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The Groundwater Runoff of Polish Rivers

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The groundwater runoff of Polish rivers displays considerable regional variations which are also manifested in the time distribution. The spatial distribution depends upon geological structure of the area. Its characteristic features together with precipitation account for conditions of groundwater runoff based on permeability and natural drainage. The time and spatial variability of groundwater runoff is due to a joint effect of environmental and hydroclimatologic factors such as rainfall, snowmelting, evaporation.

Introduction

The groundwater runoff is the part of the total river runoff which is discharged from the potamic aquifers lying in the zone of exchange with surface waters; potamic aquifers being defined as aquifers with flowing groundwater. So the groundwater runoff is a link in the hydrologic cycle fed by precipitation.

Genetic separation of the hydrograph has been chosen from among various techniques for groundwater component estimation (Kudelin 1960, 1966 and Natermann 1958).

The annual value of the groundwater runoff was estimated on the basis of the diagrams of the daily river runoff, 24-hour air temperatures for the winter period and the daily rainfall.

The criteria for the estimations are the following:

1) the line of the total runoff coincides with the line of the groundwater runoff during periods when the river is recharged exclusively with groundwater. Those periods are: the total and partial freezing of the river, the air temperatures being below 0°C.

2) the river runoff is identified with the groundwater runoff during summer periods with no rainfall, on the grounds that sporadic low summer rainfall does not cause the increase in the river runoff, due to evaporation and transpiration.

3) during the high water periods, the border line between the groundwater runoff and surface runoff is established by means of separating the base of the flood wave.

The number of the river ganging stations under investigation totalled 169. The research material covered the control of the groundwater runoff, the total area of which corresponds to 80 per cent of the territory of Poland.

The knowledge of the hydrogeological conditions of the remaining 20 per cent of the territory allows to extrapolate average values on to the neighbouring non-controlled areas.

Groundwater runoff estimations cover the period 1951-1970, thus the values obtained can be regarded as normal.

The basic numerical characteristics will represent different morphological types of catchment basins displaying spatial and time variations of the groundwater runoff in Polish rivers. The results of earlier investigations allow to conclude that the groundwater runoff in Poland shows regional variability due to the resources of the potamic aquifers which, in turn, depend upon precipitation, configuration and permeability of surface formations covering the catchment area. A distinct interrelation between the groundwater runoff and the geological structure of the area urged us in the interpretation of the results to take into account the geological and morphological types of catchments shown in Fig. 1 and Table 1. Each of the above types differs in geological structure, permeability, storage capacity and recharge.

Numerical Characteristics of Groundwater Runoff

The knowledge of long-term annual averages for the groundwater runoff is based on five basic characteristics:

a) storage capacity of the catchment basin expressed as coefficient m which is the ratio between the maximum and minimum monthly means of the groundwater runoff,

b) groundwater runoff modulus q ($1/s/km^2$),

c) ordinary coefficient of variability C_v calculated as the difference between the extreme values of monthly means; divided by the groundwater runoff modulus

