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Variation of groundwater table in Roztocze and problems of its hydrogeological evaluation

Results of observations of groundwater table in Roztocze are presented. Four types of fluctuation are distinguished. Most common and typical is the first one, dependent on annual hydrological cycle. The second type with amplitudes to 6 m depends on many years' cycle and is accompanied with insignificant influence of annual hydrological cycle. Correspondence of water table to groundwater runoff was found in several catchments but no correlation could be noted. Groundwater runoff and water table are caused by the same factor. Method of mean and determination of confidence intervals are suitable to prognoses of water table.

INTRODUCTION

Estimation of groundwater table variation to recognize hydrogeological conditions in various areas of Poland and resulting influence on resources and quality of water have been a principal hydrogeological problem in this country for several years. It has been undoubtedly connected with increasing water intake, in result of which serious problems of their quantitative and qualitative protection have arisen. Such care of multidirectional recognition of regional changes in hydrogeological conditions was expressed by a historical decision of the former Centralny Urzad Geologii (Central Geological Office) to have organized by the Państwowy Instytut Geologiczny (Polish Geological Institute) a country-wide observatory network of groundwaters. This decision was preceded by local observations carried through in the sixties and in the first half of the seventies in vicinity of Częstochowa, Janowiec near Puławy and in Roztocze. Local observations have been also collected by several universities — from Cracow, Wrocław and Lublin, and results have been already published. Such activity supplied with essential arguments on usefulness of such observations.

Table 1

Methods used at analysis of groundwater table in 1971–1991

Year	Author	Study method
1971	S. Niedzielski	Descriptive evaluation.
1973	J. Paszczyk	Theoretical analysis.Statistical method (standard deviation).
1974	J. Malinowski	Descriptive evaluation.
1978	J. Sawicki	Construction of curves of groundwater recharge and comparison with storage curves.
1978	I. Dynowska, Z. Pietrygowa	Analysis of mean mobile fluctuation of water table and comparison with precipitation, descriptive evaluation.
1979	J. Miecznicki, J. Pich, Z. Płochniewski	Analysis of pre-spring dependences of minimum water table from mean ones of a preceeding year. Analysis of minimum pre-spring water table from mean autumn ones of preceeding year. Regression formulae.
1986	J. Sawicki	Method of falling gradient in summer and winter. Dependence of water table on geological and hydrogeological factors.
1988	J. Malinowski, E. Przytuła	Statistical methods: — mean annual water table from many years' observations, — confidence interval, — rise and regression coefficient for short-term prognoses. Balance of rises and falls of water table. Evaluation of storage changes.
1989	W. Chełmicki	Statistical methods (analysis of standard deviation, regression formula).
1990	J. T. Tomaszewski	Statistical methods (regression formula).
1990	D. Małecka (*fide* D. Małecka, T. Lipniacka)	Analysis of mean annual fluctuation. Descriptive evaluation.
1991	J. Malinowski, E. Przytuła	Methods of prognosis of water table.

Observations of water table in Roztocze have been carried through in 1964–1968 in the west and in 1969–1971 in the central area. Farm wells acted as measurement sites; they generally penetrated Cretaceous sediments and only some of them — Tertiary and Quaternary series. Measurements were done every Monday by the well owners. Degree of confidence of measurements was varying what made firstly difference in accuracy of measurements themselves as they were done at different time of a day and were occasionally interrupted 1974 resulting in lack of data on daily or even weekly variation. Preliminary results from data on Western Roztocze were published in 1974, some were already discussed in successive papers of the author. At present, as observation network of water table and monitoring of groundwaters are developed, demand to elaborate these data has increased. The author finds therefore necessary to describe from a methodological point of view the most important problems exampled from Roztocze as in this region an observation network is relatively dense. He presents also a general comparison with other authors' results from different parts of the country. Most important problems include undoubtedly prognoses of water table variation and connected changes in groundwater resources. Evaluation of influence of natural factors on variation of water table is particularly important in such a prognosis.

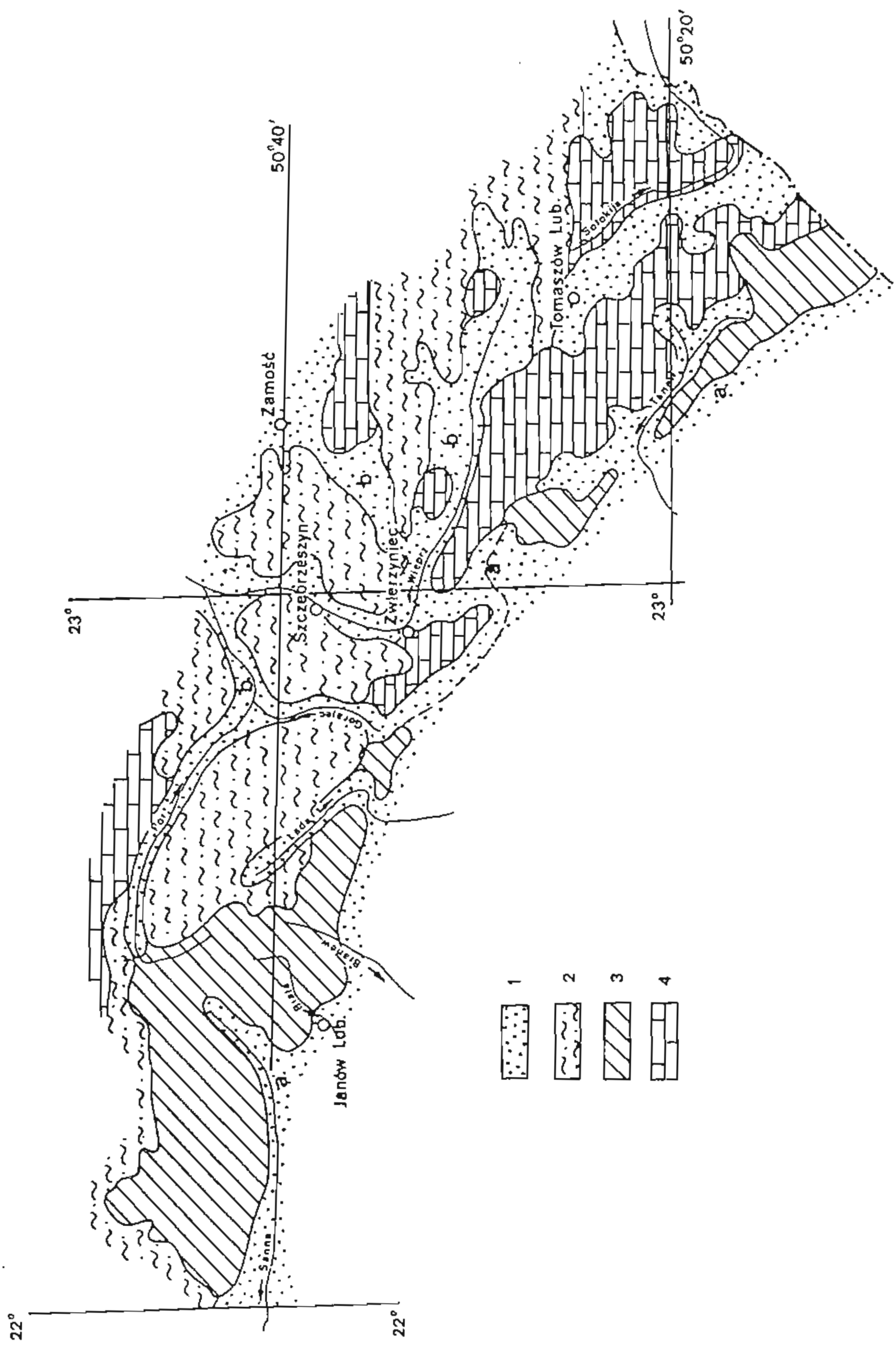
In publications and archival studies various aspects of water fluctuation are discussed. They should be treated as searching of ways to most suitable solutions and evaluations. A list of most important methods that call for peculiar attention is presented in the Table 1. Quite intensively applied statistical methods are visible what is distinctly indicated for the eighties. When discussing fluctuation of water table in Roztocze, they are compared with results of other scientists.

