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APPLICATION AND VERIFICATION OF A WATER BALANCE MODEL WITH DISTRIBUTED PARAMETERS (ON THE EXAMPLE OF REGA RIVER BASIN)

Abstract: The purpose of the study reported was to apply and verify a model of water balance of spatially distributed parameters in a meso-scale river catchment. The model was applied in the basin of Rega river, with the use of meteorological and hydrological measurement data from the years 1956–1995. In modelling, due account was taken of the land use changes having occurred during the 40-year period considered. The output from modelling was constituted by the raster maps of area evaporation, surface runoff and supply of the underground water resources. On the basis of these results the magnitude of outflow and the structure of water balance were calculated for three river gauge profiles. The deviations of the model-based calculated outflow values from the measured ones were maximally equal +10% for the entire 40-year period and +20% in one of the 5-year sub-periods.

Keywords: hydrological modeling, Geographical Information Systems (GIS), water balance.

The purpose of the study reported was to apply and verify a water balance model with the spatially distributed parameters in a river catchment of a medium size. The study constituted a stage in the research leading to the elaboration of the spatial structure of the annual average values of area evaporation, surface runoff and groundwater supply, as well as determination of its temporal changes in the five-year periods over the 40-year time horizon of 1956–1995 (Pokojska, 2000a, b, 2001, 2003).

STUDY AREA

The study was carried out over the basin of Rega river, located in the North-west of Poland, closed with the river gauge profile of Trzebiatów (Fig. 1). The basin, in terms of its surface area (2628.3 sq. km), is a meso-scale entity on the spatial scale of water cycle (Becker, 1992).

The basin of Rega is dominated by boulder clays, sands and gravel of the glaci-fluvial accumulation, as well as sands in the zone of frontal moraine, originating from the Baltic glaciation. The most common relief form is the