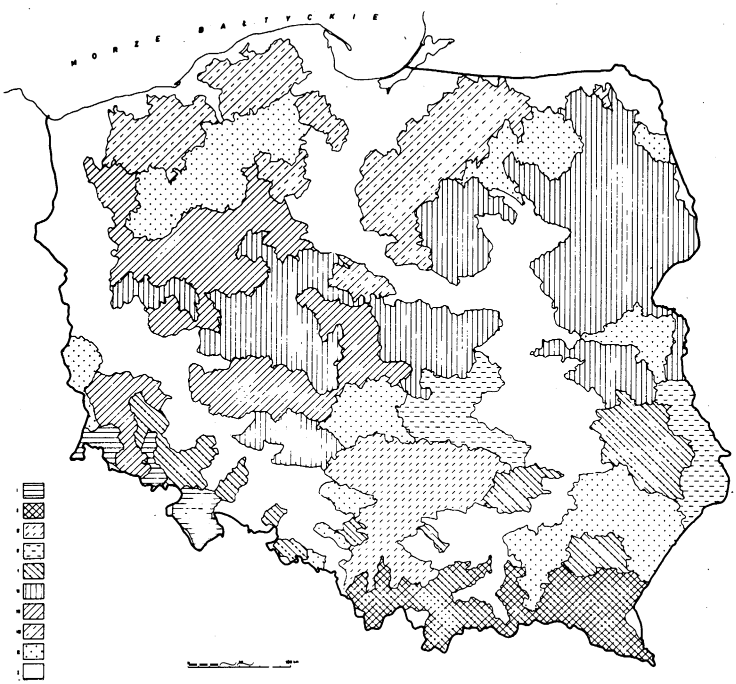


Fig. 1. Catchment basin types.

d) groundwater discharge coefficient α equal to the quotient between the groundwater runoff by the total runoff in per cent;

e) groundwater runoff coefficient β equal to the quotient between the groundwater runoff and the rainfall in per cent.

An adequate interpretation of numerical characteristics of groundwater runoff should be based on the above morphological types, chosen to fit the spatial variability of the basin hydrogeological nature. The histogram method has been used with a view to show variations in the values of the five basic characteristics of the groundwater runoff (Fig. 2 a-e). This method is extremely expedient for revealing regional variations in the values of numerical characteristics. Many authors have discussed the problem of regional variations in the groundwater runoff for Polish rivers. Their conclusions - very much in accord - stress that these variations are controlled by the interrelation of climatic and geomorphological-hydrogeological conditions.

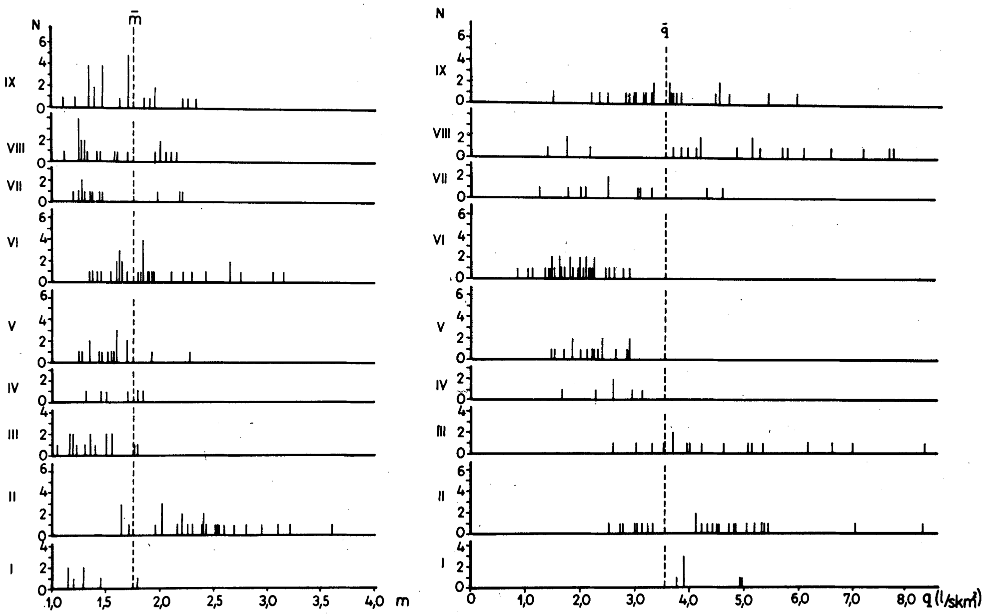
The present paper makes an attempt to find a connection between the catchment basin type and particular numerical characteristics in order to establish regional variations or similarities. This can be achieved on account of a certain regularity which has been observed in the record of mean and extreme characteristics of particular catchment types (Table I).