DESCRIPTION AND TYPE OF GROUNDWATER TABLE FLUCTUATION AND OF ITS AMPLITUDE

The main water-bearing horizon is composed of sediments of the Upper Cretaceous i.e. Turonian, Santonian, Campanian and mostly Maestrichtian, being composed of similar sediments as in remaining part of the Lublin-Radom Basin. They comprise interbeds of marly gaizes, marls, gaizes and partly chalk. Assisting and locally equivalent (through a hydraulic connection) horizon is formed of Miocene sediments (Sarmatian and Tortonian): lithothamnium and Serpula limestones, conglomerates and sandstones, passing commonly into sands (Fig. 1). From a hydrogeological point of view, lithological complexes of both these systems form a single water-bearing horizon, locally under insignificant pressure if they form a bi-layered system.

Water capacity of these complexes is determined by deep fissures that act as main conduits to a flowing water. Hydrodynamic system of groundwater flow is therefore a function of fully developed drainage expressed with deeply incised valleys, along which numerous springs occur. Intensity of fissures is not uniform as indicated by varying coefficient of permeability, calculated from well pumping to 0.1–100 m a day but occasionally even more.

Flow coefficient and filtration properties are the greatest in intensively fissured areas. The latter are developed along faults and cracks that usually accompany certain faulty zones. There are river valleys with numerous springs along them (M. Chodorowska-Kwiecień, 1973; J. Malinowski, 1974; Z. Michalczyk, 1986) and therefore, a fissure flow prevails. It could be thus possible that in zones with predominant fissure flow, amplitude of fluctuation could be the greatest and the most common. It is however not univocal, although some scientists find interdependence between fissuring and water table fluctuation (J. Sawicki, 1986).


50°20'
50°40'
23°
23°
22°
22°
Tomaszów Lub.
Zamość
Szczebrzeszyn
Zwierzyniec
Janów Lub.
Wieprz
Sołokija
Tanew
Gorajec
Por
Łada
Białka
Branew
Sanna
a
b
1
2
3
4

WESTERN ROZTOCZE

In this area stationary measurements were done at 25 wells in 1963–1968 (Fig. 2). In 1965–1968 they indicated increased, quite intensive precipitation to 982 mm a year (Tab. 2). Winters were frostless in that time and mean monthly winter temperatures were lower than many years' mean monthly ones. For this reason a snow cover could currently melt out and continuous recharge with precipitation existed. The years before 1959–1965 indicated considerable variation of precipitation and some stations recorded annual fall below a many years' mean (Tab. 2). Such variation undoubtedly influenced groundwater table. Three types of fluctuation of the water table could be distinguished due to analysis of measurements from observatory wells.

The first type of fluctuation prevails in most wells which are 10–15 m deep (wells nos. 2, 4, 6, 18, 19, 22, 24, 26 — Fig. 3). This variation indicates regular recurrence every year, resulting in spring maximum in March–May, followed by regression until the end of a hydrological year. Maximum values (rises) were however different every year. Water table in wells indicates a rising trend since 1966. Similar type of fluctuation is noted by water table in the Quaternary sequence at very quick rises — maximum of which occurs in February–March. Such fluctuation is common and seems typical in most of the area. Its average maximum amplitude does not exceed 2.5–3.0 m during a hydrological year.

The second type of fluctuation indicates "unquiet" water table changes, occasional long-term fall, rapid but non-recurrent spring rises and long-lasting regression (Fig. 4). Maximum difference between the highest and the lowest water table in the well no. 40 was equal 8 m. Frequent and quite typical is daily and weekly fluctuation, being however without influence on rise and falling trend, even if occurred quite frequently. Such fluctuation is noted in wells at depths of about 30 m. Maximum fluctuation has not been noted every year. Water table fluctuation in the well no. 40 (Fig. 4) indicates that maximum rise was initiated in 1966 and reached its maximum in 1967. The same fluctuation type occurred in two wells only i.e. nos. 1 and 40. It cannot be therefore typical for the described fragment of Roztocze, although indicates a certain, still unexplained peculiarity of hydrogeological conditions.

The third type of fluctuation indicates very small annual amplitudes of about 10–50 cm. Curve of the well no. 13 (Fig. 5) with average water table depth equal to 6 m is a typical example. Such fluctuation occurred in several wells, presenting fluctuations in a shallow well.

Fig. 1. Geological sketch of Roztocze based on the *Mapa geologiczna Polski* 1:500 000, edited by E. Rühle, 1986 (simplified)

1 — fluvial and glaciofluvial sands, locally gravels on the sediments: a — Miocene, b — Cretaceous; 2 — loesses partly clayey or sandy; 3 — Miocene lithothamnium and Serpula limestones, marls, sandstones and sands; 4 — Upper Cretaceous gaizes, marly gaizes, marls and marly limestones

Szkic geologiczny Roztocza na podstawie *Mapy geologicznej Polski* 1:500 000 pod redakcją E. Rühlego, 1986 (uproszczony)

1 — piaski rzeczne i rzeczno-lodowcowe, miejscami żwiry: a — na utworach miocenu, b — na utworach kredy; 2 — lessy, częściowo gliniaste lub piaszczyste; 3 — wapienie litotamniowe, serpulowe, margle, piaskowce, piaski — miocen; 4 — opoki, opoki margliste, margle, wapienie margliste — kreda górna

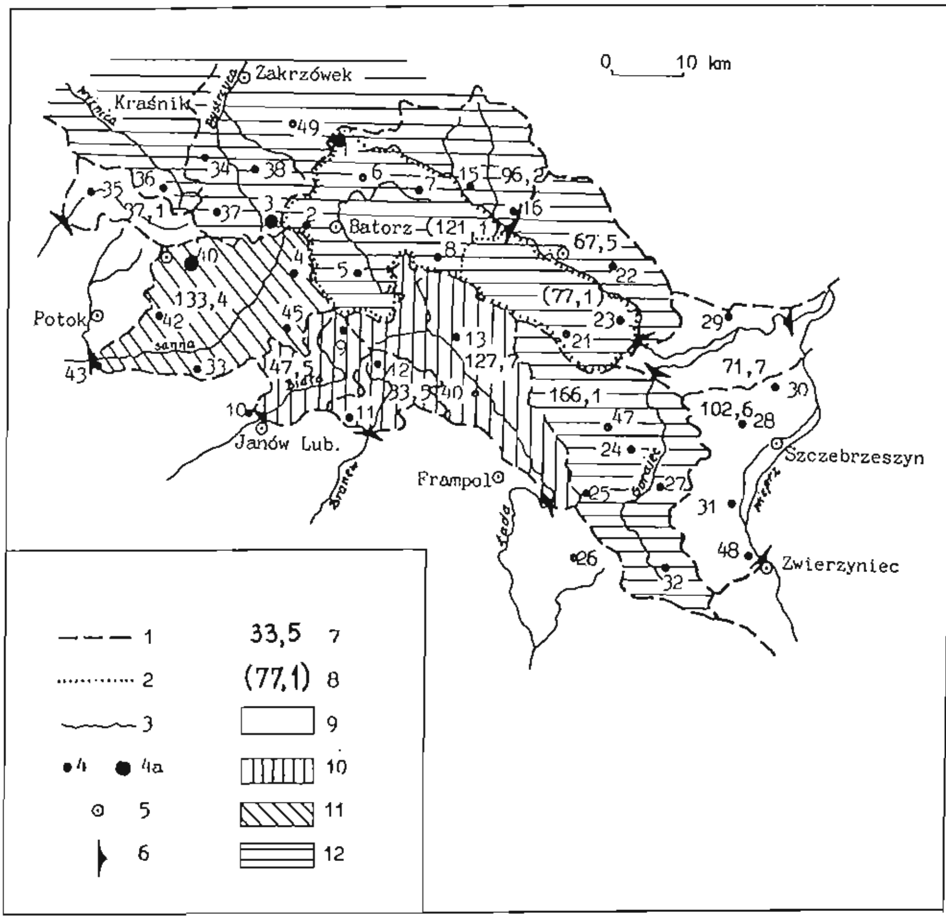


Fig. 2. Location of observation wells in Western Roztocze and amplitudes of groundwater table