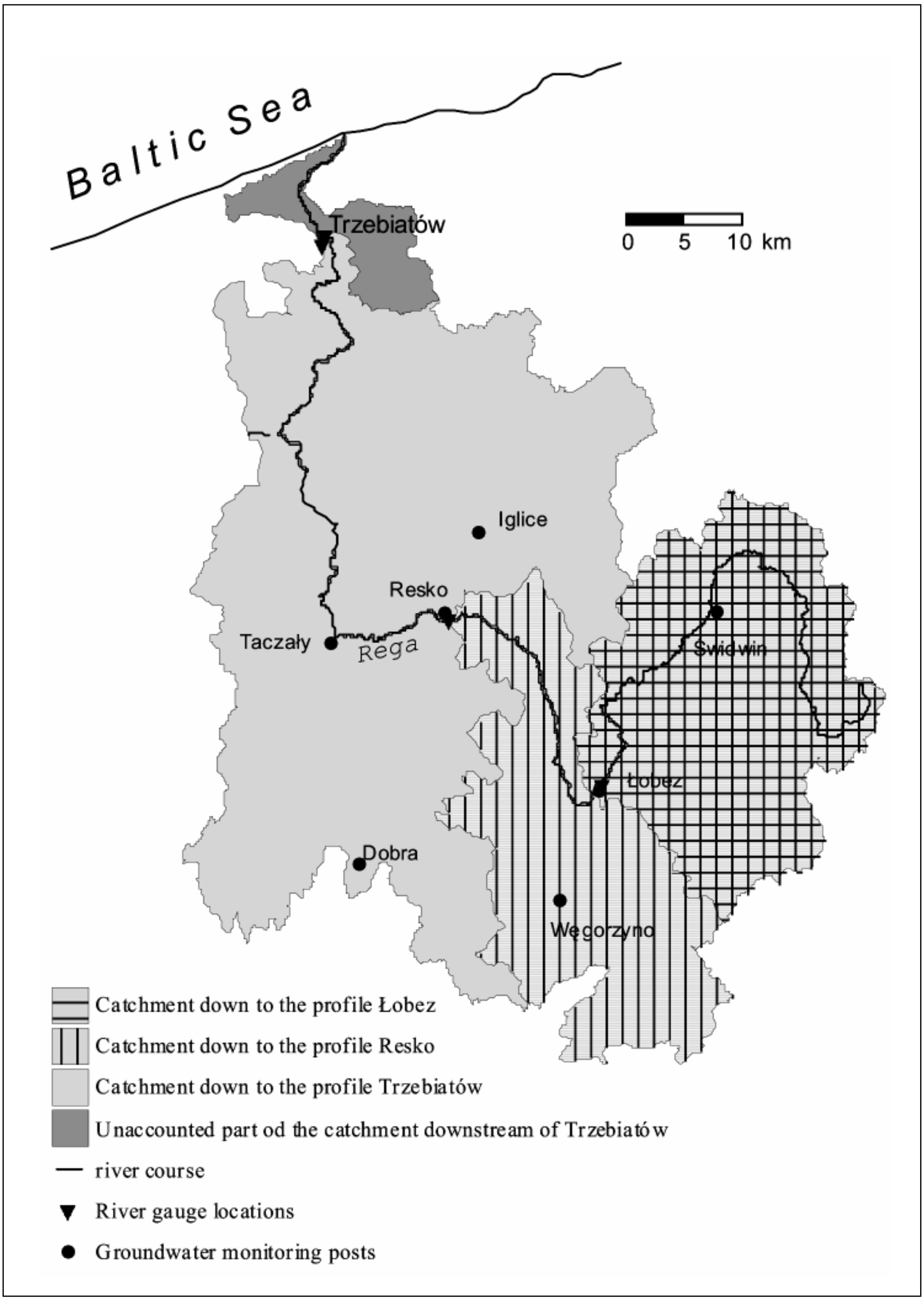

Fig. 1. Locations of river gauge profiles and the underground water monitoring posts in the basin of Rega river.

rolling moraine upland. The altitude of the area ranges between 2 and 91 m a.s.l., the gradient reaches 20%. Among the soils the dominating ones are light clayey sands (30%), loose clayey sands (24%), strong clayey sands (14%) and weakly clayey sands (13%). In terms of land use the largest share is taken by arable land (63%), forests occupy 28% of the area, while meadows and pastures – 5%. During the last 40 years the area of forests in the basin increased (+12.5%), as did the area of meadows and pastures (+3.0%), while the arable land shrank (–14%), along with the area of the bogs (–1.1%). The average flow of Rega river during the 40 years between 1956 and 1995 in the closing cross-section amounts to 21 m^3/s. The diversified relief of the basin and the differentiated lithology allowed for the expectation of a complex structure of elements of the water cycle. On the other hand, it was possible to verify the applied mathematical model, owing to the long term hydrometric control of the river Rega.

THE METHOD OF STUDY

The model used in the study, WetSpass[1] (**W**ater and **E**nergy **T**ransfer between **S**oil, **P**lants and **A**tmosphere under **S**teady **S**tate) belongs among the static, conceptual models with spatially distributed parameters. The purpose of the model is to calculate area evaporation, surface runoff and underground water supply in a grid of geometrical fields. An essential element of the concept is its integration with the Geographical Information System (Batelaan et al., 1996; *IDRISI Hydrological*..., 1997). The study area is split up in the model into a set of square fields, identified with the raster. Each pixel represents a soil-and-vegetation column, formed by the association of selected physico-geographical features, described with a set of numerical parameters. The basis for the assignment of the values characterising vegetation cover and hydrological properties to each field is constituted by the maps of these elements, provided in a digital form. The input to the model is provided by the maps of selected components of the physico-geographical environment in the basin of Rega (Table 1).

Area evaporation is calculated in the model with the use of the Penman-Monteith methodology as a function of the accessible resources of soil and precipitation water, with consideration of the depth of groundwater head. The surface runoff and the supply to underground waters are separated from the balance difference on the basis of the empirically determined coefficients in dependence upon terrain slope, land use type and soil kind. The detailed numerical algorithm of the model and the results of the earlier verifications are given by A.D. Vargas (1996) and T. Sopharith (1996).