Table 1 - Basic characteristics of groundwater runoff in the chosen types of catchment basins

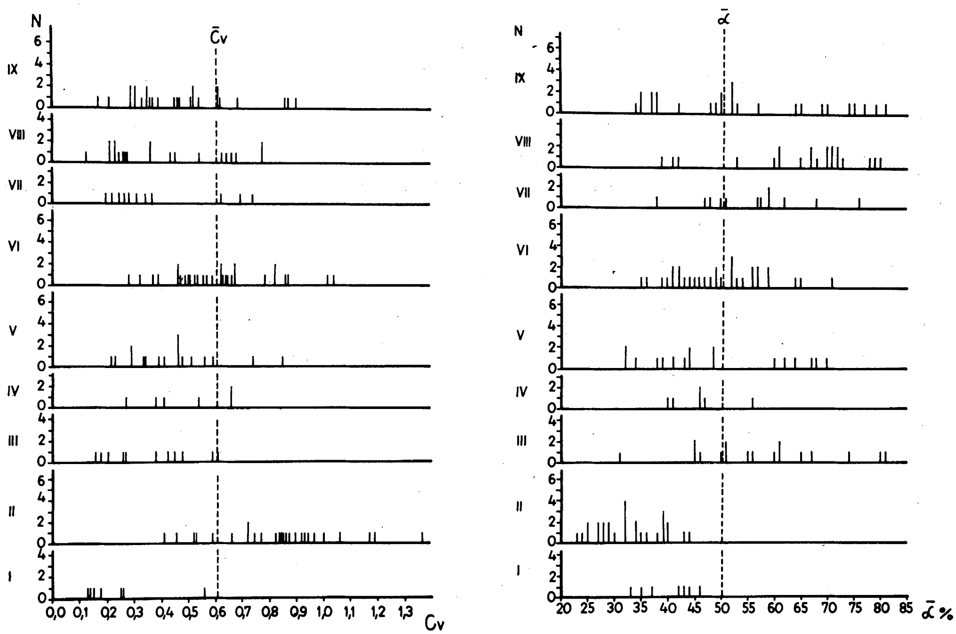
NN	Catchment basin type	$m=\frac{q_{max}}{q_{min}}$	q (l/s/km²)	$c=\frac{q_{max}-q_{min}}{q}$	$\alpha=\frac{q}{q_t}$ %	$\beta=\frac{q}{P}$ %
I	Catchment basins of the areas with discontinuous folded structure	1,78 - 1,14	4,74	0,560 - 0,130	*40*	18,4
II	Catchment basins of the Carpathian flysch areas	3,60 - 1,63	4,69	1,365 - 0,404	*33*	15,0
III	Catchment basins of the areas with prequaternary sedimentary rocks and with karst phenomena	1,78 - 1,18	4,75	0,613 - 0,160	*57*	20,6
IV	Catchment basins of the areas with prequaternary sedimentary rocks with till cover	1,84 - 1,31	2,54	0,658 - 0,273	*46*	12,0
V	Catchment basins of the areas covered with loess and loess-like formations on solid bedrock	2,26 - 1,25	2,21	0,854 - 0,216	*48*	10,7
VI	Catchment basins of moraine areas of older glaciations	3,05 - 1,33	1,82	1,036 - 0,283	*50*	11,0
VII	Pradolinas catchment basins	2,21 - 1,20	2,77	0,742 - 0,196	*56*	15,0
VII	Last glaciation catchment basins	2,15 - 1,12	4,94	0,775 - 0,126	*67*	24,0
IX	Catchment basins of sandy and sandy-gravel formations, as well as catchment basins of the areas of fluvioglacial and river accumulation	2,32 - 1,12	3,53	0,901 - 0,169	*54*	17,0

The storage capacity of the catchment basin may be expressed numerically by a monthly dynamics factor (Orsztynowicz 1971). This coefficient gives an idea of an average annual increase in the groundwater runoff. The above characteristics is usually based on extreme values of the groundwater runoff without taking its spatial distribution into account which can be seen in Fig. 3 of the present paper. To catchment areas of extremely great or fairly large storage capacity we can assign the Sudeten region with discontinuous folded structure, I, catchments with deeply reaching karst, III, as well as those of young glaciation with lakes, VIII, and sandrs, IX.[1] A smaller

[1] the alluvial plain formed by fluvioglacial streams which carry away the gravel-sandy material of the moraine and deposit it over a considerable area; the coarser material is deposited near to the glacier, the finer material farther away. (A Dictionary of Geography, W. G. Moore, 5th edition, Penguin Books, 1974).