1 — catchment border; 2 — border of the Por catchment in Roztocze; 3 — water streams; 4 — wells with stationary observations; 4a — wells with maximum amplitude; 5 — precipitation stations of the Instytut Meteorologii i Gospodarki Wodnej (Institute of Meteorology and Water Management); 6 — water gauges; 7 — catchment area in sq. kilometres; 8 — area of the Por catchment in Roztocze in sq. kilometres; amplitudes of fluctuations in metres: 9 — <1, 10 — 1-2, 11 — 2-3, 12 — 3-4

Lokalizacja studni obserwacyjnych na Roztoczu Zachodnim i amplitudy wahań zwierciadła wód podziemnych

1 — granica zlewni; 2 — granica zlewni Poru w obrębie Roztocza; 3 — cieki wodne; 4 — studnie z obserwacjami stacjonarnymi; 4a — studnie z maksymalną amplitudą; 5 — stacje opadowe IMGW; 6 — wodowskazy; 7 — powierzchnia zlewni w km^2; 8 — powierzchnia zlewni Poru w obrębie Roztocza w km^2; amplitudy wahań w m: 9 — <1, 10— 1-2, 11 — 2-3, 12 — 3-4

Water fluctuation in the well no. 13 (Fig. 5) indicates that regression initiated at the very beginning lasts two and a half year (1963–1965), and is followed at the beginning of 1966 by a rise which continued until the end of this year. Afterwards quite

Table 2

Annual precipitation in Western Roztocze after data of the Państwowy Instytut Hydrologiczno-Meteorologiczny (State Hydro-Meteorological Institute) from 1963–1968

Precipitation station	Total precipitation in a year (mm)					
	1963	1964	1965	1966	1967	1968
Wysokie	506.4	550.0	600.3	736.1	668.8	648.3
Zakrzówek	536.7	514.1	617.9	693.4	619.7	711.8
Frampol	492.3	560.8	695.7	536.2	701.2	883.2
Janów Lubelski	493.7	476.2	896.8	982.1	935.5	831.5
Potok	541.1	502.6	749.9	895.7	805.1	866.8
Polichna	528.2	656.0	770.5	904.6	697.6	790.5
Zwierzyniec	552.2	673.6	714.0	968.4	868.4	858.2
Szczebrzeszyn	514.8	581.4	627.0	832.0	677.4	793.2
Batorz	357.8	504.0	589.9	649.9	554.3	619.5
Turobin	667.6	789.0	980.8	855.2	804.7	895.9

a quick rise of about 1 m occurred in 1967 and 1968, with trend to keep the attained state.

In spite of varied fluctuations in Western Roztocze, there is a certain common feature of all the three types, marked by a long-term (1.5–2 years) lowering when water table is always below its initial location. Another common feature is indicated by a rise of water table in 1967, initiated already in 1966. In the first type of fluctuation this rise is equal to 2.5 m, in the second — to 8 m and in the third one — to 1.5 m. This phenomenon univocally presents "delayed" flow of a recharge stream with quite a large, although diversely intensive flow. Such delay is probably connected with many years' cyclicity. Initial rise of water table in 1966 seems worth mentioning as it is accompanied by increased output of springs, reaching its maximum in 1967. This phenomenon supports therefore a many years' cyclicity (J. Malinowski, 1974).

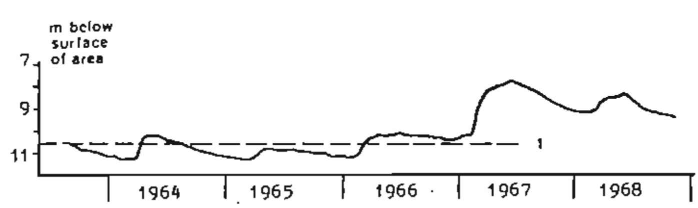


Fig. 3. First type of fluctuation; Cretaceous, well no. 6

1 — water table at the very beginning of the observations period

Pierwszy typ wahań; kreda, studnia nr 6

1 — stan zwierciadła wody przy rozpoczęciu pomiarów

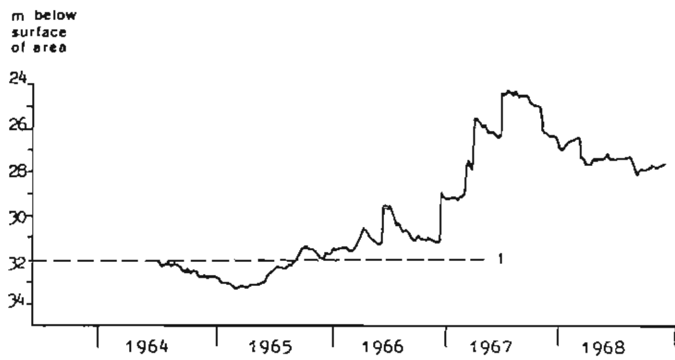


Fig. 4. Second type of fluctuation; Tertiary, well no. 40
For explanations see Fig. 3
Drugi typ wahań; trzeciorzęd, studnia nr 40
Objaśnienia jak na fig. 3

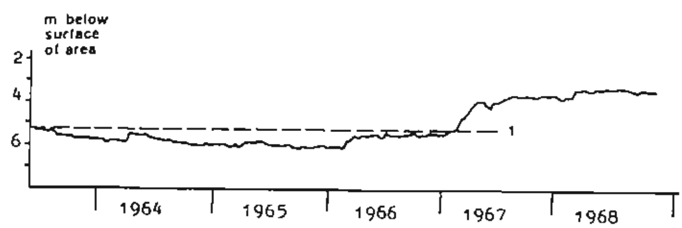


Fig. 5. Third type of fluctuation; Cretaceous, well no. 13
For explanations see Fig. 3
Trzeci typ wahań; kreda, studnia nr 13
Objaśnienia jak na fig. 3

CENTRAL ROZTOCZE

Measurements of water table were carried through in 1969–1971 in 33 wells (Fig. 6). Precipitation was much differentiated in this time (Tab. 2) and reached 861 mm in some catchments, being even over 1000 mm in preceding years. Varying recharge of water-bearing horizons was therefore noted.