[1] This model was developed at the Hydrological Laboratory of the Free University in Brussels. The study reported made use of the version 0.1., built into the Grid module in the ARC/INFO package.

Table 1.

Maps constituting the input to the WetSpass model

No.	Element	Symbol	Unit
1	Corrected precipitation	P_r	(mm/d)
2	Potential evaporation from the free water surface	E_p	mm/d)
3	Wind velocities	u	(m/s)
4	Coefficient γ/Δ*	—	(-)
5	Relief slopes	—	%
6	Soils	—	(classes)
7	Land use (two maps from different time periods)	—	(classes)
8	Depth to the groundwater head	—	(m)

* The coefficient γ/Δ is calculated as a function of air temperature

THE METEOROLOGICAL AND HYDROLOGICAL DATA

The database formed for the purposes of the study contained the following meteorological and hydrological data, covering the 40-year period of 1956 – 1995: precipitation, air temperature, wind velocity, atmospheric pressure, insolation, cloudiness, relative humidity, humidity deficit, water vapour pressure, river flow and underground water heads.

The monthly totals of precipitation, originating from 67 rain gauges, constituted the basis for elaboration of precipitation fields. The spatial structure of precipitation was elaborated with the kriging method, after having carried out the comparative analyses for the methods of automatic interpolation. The fields of annual precipitation totals were adjusted by introduction of the correcting factor of +19.5%, determined for the basin of Rega, taken from the report of J. Jaworski (1996b).

The remaining meteorological elements are out of necessity represented by the sole climatological station in the basin, situated in Resko. Location of the station in the geometrical centre of the basin allowed for the adoption of the assumption of it being representative for the climatic conditions of the study area.

The values of river flow in Rega, used in verification of the model, originate from three river gauges (Table 2, Fig. 1). The measurements concerning the underground waters, representing the changes in underground retention, which are also made use of in the verification of the model, come from seven measurement posts located in the basin (Fig. 1).

The hydrological and meteorological data are ordered according to the hydrological years, and the average annual values in the consecutive 5-year periods, being the basis for modelling, were calculated on this basis.

Table 2.

Location of the river gauges on Rega river

No.	River gauge	Km of the river course	Surface basin upstream (km^2)	Null level of the water gauge in m a.s.l.
1	Łobez	104.4	609.1	54.090
2	Resko	76.6	1122.0	35.250
3	Trzebiatów	12.9	2628.48	0.192

DIGITAL MAPS OF THE PHYSICAL GEOGRAPHICAL PROPERTIES OF THE CATCHMENT

For purposes of modelling, side by side with the maps of precipitation, digital maps were elaborated of land use, groundwater depths, soil kinds, and terrain slopes (on the basis of the previously developed Digital Elevation Map). In view of the transformations in the land use within the basin after the World War II the land use maps and the underground water head maps present the state of the basin in the 1950s and in the 1980s.

In terms of organisation of spatial data at the stage of their acquisition the vector model was selected, which was then converted to the raster format, classification of contents having been carried out in accordance with the distinctions adopted in the model.

In view of the significance of the choice of the dimensions of the unit field in hydrological modelling and in spatial analysis (Bogdanowicz, Soczyńska, 1989; Pociask-Karteczka, 1995) and the demonstrated influence of this choice on the output from hydrological modelling (Blöschl, 1997; Kienzle, 1996), the optimum dimensions of the unit field were determined for the basin of Rega, taking into account the scale of the cartographic source materials, the precision of data acquisition, as well as the density of the network of measuring points. These optimum dimensions were determined for each of the thematic layers separately, to the effect of 1 km × 1 km on the digital precipitation map and 0.25 km × 0.25 km on the remaining maps. Next, after interpolation, each pixel of precipitation map was divided into 16 equal parts. In this manner the level of detail of the spatial pattern of precipitation, having emerged from interpolation (and conditioned by the density of the measurement network of the rain gauges), was retained, the resolution of the digital image being only enhanced for map algebra purposes.