(a) Storage capacity of catchment basin. (b) Groundwater unit runoff modulus.



(c) Coefficient of groundwater runoff variation. (d) Groundwater recharge coefficient.

Fig. 2. Characteristics distribution.

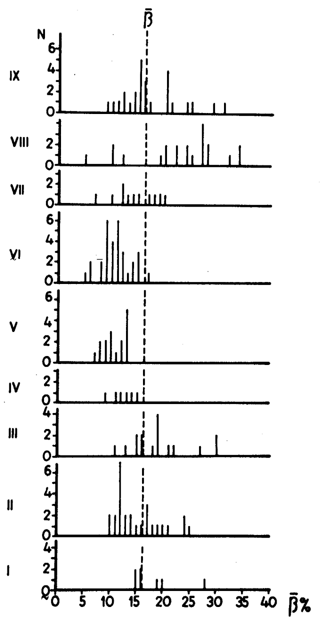


Fig. 2. Characteristics distribution.

(e) Groundwater runoff coefficient.

storage capacity, showing an average of about 1.7 can be observed in loess catchment areas on solid bedrock, V, in pradolinas, VII[2] and in moraine basins of old glaciation, VI. Detention is at its lowest in the mountain catchments of the flysch Carpathians, II[3] as well as in some moraine areas of older glaciation, VI. Using the coefficient value as a numerical criterion one can distinguish similarities, which allow to discriminate the karst, pradolinas and loess basins together with those made of prequaternary sedimentary rocks with moraine cover as the most uniform and homogeneous groups. In each group, they seem to have fairly uniform conditions of groundwater recharge. The greatest variations are to be found in flysch basins, moraine catchments of older glaciation and sandr-sandy ones. Here, coefficient m fluctuation range exceeds 1.3. The storage capacity of a basin is accounted for by the groundwater recharge conditions, especially by rainfall variations and hydrogeological and morphological structure of the area. The storage capacity can also be affected by the basin surface area, which is illustrated by the distribution of the lowest value of $m = 2.98$, as exhibited in small mountain and some lowland basins.

Spatial variations in storage capacity as observed in Poland are due both to geological and geomorphological characteristics of the areas and to the spatial distribution of

[2] wide valleys running evenly with a parallel of latitude, formed during the stability periods of the glacier. (Other names: spillway, ice-marginal valley ur urstromtal, German.)

[3] a series of sediments composed of alternate layers of clayey rock, clay or marl shales, formed during the process of the Carpathian uplifting in the upper Cretaceous period and the lower Tertiary.

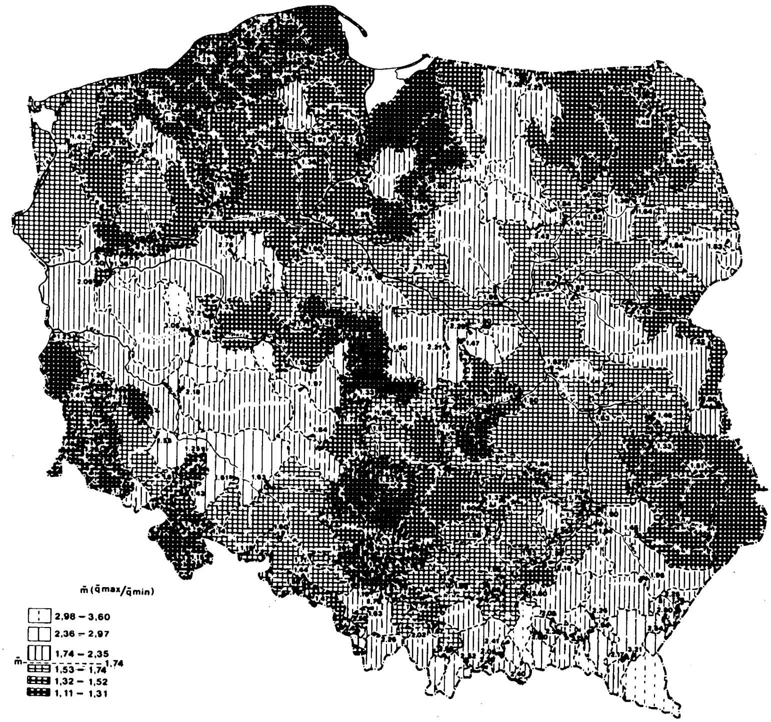


Fig. 3. Storage capacity of catchment basin.