Analysis of results indicates that water table fluctuation is similar as in Western Roztocze but *the fourth type of fluctuation* appeared. It indicates very small amplitudes of about 20–30 cm, without distinct spring rises (Fig. 7). Amongst the distinguished four fluctuation types, Central Roztocze is predominated by the third and the fourth ones, common in wells from several to about a dozen of metres deep. Fluctuation of the first type is not so frequent as in Western Roztocze. Its characteristic feature indicates quick rise of spring maximum (Fig. 8) from February

Table 3

Annual precipitation in Central Roztocze after data of the Państwowy Instytut Hydrologiczno-Meteorologiczny (State Hydro-Meteorological Institute) from 1968–1971

Precipitation station	Total precipitation			
	1968	1969	1970	1971
Krynice	733.4	477.3	762.2	506.2
Zwierzyniec	858.9	536.7	807.9	686.4
Szczebrzeszyn	793.2	454.4	861.2	562.8
Majdan Wielki	751.2	471.7	685.5	610.3
Józefów	1038.7	582.4	510.5	406.9
Tomaszów Lubelski	817.3	507.9	727.8	469.0
Bełżec	790.0	509.5	771.3	513.3

until April–June, followed by slow and long-lasting regression. Typical example is presented by the well no. 3 in the catchment of the Sołokija. In 1970 this well indicated a rise of water table equal to 5.8 m during 35 days (1970. 03.02 — 1970. 04.06). Daily rise was equal to about 17 cm. Created water table is comparable in several wells from Western Roztocze. In Central Roztocze no fluctuation of the second type was noted.

Although water table measurements in both parts of Roztocze were carried through in different years, spring rise of water table occurs in the same time i.e. at the end of February to April. It means that the same factors caused a rise of water table. Similar types of fluctuation are also noted in observatory wells of the Instytut Meteorologii i Gospodarki Wodnej (Institute of Meteorology and Water Management), located in various geological conditions.

Near Modliborzyce in Western Roztocze there is an observatory station of the Państwowy Instytut Geologiczny (Polish Geological Institute) at Łysaków. Fluctuations of a water table in the main well and in piezometers are of the fourth type. Observations from over ten years indicate fluctuation of about 20–50 cm. Maximum equal to 50 cm occurred twice.

In the whole Roztocze annual water table fluctuation is equal to 1–4 m and was greater in three cases only. In the well no. 1 from Western Roztocze the greatest amplitude was equal to 9 m in 1963–1968 and 7 m in 1967. In the well no. 40 an amplitude was also equal to 9 m during the same period and 5 m in 1967. In Central Roztocze the greatest amplitude was noted in the well no. 3: equal to 5.8 m in 1970 and 5 m in 1971.

The amplitudes of fluctuation magnitude were subdivided into four groups: <1, 1–2, 2–3 and 3–4 m. Such classification does not take into account the maximum values (wells nos. 1, 3 and 40) as being non-typical and therefore, marked as points only. Spatial distribution of amplitudes in individual catchments is presented in Figures 2 and 6. Definite values generally comprise several catchments. In the north — with the Por catchment, spring areas of the Bystrzyca and the Wyżnica and the catchment of Gorajec — amplitudes of 3–4 m predominate. In southern catchments they are more

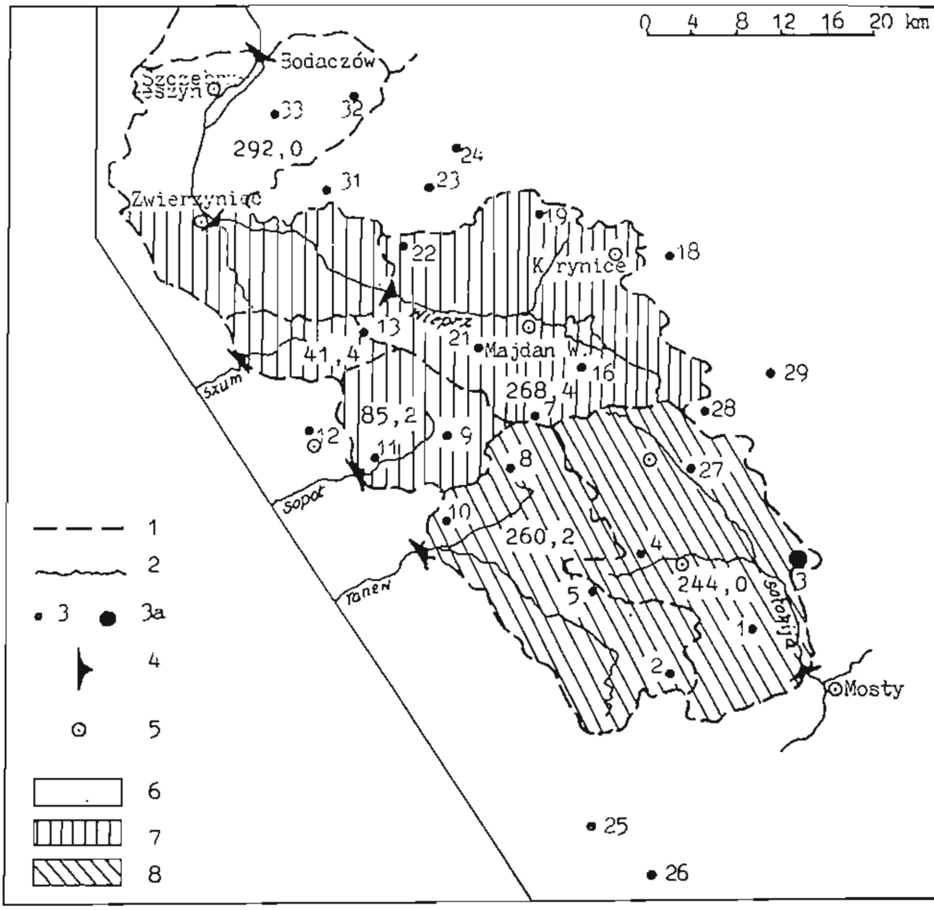


Fig. 6. Location of observation wells in Central Roztocze and amplitudes of groundwater table

1 — catchment border; 2 — streams; 3 — wells with stationary observations; 3a — wells with maximum amplitude; 4 — water gauges of the Polish Geological Institute; 5 — precipitation stations of the Instytut Meteorologii i Gospodarki Wodnej (Institute of Meteorology and Water Management); amplitudes of fluctuation in metres: 6 — <1, 7 — 1–2, 8 — 2–3

Lokalizacja studni obserwacyjnych na Roztoczu Środkowym i amplitudy wahań zwierciadła wód podziemnych

1 — granice zlewni; 2 — cieki wodne; 3 — studnie z oberwacjami stacjonarnymi; 3a — studnie z maksymalną amplitudą; 4 — wodowskazy własne; 5 — stacje opadowe IMGW; amplitudy wahań w m: 6 — <1, 7 — 1–2, 8 — 2–3

differentiated: 2–3 m in the Sanna catchment but 1–2 m in catchments of the Biała, the Branew and the Łada. Downstream the Por and the Gorajec amplitudes are below 1 m. In Central Roztocze amplitudes are less differentiated. In the Sołokija and the Tanew catchments they are equal to 2–3 m, in the remaining ones — 1–2 m and downstream part the Wieprz catchment — below 1 m.

