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Zdzisław Mikulski

THE DEVELOPMENT OF RESEARCH ON WATER BALANCE IN THE 20TH CENTURY IN POLAND AND AN ATTEMPT OF ITS ASSESSMENT

THE BEGINNINGS AND THE DEVELOPMENT OF THE NOTION OF WATER BALANCE

In order to be able to conduct a rational water economy of a region we must express the water cycle taking place in nature in terms of numbers. It is customary to refer to such a quantitative expression of the water cycle as to water, or hydrological, balance. The first such quantitative model is ascribed the German hydrologist A. Penck (1858–1945), who formulated it as the equation

$$\text{precipitation } (P) = \text{outflow } (H) + \text{evaporation } (E)$$

This equation served initially to determine outflow on the basis of knowledge of precipitation and evaporation, or to determine evaporation on the basis of precipitation and outflow, in view of the shortage of measurement data.

In 1904 a Russian hydrologist Y.V. Oppokov (1869–1938) made use of the equation of Penck to demonstrate the differentiation of the hydrological balance over a longer time period with respect to the annual averages. He added the component $\pm\Delta R$ (called balance difference), indicating the changes of watershed retention. Thus, the equation acquired now the form

$$P = H + E + \Delta R$$

called thereafter the Penck-Oppokov equation. This equation has been in use in principle until today, especially in the general calculations of the hydrological balance of a watershed.

In 1940s the American climatologist W.C. Thornthwaite proposed the following form of the water balance equation (Thornthwaite, Mather, 1955):

$$P = PE + \Delta S + R$$

in which P is total precipitation, PE is potential evapotranspiration, ΔS is the difference of water storage in the soil, and R is the free surplus of water (most often it is assumed that $R = 0$).

This approach, having become quite common in the American conditions, has not gained acceptance in Europe, possibly because of the inordinately complicated calculations of evapotranspiration as an element of climate.

The study of hydrological water balance developed quite early in Poland, pioneered by K. Dębski (1895–1968). The starting point was marked by the paper presented by Dębski at the Plenary Meeting of the International Association of Scientific Hydrology in Lisbon in 1933, entitled "Les relations entre les précipitations, l'écoulement et la rétention dans le bassin de la Prypeć". In 1938 he published, in Polish, *Wytyczne metodyki bilansowania wód* (Indications on the methodology of development of the water balance). He returned to this subject domain just after the World War II and published the paper entitled "The study of the water balance for Poland". At the beginning of the 1950s the Committee for Water Economy of the Polish Academy of Sciences undertook the work on the long-term plan of water economy in Poland. In the course of this work the first water balance of Poland was elaborated. It was put together on the basis of not quite homogenous data, dating yet from the pre-war period. This balance can generally be treated as representing the hydrological conditions of the first half of the 20th century. In view of the high rank of the long-term plan, the values of components of the balance were, however, commonly accepted as valid for the whole second half of the 20th century in Poland.

In the calculations of the water balance, mentioned before, it turned out possible already to separate two components of the outflow: surface outflow (H') and underground outflow (H''), this possibility being due to the study of ground water over the area of the country. The surface component develops primarily in the upper part of the basin, where there are no advantageous conditions for the infiltration of the precipitation and the meltdown waters into the ground (important slope inclinations, and a usually thin soil layer in the mountains). The underground component is active in principle along the whole course of a river (as river drains the area through which it flows). These reasons determine the character of the two components — the surface outflow emerges in a short time, is short-lived and has a large volume, while the underground component features high stability and much larger hydrological inertia.

The division of the river outflow into two components has been developed only in the middle of the 20th century, bringing the balance equation to the following form:

$$P = (H' + H'') + E \pm \Delta R$$

Yet, this form of the equation did still not account for an important element of the water cycle, namely soil moisture (W), this quantity being hidden in both outflow (H) and evaporation (E), since both these elements are in close relation with inflitration and water content in the soil. At the same time, soil humidity is an important component of the water balance, especially from the point of view of needs of the plants.

In the 1950s the Russian hydrologist M.I. Lvovich (1974) proposed the water balance equation into which six balance elements were introduced:

$$P = H + E\,; \qquad P = H' + H'' + E$$
$$P - H' = H'' + E = W$$

where: H' and H'' are, respectively, surface and underground outflows, and W is the total humidity of the area.

The same author introduced additionally two balance characteristics, namely:

— underground outflow coefficient: $K' = H''/W$; and

— evaporation coefficient: $K'' = 1 - K' = E/W$;

which provide information on what part of annual percolation (sinking) forms the underground outflow and what is used up through evaporation.

The method of differentiated water balance of Lvovich corresponds to the contemporary opinions on the way in which the water balance of a watershed is shaped. This kind of balance distinguishes the genetically different components of the river outflow, as well as the soil-related link of the water cycle. This particular link encompasses a part of the precipitation and meltdown waters percolating into the ground, as well as evaporation from the water surface and evaporation of the water wetting plants during rain. Both these paths through which precipitation is divided have an especially high importance in the lake and forested basins.