rainfall, which is the main source of recharge. The effect of particular physic-geographical elements such as forests, lakes, bogs is felt fairly much; they can reduce or increase the storage capacity, and also they interfere with detention uniformity of different regions.

Mean groundwater runoff and its variability. The groundwater runoff modulus, which is understood as the mean value of the unit runoff (l/s/km^2), is the basic numerical characteristic to be found on most of the maps. Poland displays fairly well-defined zones of groundwater recharge arranged almost in parallel (Fig. 4). The highest values of groundwater runoff are recorded in the north and south of the country, $q>4{,}0$ *l/s/km*^{2}, while the lowest are found in the middle belt $q<1.73$ l/s/km^2. Alongside the general zonation of the basic groundwater recharge parameter, there is regional differention due to particular basin types. By correlating convergence of the features controlling the groundwater runoff in particular catchment types with numerical characteristics, we can determine analogies and differences in the groundwater runoff values.

The highest groundwater runoff values ($q>4.1$ l/s/km^2) are observed in the basins of the Sudeten region with discontinuous folded structures, I, in those of young glaciation, VIII, as well as in the karst areas and in the Carpathian flysch. The groundwater

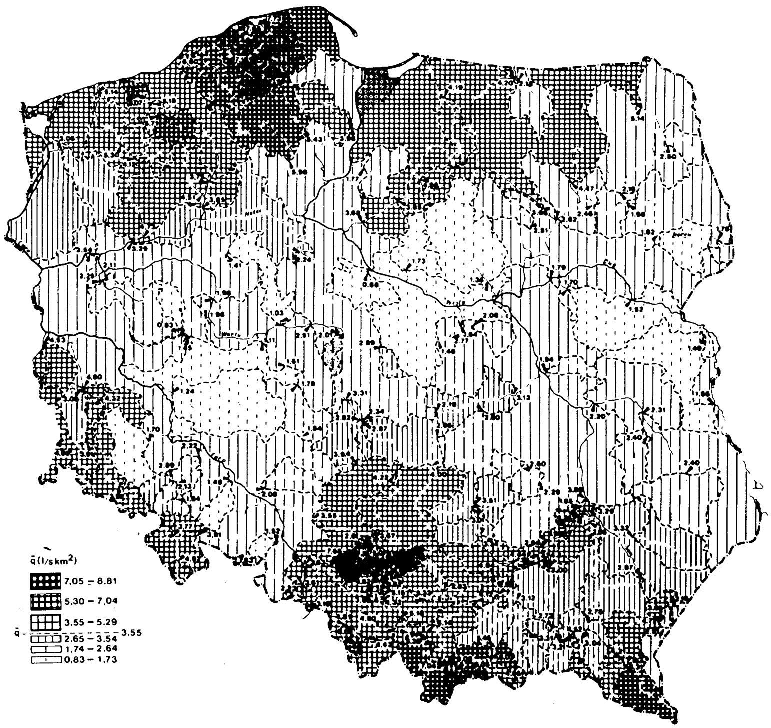


Fig. 4. Groundwater runoff modulus.

runoff is moderate ($q \approx 3,5$ l/s/km²) in sandr and sandy basins and also in the pradolinas (Fig. 2b). Fairly low groundwater runoff values ($q<2,2$ l/s/km²) are reported from loess basins on solid bedrock and from prequaternary sedimentary rocks with till cover. The lowest values (averaging about 1.8 l/s/km²), are yielded by the denudated moraine areas of older glaciation where the groundwater alimentation is extremely meagre. The most uniform and homogeneous groups are formed by the basins occupying till areas of older glaciation, those with loess ground and prequaternary sedimentary rock with till cover as well as by the pradolinas and sandrs. The flysch and karst basins, sandy catchments of river accumulation and drainage areas of young glaciation display the greatest variations. The distribution of the average groundwater runoff is determined by the potamic groundwater aquifer resources together with conditions of natural drainage and affluency due to the type of formation covering the basin area and producing the saturation zone.