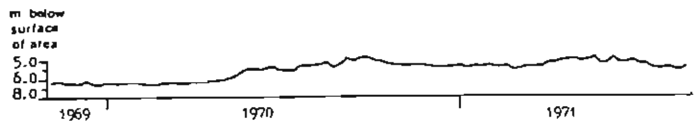


Fig. 7. Fourth type of fluctuation
Czwarty typ wahań

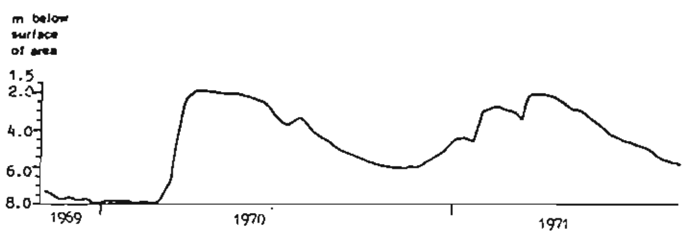


Fig. 8. Example of a first type fluctuation with a quick spring rise
Przykład pierwszego typu wahań z szybkim wzniosem stanu wiosennego

Comparison of the above described fluctuation types with data of other scientists indicates almost full similarity, although observations were collected in different years. Most common is fluctuation of the first type what expresses influence of annual hydrological cycle. It is visible in data of J. Paszczyk (1973) for the Lublin Upland and from the observatory network of the Polish Geological Institute of 1979–1988 (J. Malinowski, E. Przytuła, 1988). Considerably less intensive is fluctuation of a many years' cycle i.e. the second and the third type of Roztocze. Regularity of variation in the annual cycle is also supported by observations from other regions. J. Sawicki (1986) collected observations in southwestern Poland where distinct variation corresponding to the first and the second types of Roztocze occurs, with less intensive second rise in July–August (Fig. 9). I. Dynowska and Z. Pietrygowa (1978) present an example of a second type fluctuation at the post Futory (upstream part of the Tanew drainage basin). Interesting results are presented from Podhale (D. Małecka, T. Lipniacka 1990) from 1971–1975; they indicate that a rise of water table on slopes begins in February and reaches its maximum in July, followed by a long-lasting regression (Fig. 10). Water table locations are similar to fluctuation of the first type, with time shift of 2–3 months if referred to maximum in the area outside the Carpathians. Interesting results were collected by H. Niedzielski (1971) in the Miechów Upland for 1964–1965 (Fig. 11). He distinguished three types of fluctuation. The first one with maximum in summer is connected with intensive precipitation in July and August. Maximum rise of the second type occurs in spring (March–April). These two types are different from the third one with climaxes in spring (April–May) and in summer (July) — Fig. 11 — similarly as noted by J. Sawicki (1986). Depression between these two rises occurred at the turn of May and June. Observations of H. Niedzielski agree in time with the

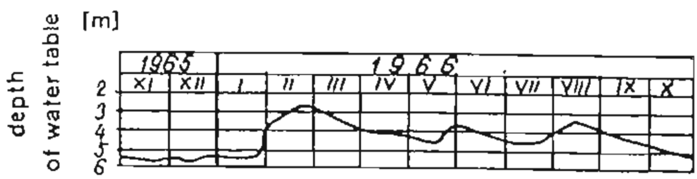


Fig. 9. Fluctuation of a water table after J. Sawicki (1986), similarity to fluctuation of a first type
Wahania zwierciadła według J. Sawickiego (1986), analogia do pierwszego typu wahań

ones in Western Roztocze and the second type of fluctuation is almost the same as fluctuation of the first type in Roztocze. Fluctuation of the first and the second types can be also compared to data of J. T. Tomaszewski (1990) from the Lower Silesia as far as the Częstochowa Jura (Fig. 12). Similarity with fluctuations of the third and fourth types is less distinct.

In spite of certain regularities in water table location, connection between fluctuations and natural factors is not very distinct. There is only coincidence of water table location and groundwater runoff in several catchments. The Por catchment is a good example of such coincidence in Western Roztocze (Fig. 13). Time shift if referred to precipitation is equal to 3–4 months there. In other catchments such coincidence is less distinct. In Central Roztocze it occurs only in the Sołokija catchment (Fig. 14) and is absent in a remaining area e. g. in the Tanew catchment (Fig. 15) where a rise of water table is insignificant if related to increased groundwater runoff.

To check coincidence between water table (H) in a well and groundwater runoff (Q), correlation coefficient (r) in several catchments was calculated. It is equal to 0.697 in the Sanna catchment (shift Q against H for a single month increased a coefficient r to 0.806). In the Por catchment, being representative for Western Roztocze, r is equal to 0.708 whereas at a month shift — to 0.768. Attempts to shift Q against H for two months have not resulted in correlation significance. The latter is also absent in other catchments of Western Roztocze. In Central Roztocze a significant correlation was received only in the Sołokija catchment ($r = 0.789$). It has not been however noted between precipitation and water table and also — between precipitation and under-

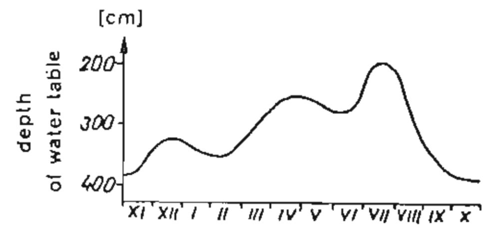


Fig. 10. Fluctuation of water table in Podhale after D. Małecka and T. Lipniacka (1990)
Wahania zwierciadła na Podhalu według D. Małeckiej i T. Lipniackiej (1990)

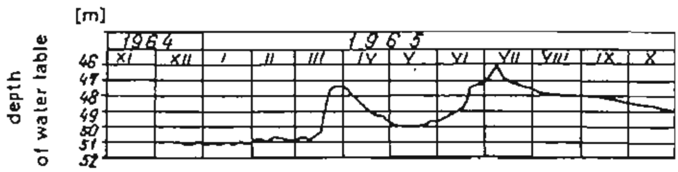


Fig. 11. Fluctuation of a first type in the Nida Basin after H. Niedzielski (1971)
Wahania pierwszego typu z obszaru Niecki Nidziańskiej według H. Niedzielskiego (1971)

ground runoff. Calculated values were equal to 0.2–0.3. Only in the Łada catchment $r = 0.498$ i.e. at a significance limit.

All these data suggest that in water table and in groundwater runoff a decisive is the same factor i.e. recharge effect, dependent on geological conditions. It is influenced firstly by a thick (locally to 30 m) loessy cover, through which a percolation generally occurs what results in retarding effect in water table location. This retardation can be influenced by interjacent isolation in Cretaceous and Tertiary sediments that, although fissured, can stop circulation of infiltration water. Such suggestion is supported in opinions of J. J. Coonoy and I. E. Pehrson (*fide* K. Starmach et al., 1970). According to a scheme of these authors, penetration of elementary infiltration stream from rainfalls in clayey soil to depth of 150 cm is twice smaller than in sandy till, with a scattering radius of 150 cm. Thus if a more impermeable bed occurs on the way of elementary infiltration stream, then it results in a change of its direction and reaching a saturation zone considerably later. From a geological point of view influence of isolation cover is therefore undoubtedly decisive on water table location, although it does not act as the only one. A thick loessy cover as pointed previously, creates a barrier in inflow of infiltration water to a saturation zone. Besides, Tertiary sediments comprise clayey interbeddings that play the same role.