RESULTS OF STUDY

The results of the modelling are constituted by the digital images of the spatial distribution of the annual average values of area evaporation, surface runoff and underground water supply in the 40-year period of 1956–

1995, and in its consecutive 5-year sub-periods (Pokojska, 2000a, 2001). These maps have the form of a raster, in which every pixel represents the magnitude of the respective component of the water balance, expressed in the layer thickness (in mm).

Verification of the model consisted in the calculation of the differences between the annual averages of runoff, measured at definite cross-sections, and the runoff calculated on the basis of the maps of runoff components, resulting from modelling. Outflow was calculated as the sum of the area averages of its components in three sub-basins, closed by the locations of river gauges in Łobez, Resko and Trzebiatów (Table 2, Fig. 1). In view of the long time intervals, for which verification was carried out, the assumption was adopted that the supply to underground waters is equal to the underground runoff. Besides, the obtained structure of the water balance for the Rega river basin was compared with the results of studies of other authors.

The differences between the average measured and calculated outflow in the 40-year period of 1956 – 1995 range between – 0.5% at the river gauge of Łobez and +10.3% at the river gauge in Trzebiatów, meaning that there is a propagation of error along the increase of the basin's area (Table 3). For the 5-year sub-periods the differences are bigger and range between –19% and +20%, with altogether 17 cases, in which the values obtained from the model are higher than the measured ones, and 5 cases to the contrary.

The too high values of the runoff, resulting from the modelling, are the effect of the simplifications adopted in the model – first of all the omission of the snow cover thawing subsystem and the changes in water retention in the basin. An influence on the results of modelling could also be exerted by

Table 3.

Results of verification of the WetSpass model in the basin of Rega. H_{pom} – measured runoff; H_{obl} – runoff calculated on the basis of model output

5-year	Łobez								
1956-1960	219	224	+2.44	–	–	–	230	258	+12.12
1961-1965	253	242	-4.35	241	271	+12.34	234	281	+20.25
1966-1970	258	288	+11.82	270	299	+10.67	261	307	+17.70
1971-1975	234	278	+18.67	235	280	+18.96	241	275	+14.09
1976-1980	248	280	+12.73	275	288	+4.89	272	306	+12.48
1981-1985	281	228	-18.98	283	241	-14.91	284	245	-13.71
1986-1990	316	255	-19.34	247	276	+11.72	255	275	+7.74
1991-1995	223	226	+1.51	228	261	+14.61	229	265	+15.59
1956-1995*	254	253	-0.50	254	273	+7.70	251	276	+10.30

* at the Resko river gauge the values concern the time period 1961–1995.

the lack of consideration of variability of the basin's lithology in the vertical cross-section and, though to a lesser degree, by the neglect of the no-outflow areas, which, however, was conditioned by the scale of the topographical maps.

Then, the negative differences between the modelled runoff and the measured one should most probably be assigned to the application of a too low correction of the precipitation sums. Thus, in the 5-year period of 1981–1985, in which there were too low model-provided runoff values at three river gauges, the annual precipitation was characterised by a high share of solid precipitation (on the average 28% in a year), which allows for supposing that the magnitude of precipitation introduced into the model was, despite the correction applied, too low, for the measurements of solid precipitation are charged with the highest errors. Besides, during the 5-year period of 1976–1980, characterised by high precipitation, there had been an increase of underground water retention in the basin, as witnessed by the raising of the groundwater heads in six out of seven underground gauge posts in the basin during the second half of the 1970s. Extraction from these resources, demonstrated by the lowering of the groundwater heads at the same gauges in the years 1981–1985, was a significant source of supply of river flows, this fact not having been accounted for in the model, due to its structure.

The remaining cases of the too low runoff values obtained from the model, occurred in the upstream part of the basin, closed off by the river gauge in Łobez. This area is most distant from the warming influence of the Baltic Sea, is characterised by the highest absolute altitudes in the basin, and so the share of solid precipitation is higher in this part of the basin than in the remaining ones. It can therefore be expected that the measurement error of the precipitation in this part of the catchment is higher than the correction factor applied.