The coefficient of variation for groundwater runoff C_v describes its stability during the hydrological year. Among the catchment types quoted above, the highest stability ($C_v<0,4$) can be observed in the basins of the Sudeten region with discontinuous folded structure, in the karst catchments and most of the pradolinas, young glaciation with lakes and sandr basins. The greatest groundwater recharge fluctuations are displayed by the flysch (c_v>0,7) and loess catchment areas as well as by the moraine ones of older glaciation.

The most homogeneous group is formed by the catchment type with discontinuous folded structure, by the catchments of pradolinas group and by moraine areas of older glaciation. The least homogeneous, as would be expected, is the flysch group. The catchments of moraine areas of older glaciation and the loess ones show moderate variation during the year. The spatial characteristic is evidently related to the spatial distribution of storage capacity and to the underground modulus.

The Share of the groundwater runoff in percentage of the total runoff is expressed by the groundwater discharge coefficient α. Alongside the modulus, this is one of the most important numerical characteristics of the groundwater runoff. The catchments of young glaciation as well as the sandr and sandy basins display the highest percentage of the groundwater runoff in the total one. Here, the groundwater discharge coefficient exceeds the value of 60 per cent (Fig. 2d). The moraine catchments of older glaciation and some sandy basins from group IX are distinguished by moderate values, α = 50 per cent, while the lowest groundwater discharge coefficient, α<45 per cent, is to be found in the mountain catchments of flysch type or with discontinuous folded structures and in most of the basins covered with loess.

Quite different from the other basins are the lake and boggy catchment basins, where the groundwater recharge coefficient averages 70 per cent. These values make the range of groundwater recharge fluctuations much wider within the group in question. The most homogeneous isolated group is formed by the catchments of flysch type and those with the Sudeten discontinuous folded structures, though on the whole, this group would rather yield low values of total runoff, 23-28 per cent. The least homogeneous, or the most variable are the karst catchments and the basins covered with loess on solid bedrock. Their non-homogeneity is due to the depth and size of fissures as the main source of natural drainage transport.

The share of groundwater in the water balance is expressed by the groundwater runoff/rainfall ratio. That ratio is taken as the groundwater runoff coefficient β. It is the least variable parameter of all characteristics discussed above for the Polish territory (Fig. 2e). This value can be interpreted in two ways - as effective infiltration or natural affluencey. In Poland, the groundwater outflow coefficient ranges from 5-10 per cent for the areas with loess cover or morains of older glaciation to over 30 per cent for sandr and last glaciation catchments. It also seems to display the most regular distribution. The groundwater runoff coefficient being usually small, 16 per cent of the rainfall on the average, the bulk of the rainfall goes into the surface runoff, evaporation and transit apotamic (non-circulating water to river) runoff, which is beyond the scope of our investigations.

Let us note that the maximum values of the groundwater runoff coefficient (β>25 per cent) are recorded for the sandr and last glaciation catchment areas where rainfall is under 750 mm, while in the flysch basins - inspite of the rainfall being considerably above 800 mm - the share of effective recharge is insignificant, usually below 15 per cent. This is another proof of the importance of the catchment environmental features which account for the magnitude of the groundwater runoff coefficient to a much greater extent than does precipitation. In the Warta river catchment area, however, there is a distinct dependence of the groundwater runoff coefficient on precipitation, which regularity is corroborated by the results obtained by Paslawski and Koczorowska (1974).