Fissuring zones connected mainly with valleys, are separated with only slightly fissured blocks with water flow being more difficult. They have not been however sufficiently recognized and therefore, occasional troubles arise to find in what geological conditions a selected well is located. In broad literature of the item there are distinct opinions on role of fissuring in a system of groundwater table. J. Sawicki (1978) presents an unívocal opinion, resulting from relations between water table levels in a

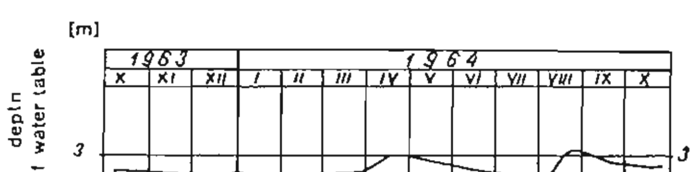


Fig. 12. Fluctuation of a water table in Lower Silesia after J. T. Tomaszewski (1990), similarity to fluctuation of a first type
Wahania zwierciadła z obszaru Dolnego Śląska według J. T. Tomaszewskiego (1990), analogia z wahaniami pierwszego typu

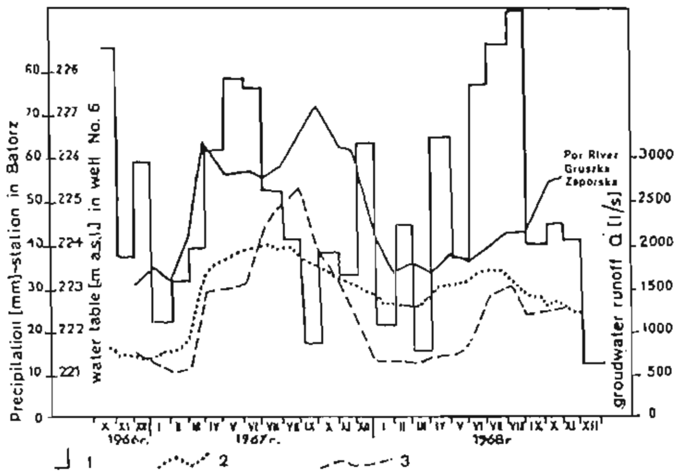


Fig. 13. Curve of precipitation, groundwater runoff and water table in the well no. 6 in the Por catchment; section Tarnawa, example of concordance

1 — precipitation; 2 — wells; 3 — groundwater runoff

Wykres opadów, odpływu podziemnego i stanów zwierciadła w studni nr 6 w zlewni Poru; przekrój Tarnawa, przykład zgodności

1 — opady; 2 — studnie; 3 — odpływ podziemny

well and groundwater flow. He obtained curves of underground stream recharge and storage curves and concludes that water table location results from geological factors. The same author (1986) says that water table fluctuation depends on degree of covering of water-bearing horizons. If a water table indicates no pressure and occurs at shallow depths, then its fluctuation is subjected to annual hydrological cycle. On the other hand, deep occurrence of water table results in several years' regression.

Fluctuation of the first type in Roztocze can be strictly connected with annual hydrological cycle, resulting from intensity of recharge in early spring, reflected in spring maximum (March–May) and followed by slow regression until the end of October or slightly longer, independently on water table depth. No such connection is noted between fluctuations of the second and the third types.

Similar opinions are also presented by J.T. Tomaszewski (1990) that presents examples of several months' and several years ' regressions. In wells with a confined water table, regressions lasted 16–18 years (Fig. 16) with maximum fall of 3 m, and in a well with a non-confined one — 12 years, with a water fall of 0.4 m. This author doubts in uniform influence of climatic factors on water table fluctuation, the more so as these are shallow wells.

J. Miecznicki et al. (1979) analyzed relation of a water table from a storage just before a spring rise. Applying a regression method and elaborating 43 wells, these authors received in three wells a correlation of 0.9 only and in thirteen — below 0.6. Thus, only in about 30% of wells, a spring rise could be evaluated, although its accuracy is different.

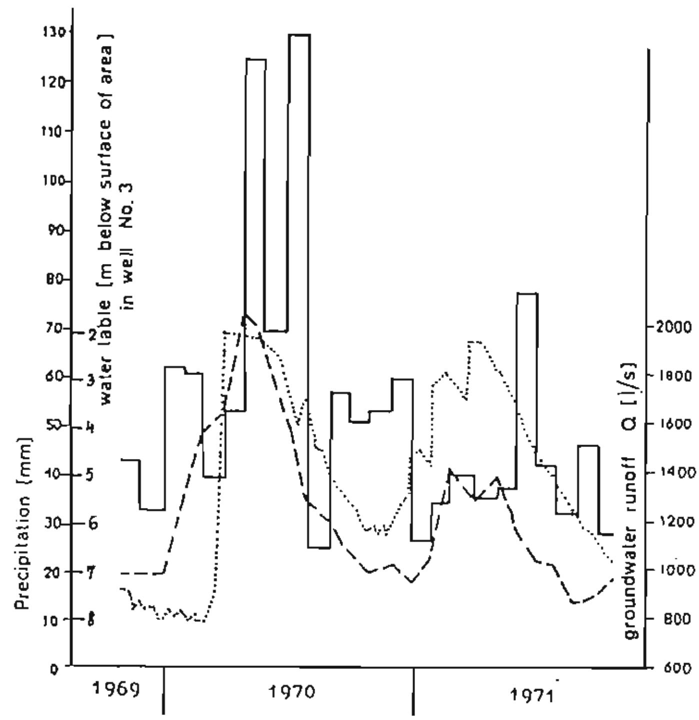


Fig. 14. Curve of precipitation, groundwater runoff and water table in the well no. 3 in the Sołokija catchment; section Mosty

For explanations see Fig. 13

Wykres opadów, odpływu podziemnego i stanów zwierciadła w studni nr 3 w zlewni Sołokiji; przekrój Mosty

Objaśnienia jak na fig. 13

D. Małecka (D. Małecka, T. Lipniacka, 1990) expressed an opinion that water table variation depends on morphological location i.e. valley, slope and watershed. Peculiar features of the area studied by the authoress suggest reality of the presented opinions.

Basing on results from studies in Roztocze, also carried through by other scientists, there is a distinct opinion on decisive role of geological, hydrogeological and morphological factors, although none of the authors received univocal relations. Described connections are still referred to single cases.

In wells of Western Roztocze a water rise, initiated in all the wells in 1966 and reaching maximum in 1967 with varying intensity, is the common feature of the first three types. It seems to indicate a many years' hydrological cycle that results in more intensive recharge every several years. If it were the case, then two recharge cycles could occur in Western Roztocze: annual — represented by fluctuation of the first type and many years' — indicated in fluctuation of the second type.

Comparison of water table fluctuation in Roztocze with other areas of the country indicates great similarity of water table in annual cycle, resulting in spring rises —

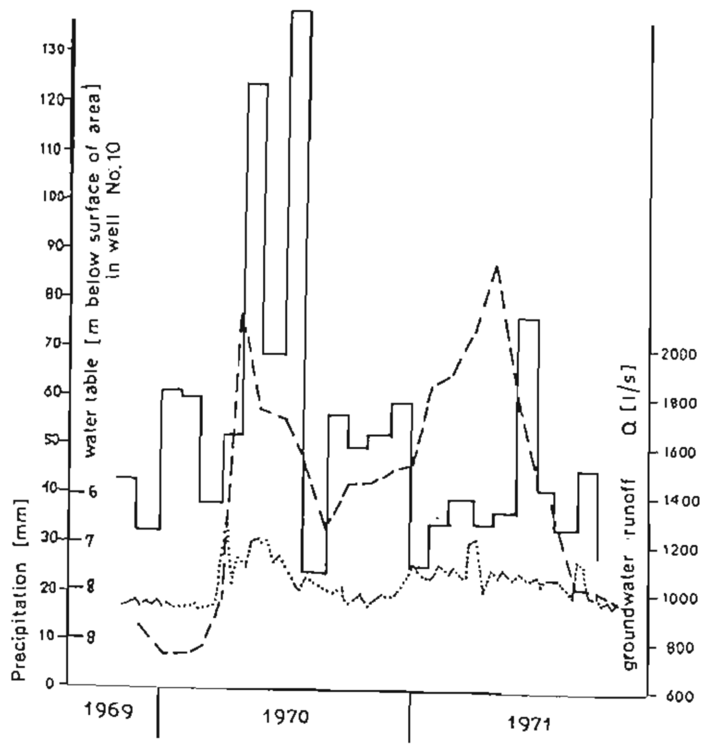


Fig. 15. Curve of precipitation, groundwater runoff and water table in the well no. 10 in the Tanew catchment; section Rebizanty, example of no concordance

For explanations see Fig. 13

Wykres opadów, odpływu podziemnego i stanów zwierciadła studni nr 10 w zlewni Tanwi; przekrój Rebizanty, przykład braku zgodności

Objaśnienia jak na fig. 13

many a time long-lasting (February–June) and in regression until the end of October. Such type prevails, although observations were collected in different time. The other types distinguished in Roztocze (second, third and fourth) have already no such frequent equivalents. Such distinct coincidence proves that there is a certain definite type of hydrogeological conditions, typical for similar course of recharge phenomena and flow. Existing recognition in this field by different authors indicates it univocally, although it comes from different years. It seems obvious that previous results formed essential basis to elaborate measurements of the observatory network owned by the Polish Geological Institute.