The digital maps of area evaporation and the runoff components made it possible to calculate water balance in the Rega river basin. Hence, a comparison could be carried out of its structure with the results of studies made for the Rega river basin by other authors.

The average annual area evaporation in the basin for the 40-year period studied, i.e. 1956–1995, amounted to 549 mm (Table 4). The highest area evaporation took place in the 5-year periods of 1966–1970 and 1991–1995, while the lowest one was recorded in the period of 1961–1965. The share of the average annual area evaporation in the water balance of the basin in the 40-year period analysed decreases with the downstream increase of the basin's area, from 69.6% of precipitation in the upper part of the catchment, closed off with the river gauge at Łobez, down to 66.5% for the entire basin (Table 4). This regularity is also observed in almost all the 5-year sub-periods of the whole period.

The studies of J. Jaworski (1988, 1996a) showed that the average annual evaporation in the basin of Rega river was equal in the decade 1961–1970 amounted to 540 mm (Jaworski, 1988), while in the 30-year period 1961–1990 – to 580 mm (Jaworski, 1996b). In both time intervals area evaporation

Table 4.

The structure of the water balance of the Rega river basin
in the consecutive 5-year sub-periods and the entire period of 1956–1995

Time interval	P_r (mm)	E_t (mm)	H_{surf} (mm)	H_{und} (mm)	H_{tot} (mm)	E_t (%P_r)	H_{tot} (%P_r)	H_{surf} (%H_{tot})	H_{und} (%H_{tot})
Łobez									
1956-1960	794	570	68	156	224	71,79	28,21	30,36	69,64
1961-1965	797	555	75	167	242	69,64	30,36	30,99	69,01
1966-1970	885	597	90	198	288	67,46	32,54	31,25	68,75
1971-1975	853	575	84	194	278	67,41	32,59	30,22	69,78
1976-1980	855	575	84	196	280	67,25	32,75	30,00	70,00
1981-1985	798	570	66	162	228	71,43	28,57	28,95	71,05
1986-1990	829	574	76	179	255	69,24	30,76	29,80	70,20
1991-1995	823	597	65	161	226	72,54	27,46	28,76	71,24
1956-1995	**829**	**577**	**76**	**177**	**253**	**69,59**	**30,41**	**30,04**	**69,96**
Resko									
1956-1960	–	–	–	–	–	–	–	–	–
1961-1965	807	536	80	191	271	66,42	33,58	29,52	70,48
1966-1970	872	573	89	210	299	65,71	34,29	29,77	70,23
1971-1975	828	548	78	202	280	66,18	33,82	27,86	72,14
1976-1980	836	548	80	208	288	65,55	34,45	27,78	72,22
1981-1985	785	544	65	176	241	69,30	30,70	26,97	73,03
1986-1990	826	550	76	200	276	66,59	33,41	27,54	72,46
1991-1995	835	574	70	191	261	68,74	31,26	26,82	73,18
1961-1995	**827**	**553**	**77**	**197**	**274**	**66,93**	**33,07**	**28,04**	**71,96**
Trzebiatów									
1956-1960	804	546	72	186	258	67,91	32,09	27,91	72,09
1961-1965	816	535	80	201	281	65,56	34,44	28,47	71,53
1966-1970	878	571	88	219	307	65,03	34,97	28,66	71,34
1971-1975	816	541	73	202	275	66,30	33,70	26,55	73,45
1976-1980	852	546	82	224	306	64,08	35,92	26,80	73,20
1981-1985	784	539	63	182	245	68,75	31,25	25,71	74,29
1986-1990	819	544	72	203	275	66,42	33,58	26,18	73,82
1991-1995	834	569	68	197	265	68,23	31,77	25,66	74,34
1956-1995	**825**	**549**	**75**	**201**	**276**	**66,54**	**33,46**	**26,99**	**73,01**