The genetic division of the river outflow into the surface and underground components allows to develop the equation of the hydrological water balance and is of practical significance, since each of these components has a different meaning in economic terms. A stable underground outflow — contained in the riverbed — constitutes in a way a guaranteed water reserve in a river, ensuring an easy coverage of water needs. On the other hand, surface outflow appears occasionally under the impact of sudden melting of snow or heavy rains, has a violent character and brings about the threat of erosion or shallowing of the riverbed. It necessitates regulation through creation of artificial reservoirs in order to be used in an economic manner. That is why it ought to be treated as a potential water reserve, and the respective calculations must involve stochastic methods, accounting for the frequency and probability of appearance of such outflow in the particular periods of time (Mikulski, 1977).

Generally, the method of differentiated equation of the water balance allows — basing upon the course of outflow in the river profile and the precipitation — to determine quantitatively the additional balance components, that is: the underground supply of the rivers, the surface outflow, the soil humidity, and the evaporation. This question can also be approached from the point of view of the mathematical model of water cycle in a watershed. While the classical approach to water balance presupposed the form of a usual mathematical "black box" model, the new approach represents rather a "white box model", accounting for a set of processes forming the water cycle. In this perspective the system of water cycle in a watershed is treated as composed of a number of subsystems (evaporation, infiltratition surface and underground outflow, etc.). This allows for a much more complete recognition of this complex natural process, a better identification of water resources in a basin, and consequently also a more effective use of these resources.

In the elaboration of water balances to date too little attention was paid to the degree of precision in estimation of the balance components. Yet, the study of precision of measurements of precipitation, conducted in various countries, demonstrated that the instruments used give in the majority of cases the values lower than the actual ones. The errors in liquid precipitation range from 10 to 20% on the negative side, and in solid precipitation the range of errors attains even 40–60% on the negative side, as well. The reason behind is the disturbance of the precipitation measurement caused by wind around the instrument, by evaporation of the precipitation, and by wetting of the instrument walls, especially important in a drizzle.

The study of water balance of the globe became the object of work during the decade of 1965–1974, the International Hydrological Decade, IHD, the largest research programme in hydrology on a global scale. As one of the results, a guidebook was published concerning calculation of water balances, entitled *Methods for Water Balance Computation* (1972). This guidebook concerned larger areas, water bodies, and atmosphere.

The National Committee for IHD of the Soviet Union published in 1974 an ample monograph of the global water balance. This edited monograph is composed of a volume of text and tables, and, separately, an atlas of 65 maps presenting the balance components of particular continents. This publication summarises the results to date, primarily those of the Soviet scholars, in the field of theoretical as well as experimental studies, and generalises an enormous statistical material from almost the whole world. The balance presented encompasses the whole of the Earth and the particular continents, larger water bodies, and regions. All the elements of balance were considered, including corrected precipitation, with corrections introduced for the whole globe.

This monograph remains until today the basic source of data on the waters of the Earth. In 1978 it was translated to English, and in 1980 — to Spanish. In the same time a different presentation of the world's water balance was elaborated in Germany (Baumgartner, Reichel, 1975), consisting in its calculation in the setting of latitude belts, separately for the northern and southern hemispheres.

During the IHD, and then afterwards during the International Hydrological Programme, IHP, of UNESCO, which constituted a continuation of the IHD since 1975, the countries of Central and Eastern Europe, in the framework of regional hydrological collaboration, undertook elaboration of maps of balance elements for the areas of respective countries. This concerned precipitation, outflow and evaporation, due consideration being given to the course of these processes along the state boundaries. These maps encompassed the period of 1931–1960. In this manner a correct — at least within the existing capacities — estimation was made for the first time of the true balance quantities. At the same time this was the first attempt of verifying the hydrological water balances that had been put together by the participating countries within their confines only (*Water Balance Maps...*, 1984).

The experience and the output from the IHD/IHP in the field of water balances were also made use of in Poland. Owing to the international hydrological collaboration determination of the elements of water balance of Poland was undertaken at the turn of the 1980s in the Department of Hydrology of the University of Warsaw, based on the methodology of M.I. Lvovich. Soon, a fundamental work of M. Gutry-Korycka (1985) was published, showing a new perspective on the structure of water balance of Poland, with consideration, in particular, of the corrected height of the precipitation layer, humidity of the area, as well as the division of outflow into surface and underground components. The elaboration encompassed the period of 1931–1960, in accordance with the postulates of the World Meteorological Organization, WMO.