As regards that characteristic distribution, the most homogeneous groups are formed by the moraine catchments of older glaciation, the pradolinas basins, drainage areas covered with loess on solid bedrock and those built of sedimentary prequaternary rocks with moraine cover. Such little variations in value β is indicative of homogeneous recharge conditions within the above regions. The largest variations were observed in the young glaciation catchments with lakes, in the sandr and sandy basins as well as in the karst ones. Differences in the groundwater runoff values are due to rainflow variations and to particular environmental features, which affect the storage capacity of a basin accentuated by lakes and bogs. As has been observed in the course of our studies, some catchment areas do not behave in accordance with the natural conditions, thus distorting the distribution of the above characteristics in particular catchment types. This is due to a distinct antropogenic effect, and the values obtained for such areas should be considered as overrated and doubtful.

Time - Spatial Distribution of Groundwater Runoff

The seasonal rhythm in the groundwater runoff fluctuations has been so far discussed in Poland on the basis of short-term observations. Taking into account spatial variations of the characteristics, an attempt has been made to study the time distribution of groundwater recharge for an average hydrological year. In spite of considerable inertia, the groundwater runoff displays certain time variations.

Our calculations show that in Poland winter yields a much higher groundwater runoff than summer, except for the mountain flysch areas of the western Carpathians (the border passes to the west of the Dunajec river). We can also discriminate some areas having a slightly larger groundwater runoff in summer, which may be due to the annual distribution of karst recharge prevailing in those regions.

The higher percent of the winter groundwater runoff as compared to the annual means is chiefly accounted for by the storage. The greater the catchment storage capacity the more uniform is the groundwater runoff during the year. Such uniformity has been proved for the catchment areas with discontinuous folded structures and for the karst and pradolinas basins. The moraine areas of older glaciation have scanty water resources and, thus, a very low storage capacity. The same is true for the flysch catchments of the eastern Carpathians, where the prevalence of the winter recharge is extremely great, about 30 per cent of the mean value.

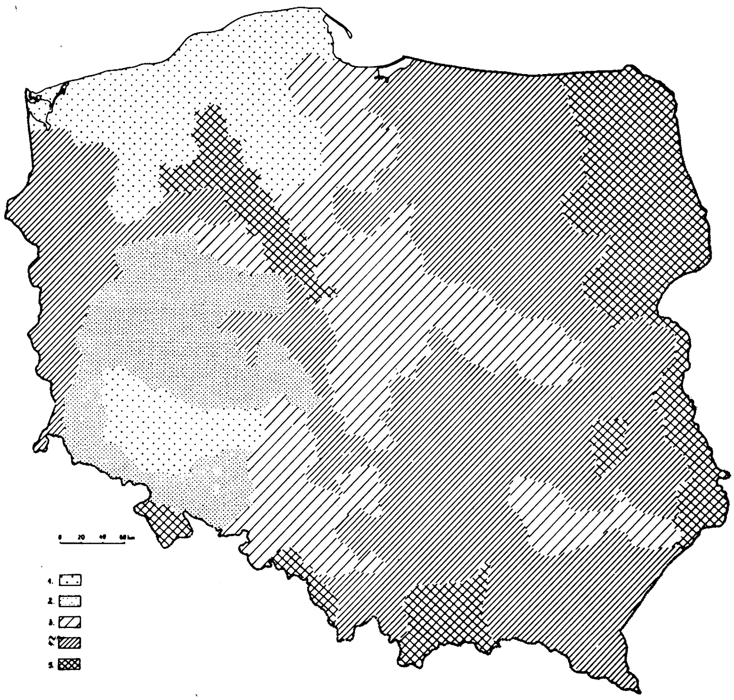


Fig. 5. Typical time of underground floods.

A characteristic rhythm of groundwater runoff during the year is associated with the nature of the water renovation owing to infiltration, which controls the annual rainfall and evaporation distribution and the aquifers storage capacity related to the natural drainage ability.

