa	136.2	136.2	1.18	0.60	0.60	0.40	0.40	–33.3	0,52
5	Czarny Potok	Mirsk	51.1	51.1	0.90	0.35	—	0.24	0.24	–31.4	0,35
12	Bóbr	Żagań	4192.3	4243.4	37.93	23.14	23.14	16.17	16.41	–29.1	30,55
		Sum	16761.5				57.64	58.06		0.7	
					Recharge [mm]		108.4	109.2			153.6

* Dubicki (ed.) 2002

Four recharge assessment methods were applied: (1) lysimeter infiltration; (2) groundwater drainage by gallery; (3) river baseflow; (4) groundwater table fluctuation method. The obtained results showed that: (i) the recharge had an impulse character and was largely temporally variable; (ii) different methods of recharge assessment resulted in different recharge estimates mainly due to different spatial scales of assessment and different rainfall contributing areas; (iii) except of lysimetric method, the recharge-to-rainfall ratio was consistent and was estimated as ~50% of precipitation; such large recharge–to–rainfall ratio, was mainly due to high all year round soil moisture status and low 1–3 m thickness of weathered deposits implying relatively low soil retention capacity; (iv) the groundwater residence time was approximately 7–10 years as defined by tritium isotopic sampling and model simulation; (v) the investigated aquifer of this study, as many other mountainous hard rock aquifers, receives large quantity of recharge that results in significant groundwater flow; despite relatively low transmissivity that groundwater flow is efficiently transferred through the aquifer system to drainage lines (rivers and streams) and drainage points (springs) mainly thanks to large hydraulic gradients, typical for mountainous catchments (Staśko et al., 2010).

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