Very interesting results concerning water balance were obtained. For the first time the corrected annual average precipitation in Poland could be determined (716 mm), and thereby the real input value of the water balance was established, equivalent to 120% of the previously adopted value. Likewise, for the first time soil moisture content of the country area was estimated and equivalent to as much as 88% of precipitation. Similarly, the obtained value of the annual area evaporation (645 mm) was bigger than had been used until then (430 mm). The value of outflow remained unchanged, similarly as its surface and underground components.

The first, long expected *Hydrological Atlas of Poland* (in Polish) appeared soon after this publication, in 1986–87. The image of the water balance, presented in it, contained only two elements: precipitation (uncorrected) and total river outflow, as well as the so-called balance difference, equivalent to the area evaporation. This elaborate encompassed the period 1951–1970, and the results obtained could only be compared to the results of calculations for the first water balance of Poland of the end of 1950s. A slight increase of precipitation took place (600 mm, i.e. 101%), indicating a somewhat more humid period (mainly of the 1960s), and a slightly bigger increase of area evaporation (444 mm, i.e. 103%), while outflow decreased (164 mm, i.e. 96%). The balance elements for the more important basins in Poland were presented in the Atlas through respective tables and maps.

AN ATTEMPT OF ASSESSING THE AVERAGE WATER BALANCE OF POLAND IN THE 20TH CENTURY

The complete and precise magnitudes of the elements of water balance for the 20th century will be known only in a couple of years after the end of this century — when the necessary corrections and calculations on the basis of the measurement material will have been done. Yet, it is possible already now to try to estimate these quantities, assuming the necessity of taking their averages.

The observed amounts of precipitation in the 20^{th} century, in accordance with the materials of the hydrological and meteorological service, amount in Poland on the average to 630 mm per annum. The corrected values of precipitation on the area of the country are currently not calculated — the official sources do not quote such data. If we assume, though, the average annual error correction to be equal +20%, then we obtain the corrected normal annual precipitation at the round number of 750 mm (235 cu.km).

Assuming that the data provided by the hydrological service are representative for the whole 20^{th} century we can take the annual river outflow magnitude as equal 60 cu.km (192 mm). The division of the river outflow into surface (*H'*) and underground (*H"*) components shows a slight domination of the underground component (55%) over the surface component (45%). Treating this division as valid for the whole 20^{th} century we obtain the magnitudes of surface outflow (H' = 86 mm = 27 cu.km) and underground outflow (H'' = 106 mm = 33 cu.km).

The estimate of the magnitude of area evaporation on the territory of Poland, based upon the indirect method, taking into account the corrected precipitation, for the period 1931–1960, was provided by M. Gutry-Korycka (1985). Its value is E = 545 mm = 170 cu.km. It is most often assumed in the water balance that the magnitude of area evaporation is identical with the outflow deficit, that is — the difference between precipitation and outflow. If so, given the corrected precipitation P = 750 mm = 236 cu.km, we obtain the volume of actual evaporation $E = P - H = 750 - 192 = 558$ mm (or: 235 – 60 = 175 cu.km).

A particular place is occupied in the water balance of M.I. Lvovich by the total humidity of the area. The author quoted defines it as $W = P - H' = E + H''$ = 750 – 80 664 mm (or: 235 – 27 = 208 cu.km). The additional balance characteristics of Lvovich take the following values:

— the ground outflow coefficient $K' = H''/W$ = 106/664 = 0,159 ≈ 16%,

— the evaporation coefficient $K'' = 1 - K'$ = 1 – 0,159 = 0.841 ≈ 84%.

The average water balance for Poland in the 20^{th} century (see Table 1) shows a considerable stability of its elements, which supports the conviction that the water conditions of our country, provided, of course, preservation of the precepts of the sustainable development, will not undergo an essential change. The water balance for Poland, occupying a significant part of Central Europe, and especially of its plains, may be treated as to a certain degree representative for the whole territory of Central Europe. Taking the magnitudes of the natural elements of water balance, defined through the thickness of the water layer (in mm), we can treat these values as representative for the whole territory. It would be interesting to make a comparison with similar calculations for other countries.

Table 1.

Water balance of Poland according to different sources (mm/cu · km)

Author — source	Year	Corrected precipitation P_t	Measured precipitation P_o	Soil moisture *W*	Evaporation *E*	Outflow *H*	Surface outflow *H'*	Underground outflow *H"*
Committee for Water Economy of the Polish Academy of Sciences	1959	–/–	603/187	–/–	430/134	171/58	74/25	97/33
Soviet Committee of the IHD	1974	730/227	–/–	–/–	557/176	156/49	–/–	–/–
Gutry-Korycka M.	1985	716/224	–/–	632/193	545/170	171/54	76/24	95/30
Hydrological Atlas of Poland	1986	–/–	608/–	–/–	444/ –	164/ –	–/–	–/–
Mikulski Z.	2000	750/235	630/197	664/208	558/175	192/60	86/27	106/33

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