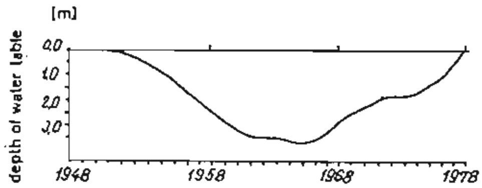


Fig. 16. Water table in the well Polska Cerkiew after J. T. Tomaszewski (1990)
Stan zwierciadła w studni Polska Cerkiew według J. T. Tomaszewskiego (1990)

PROBLEM OF WATER TABLE PROGNOSES

Prognosis of water table fluctuation is a very complex task. From one side it concerns a cognitive aim of hydrodynamic phenomena and processes, and from the other — evaluation of quantitative and qualitative changes in groundwater resources. Previous knowledge in this field, coming from short-term observations — in the best case lasting several years — indicates a repeated annual cyclicity of a water table what makes prognoses relatively easy. On the other hand fluctuations cited in publications as well as the author's results suggest deviation from such a scheme. It proves presence of other natural factors that deform this annual cycle. Most scientists agree that water table is varying. Providing a multi-factoral analysis with a present observatory system when only single data but measurements (precipitation, geological conditions of a well, land relief) are available, is not however possible. J. Lambor (1962) suggests sun-spots as a very important factor. Influence of spots was already noted in the XIXth century. In 1865–1880 Mendel collected observations in a well in Moravian Brno and indicated connection with sun-spots. During spot maximum in 1870 a falling trend of water table was noted whereas minimum of spots in 1879 occurred at a maximum rise. Similar cyclicity was noted in the well Elscholz in Germany (W. Koehne, 1948). Such dependence was noted also by J. T. Tomaszewski (1990). Having observations from 1944–1981 in the Lower Silesia, this author indicated four maxima of sun-spots and corresponding water table minimum in 11 wells. These connections although very distinct, remain still discussive as we still have not recognized course of the phenomena that occur during spot intensification period.

H. Więckowska (1960) connected water table with hydrodynamic equilibrium, according to which shape of a first groundwater table depends on climatic humidity and depth of impermeable bed. Starting from the formula of W. Koehne (1948) the authoress distinguished 11 types of such stability. A scheme of H. Więckowska (1960) refers to shallow open groundwater reservoir. It seems however difficult to be applied and interpreted in case of a tight reservoir with isolating cover and deep reservoir.

Practical examples of prognoses are presented by A. A. Konoplancev and N. N. Siemionov (1979) — they can be effectively applied when terms of well location and of observations are fulfilled.

First attempts of a broad analysis of prognosis methodology have been undertaken in Poland by J. Miecznicki et al. (1979). They used a total annual curve of monthly amplitude, thus presenting annual storage fluctuation. Discussing wider phenomena, they noted relation between variation and recharge intensity. Prognosis of water table is based on statistical analysis and evaluation of a correlation coefficient. If the latter

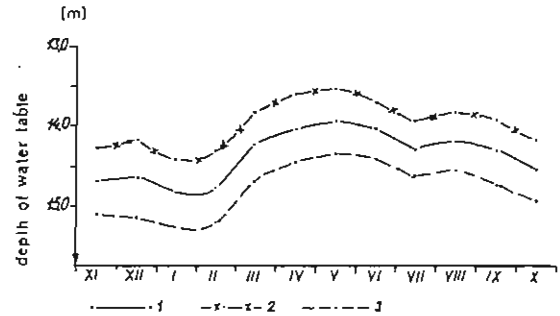


Fig. 17. Ten-year mean water table and confidence limits in the well Giełczew after J. Malinowski and E. Przytuła (1991)

1 — many years' mean; 2 — upper limit of a confidence interval; 3 — lower limit of a confidence interval

Średnia stanów zwierciadła i granice ufności w studni Giełczew z dziesięciu lat według J. Malinowskiego i E. Przytuły (1991)

1 — średnia z wieloleeia; 2 — górna granica przedziału ufności; 3 — dolna granica przedziału ufności

is equal to 0.9, then prognosis was favourable. Correlation coefficient (r) below 0.6 resulted in unfavourable prognosis. These authors analyzed also connections between minimum pre-spring water table and mean annual state of a preceding year. Applying a correlation method for 52 observatory sites, they received: $r = 0.9$ for 3 sites (5.8%), $r = 0.8$ to 0.9 for 13 sites (25%), $r = 0.6$ to 0.8 for 18 sites (34.6%) and $r = 0.6$ for 18 sites (34.6%). In conclusion they find the method of analysis of water table from mean annual ones of a preceding year to be applied if $r = 0.9$ or from 0.8 to 0.9. Analysis of minimum pre-spring water table from mean autumn ones in 95 wells indicated: $r > 0.9$ for 3 wells (7%), $r = 0.8$ to 0.9 for 10 wells (23.3%), what makes together 30.3% of positive values. The authors point out certain, although limited possibilities in application of these methods.

J. Sawicki (1978) introduced a method to construct curves of underground stream recharge and their comparison with storage curves on the Rakówka river near Bełchatów in several sections. He suggests possible application of the afore-mentioned curves to define balance calculations and a water table. This method seems to be applied in small catchments. He introduced also an idea of falling gradient (1986) as difference between initial and final states for winter and summer time. When analyzing the experimental curves, he found dependence from hydrogeological and geological factors.

In 1988 J. Malinowski and E. Przytuła elaborated data for groundwater table in the Lublin-Radom Basin, collected during ten years. To this purpose they used a statistical method of mean annual as a total of mean monthly water table, delimited a confidence interval, introduced rise and regression coefficients to prognosis of short-term variation and also, balancing of rises and losses to estimate annual changes in water affluence. Ten-year observations from 40 wells were analyzed and to their description a method of averaging a water table was applied to every month in the ten-years' observation cycle. In this way mean annual water table and confidence interval were defined (Fig. 17). Such description of wells enables water table prognoses for every month of a hydrological year (J. Malinowski, E. Przytuła, 1991).

For short-term prognoses the authors suggest to use regression and rise coefficients of a water table. These coefficients can be used at distinct rise or fall trends. The method is generalization as a resulting eurve is smoothed. However, from a point of view of expected changes, results seem to be quite accurate. In such a procedure the question however arises whether rise and fall coefficients are identical i.e. if they present objective conditions of saturation and drainage. From the author's various recalculations they seem to be very close to each other. This problem has however a considerably broader aspect and its description outruns limits of a short paper.

Similar method was applied also by J. Sawicki (1986) who introduced the term of "dropping gradient" to delimit curves of a falling table in summer and winter. This gradient is of regression type and could be expressed as a fraction. When recalculating data of J. Sawicki, the author of this paper received a regression coefficient of 0.0193 for winter and 0.0124 — for summer.