The autumn and winter precipitation, stored in the ground, is responsible for a distinctive underground flood. It is already in November and December that this flood yields maximum annual unit groundwater runoff (Fig. 5). Some moraine catchment areas of older glaciation as well as loess and pradolinas basins attain maximum groundwater discharges early in winter but such discharges are of a limited runoff. The late winter underground floods are typical for fairly large areas in western Poland, while those occurring early in spring can be observed on the rivers of central Poland and in the upper reaches of the Odra and Warta rivers, in the south. The largest regions, however, are associated with underground runoff of a typical snowmelting kind culminating in April. This type is to be found in the lower reaches of the Odra, central Warta, in highland rivers and in the flysch rivers of the Carpathian Mountains, east of the Dunajec river. The typical mountain catchment basins are distinguished by the latest underground floods with extreme propagation in May. There are also some other regions having their maximum underground floods late in spring, they are the rivers of eastern Poland and catchment areas with a high share of lakes and bogs. Overall, one can say that in Poland the underground floods vary in time from early winter to early summer lasting through a total period of seven months. Such time and spatial distribution is also due to climatic factors, the time of snowmelting in particular; but also delays and time shifts result from environmental prerequisites. The periods of surface runoff do not coincide with the maxima of groundwater recharge in the rivers. There is often no concurrence in the typical periods of surface and underground runoff. Periods of maximum groundwater discharge are shifted in relation to the typical flood time both in the mountain and lowland catchment areas. In northern Poland, underground floods are at least 2 to 3 months ahead of snowmelting floods. In central and eastern Poland there are some short delays, while the floods are synchronous with the surface ones. The mountain regions is an exception to the basic time and spatial distribution, as the snowmelting recharge accounting for the underground flood in May causes no surface flood. The minimum groundwater runoff can be usually observed during the seasons, exept spring (Mikulski 1962). These are periods of reduced groundwater recharge solely due to groundwater resources. The time and spatial distribution of typical groundwater low flows depends on the recharge, which is limited by the natural affluency of potamic waters. Most of the catchment areas of central and north-western Poland will have their minimum groundwater discharge during the summer low water periods that last from summer to winter. The occurrence of a minimum groundwater discharge in the autumn can be associated with the areas of greater potamic waters abundance which accounts for a more slowly exhausted alimentation. This is the case with sandr catchment basins, drainage areas of last glaciation with lakes as well as with bog and karst basins. The autumn low water periods can be also observed in the mountain areas with discontinuous folded structures of the Sudeten and in the flysch catchment areas of the eastern Carpatians.

High mountainous areas and some of the karst and sandr catchment basins reach a minimum in groundwater recharge in winter, I-II, which may be chiefly the result of temperature drops together with deep circulation in karst formations. Some flysch catchment areas lying somewhat below and having smaller water resources, reach their minimum values as early as the beginning of winter. Restriction of the groundwater recharge to the minimum in winter is due to freezing of the upper layer of the ground, while its being at the lowest in summer or autumn is the result solely of an increased evaporation and lack of rainfall.

Conclusions

The groundwater runoff of Polish rivers displays considerable regional variations which are also manifested in its time distribution.

The spatial distribution depends upon the geological structure of the area. Its characteristic features together with precipitation account for conditions of groundwater runoff based on permeability and natural drainage. The time and spatial variability of groundwater runoff is due to a joint effect of environmental and hydroclimatologic factors such as rainfall, snowmelting, evaporation etc.

The catchment areas of the flysch Carpathians and the Sudeten Mountains show the greatest departure from the average values observed in the rivers under study. These variations can be seen both in time and spatial distribution patterns. A fairly distinctive group is formed by catchments in the areas of young glaciation with lakes and karst basins. Here, the groundwater recharge is affected by the presence of lakes, bogs or deep complex fissures, which change the natural routes of groundwater circulation and, at the same time, change the natural affluency conditions. Whenever loess covers the catchment area, it is almost invariably connected with a considerably reduced groundwater runoff. The sandr catchments make up a homogeneous group standing out among other areas. The most scanty groundwater recharge is reported for the moraine formations of older glaciation. They occur in the zone of the lowest rainfall and high evaporation. As lakes or bogs are lacking in the area, it fails to produce a higher groundwater runoff.

Numerical characteristics of the groundwater runoff, their values and time and spatial distribution as observed in the above geological and hydrogeological types of catchment areas, allow to reveal certain regional regularities.

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