Methods of statistical analysis in evaluation of many years' and seasonal variability, and many years' trend of water table was applied by W. Chełmicki (1989) who ascribed considerable significance to analysis of standard deviation at defining a water table, regression method inclusive. These methods were applied during analysis of water table fluctuation in the Cracow Region. This author does not present however any example of solution.

J. T. Tomaszewski (1990) analyzed water tables in southwestern and central Poland, using regression formulae and delimiting progression (rise) and recession (regression) curves for short-term prognoses.

This review indicates that short-term prognoses, dependent on delimiting a water column height in a well, can be applied with great accuracy if any of the mentioned methods is used. Such prognosis indicates its usefulness to analyses of changes of intake resources during intervals devoid or with excess of precipitation. It can be applied for a catchments if a number of wells is large.

Results of observations can be also applied to balance increase (recharge) and loss (outflow) — to estimate resources at the end of a hydrological year (i.e. storage). Knowing it, spatial interpretation can be carried through. In this way comparative material from a longer observatory interval can be collected what enables to delimit recharge zones with greater probability.

RECAPITULATION AND CONCLUSIONS

Comparison of various types of water table fluctuation in Roztocze suggests that most common is fluctuation of the first type. It is connected with annual hydrological cycle. This type of fluctuation is expressed by H. Niedzielski (1971), J. Sawicki (1986) and J. T. Tomaszewski (1990) as referred to a spring rise maximum. On the other hand there is no distinct equivalent of a summer rise, noted by the mentioned scientists.

The second type of fluctuation in Roztocze is connected with a many years' cycle that has not been expressed previously by greater intensity. It occurs also in other areas what is obvious from papers of the mentioned scientists.

The third type of fluctuation in Roztocze is also connected with a many years' cycle, although during intervals with a low water level there are spring rises with very small amplitudes. They predominate in Central Roztocze.

The fourth type with minimum fluctuation does not indicate direct correlation with hydrological cycles and proves recharge continuity if a water-bearing horizon is not deep. On the other hand in deep wells a small fluctuation can indicate transit flow recharge, without influence of local infiltration.

Carried observations do not permit to connect fluctuation types with definite conditions of well location as similar fluctuation types occur in wells that conduct water from various depths, even from the same sediments, in different geological and geomorphological setting. For this reason no, even general hypotheses either on dependences or regularities can be formulated, in spite of finding obvious relations in single cases. Further studies and research analyses are needed in this direction. Fixing representative qualities of wells in definite geological and hydrogeological conditions is particularly important. This acts as a most difficult problem in choosing wells to stationary observations.

Analysis of watertable fluctuations in Roztocze indicates also that fluctuations of the first type are connected with annual hydrological cycle whereas fluctuation of the second and the third type — with annual but also with many years' cycles. Fluctuation of the first type should be assumed to have been also indicated in many years' cycle but interrupted observations do not allow for a univocal attitude. Fluctuation of the fourth type does not remain under indirect influence of hydrological cycles. Explanation of this problem constitutes also a more important one to be solved. Presented dependences are confirmed by opinions of the mentioned scientists, although not every one assumes a clear opinion.

In water table prognoses a most suitable method is based on fixing mean states with statistical method and finding a confidence interval. A characteristic mean created in this way enables to evaluate changes in watertable location on the basis of current data, particularly of trends in rise or regression. On the other hand numerical changes can be defined on the basis of rise or regression coefficients (J. Malinowski, E. Przytuła, 1991), gradients of falling after J. Sawicki (1986), through balances of rises and regressions, delimiting of storage to estimate changes in groundwater resources. Such analyses can be prepared for winter, spring and summer, and also changes of resources can be defined for these intervals. To gain this, continuity of studies is needed as they should be intensified with more and more data collected.

Carried observations of groundwater table in Roztocze do not indicate that fluctuation resulted in considerable changes in their resources. The noted cycle — spring rise and long-lasting regressions are characteristic states for each well. This opinion cannot be referred to anomalous states recorded in the wells nos. 1 and 40 in Western Roztocze and no. 3 in Central Roztocze. Maximum fluctuation, noted by rapid several metre rise, indicates increased resources lasting for several months or even longer.

Presented features of groundwater table indicate, independently on geological and hydrogeological or other conditions, existence of many problems that call for explanation and resolving. In this aspect significance of the observatory network of the Polish Geological Institute is reflected, a role of which increases every year as only a continuity of observations can support univocal interpretation of observed phenomena.

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Jan MALINOWSKI

ZMIANY ZWIERCIADŁA WÓD PODZIEMNYCH ROZTOCZA I PROBLEMY ICH OCENY HYDROGEOLOGICZNEJ

Streszczenie

Na obszarze Roztocza przeprowadzono stacjonarne pomiary zwierciadła wód podziemnych dla oceny zmian w zasilaniu poziomów wodonośnych, ich częstotliwości i pewnej prawidłowości. Warunki hydrogeologiczne Roztocza są stosunkowo proste. Poziomy wodonośne tworzą opoki i margle górnego mastrychtu oraz wapienie, piaski i piaskowce sarmatu i tortonu. Stanowią one przeważnie jeden kompleks wodonośny połączony hydraulicznie, pokryty częściowo grubą warstwą lessów do 30 m miąższości, częściowo zaś odsłonięty. Utwory czwartorzędowe nie tworzą zwartych poziomów wodonośnych i występują tylko w dolinach rzecznych. Obserwacje na Roztoczu Zachodnim prowadzono w latach 1964–1968, a na Roztoczu Środkowym — 1969–1971 (fig. 2 i 6).

Analiza stanów zwierciadła pozwoliła wydzielić cztery typy wahań:

Typ pierwszy (fig. 3) cechuje się wyraźnymi wzniosami wiosennymi w okresie luty–maj, po czym występuje regresja, a potem niewielki wznios w sierpniu–wrześniu, regresja do końca roku hydrologicznego i powolny wznios. Są to wahania najbardziej powszechne dla całego Roztocza i wynikają z rocznego cyklu hydrologicznego, na co wskazuje porównanie z opadami atmosferycznymi.

Typ drugi (fig. 4) charakteryzuje się małymi wzniosami wiosennymi przez kilka lat i jednorazowym dużym skokiem przypadającym podczas obserwacji na okres wiosenny. Wahania te należy wiązać z wieloletnim cyklem hydrologicznym, przy nieznacznym wpływie cykli rocznych.

Typ trzeci (fig. 5) charakteryzuje się małymi wzniosami wiosennymi, bez wyraźnych zależności od cykli hydrologicznych. Wahania te są również sporadyczne.

Typ czwarty (fig. 7) wykazuje minimalne amlitudy, rzędu kilkunastu centymetrów, a związki z cyklami hydrologicznymi są tu niewidoczne.

Wydzielone typy wahań porównano z wahaniami z innych obszarów Polski i stwierdzono duże podobieństwa do wahań pierwszego typu, co ilustrują fig. 9, 11 i 12. Wahania z całego obszaru Roztocza porównano również z odpływem podziemnym i stwierdzono, że w kilku zlewniach są one równoległe (fig. 13 i 14). Jednak analiza statystyczna nie wykazała istotności korelacji, a współczynnik był niższy od 0,5. W niektórych zlewniach tej równoległości nie stwierdzono (fig. 15).

Ważnym elementem w ocenie wahań jest prognoza stanów zwierciadła. Zwrócono uwagę, że przy obecnym stanie danych, najwłaściwsza jest metoda uśredniania stanów zwierciadła i wyznaczenie przedziałów ufności w granicach, w których można oczekiwać zmian w układzie zwierciadła. Przykład takiego opracowania danych przedstawia fig. 1. Metodę tę można stosować przy dłuższych okresach obserwacji. Dla prognoz krótkoterminowych można stosować metodę współczynnika wzniosu bądź regresji.