H_{tot} – total runoff; H_{surf} – surface runoff; H_{und} – underground runoff

constituted 69% of precipitation. Calculation of the average values in these time intervals on the basis of the results from modelling shows that in the decade of 1961–1970 the average area evaporation was estimated at 553 mm, while for the 30-year period of 1961–1990 – at 540 mm. According to the results of M. Gutry-Korycka (1978, 1985) concerning the structure of the water balance of Poland, the average annual area evaporation within the

Coast of Szczecin and the Western Pomeranian Lakeland ranged in the 30-year period of 1931–1960 between 500 and 600 mm. High area evaporation from the lowland territories of the Western Coastland is assigned by M. Gutry-Korycka to the influence of the Baltic Sea. The average values of area evaporation, calculated with the WetSpass model are, therefore, similar to those obtained by both J. Jaworski and M. Gutry-Korycka.

Conform to the numbers quoted before, in the 40-year period analysed the runoff constituted 30.4% of precipitation in the upper part of the basin, and 33.5% in the entire basin. In the upper part of the basin runoff had the smallest share in the water balance during the 5-year period of 1991–1995 (27.5%), and the highest – in the 5-year period of 1976–1980 (32.8%), Table 3. In the entire basin these extreme shares occurred at the following time periods: the lowest share of the outflow took place in the 5-year period of 1981–1985, while the highest – similarly as for the upper part of the basin – in the period 1976–1980 (35.9%).

The annual average of the surface runoff at the gauge in Trzebiatów amounted in the entire period of 1956–1995 to 75 mm and accounted for 27% of the total runoff in the same period (Table 4). The respective values at the Łobez and Resko gauges were similar, namely 30% and 28%.

The average annual supply to underground waters in the period 1956–1995 amounted to 177 mm in the upper part of the basin and 201 m in the entire basin, constituting, respectively, 70% and 73% of the total runoff (Table 4). In the consecutive 5-year periods the average area supply to underground waters was characterised by high differences and ranged for the entire basin between 182 mm (the 5-year period of 1981–1985) and 224 mm (5-year period of 1976–1980).

According to the studies of M. Gutry-Korycka (1985) on the structure of the water balance of Poland in the period 1931–1960, the average annual runoff in the region considered amounted to between 200 and 250 mm, accounting for 30% of the corrected precipitation. Surface runoff is contained between 50 and 100 mm, while the underground component of the runoff is roughly equal 150 mm. The coefficient of the underground supply was more or less at the level of 0.2. These values are somewhat lower than calculated from the model, but the studies referred to concerned a different spatial scale, which limits the scope of their use.

J. Orsztynowicz (1974) dealt with the variability of underground supply of the rivers in Western Pomerania. According to this author the average annual coefficient of the underground outflow in the basin of Rega, i.e. the share of the underground runoff in the total runoff amounted to 73% at the profile of Łobez (in the years 1956–1965), and 70% at the profile of Trzebiatów (for the years 1951–1965), while the coefficient of the underground supply of the river, representing the share of the underground runoff in precipitation was equal at both river gauge profiles to 25%. The average annual effective supply of the groundwater down to the profile of Trzebiatów was at 166.5 mm, while the coefficient of effective supply of underground water was equal 0.26. J. Orsztynowicz (1974) determined also the magnitude of losses in the water balance of the basin of Rega on the basis of the difference between precipitation and the sum of surface runoff and the effective underground water supply, this estimation (410 mm) being, however, too low in view of the fact that correction was not introduced to precipitation value.

Against the background of the average water balance of the basins of Baltic Coast in the years 1931–1960 (Gutry-Korycka, 1985), the basin of Rega is characterised by the share of total runoff higher by 4%, while the share of underground runoff in total runoff is lower by 8.5%. Percolation, which is over a longer time period (here: 1961–1990) identified with the river runoff, was calculated also for the basin of Rega river by J. Jaworski (1996b), who obtained the value of 258 mm, equivalent to 30% of the corrected precipitation.

Comparison of the values of area evaporation, surface runoff and underground water supply, calculated with the WetSpass model, with the ones obtained by the independent methods by other authors, shows no essential differences. In the light of the here quoted results of studies and on the basis of the comparative analysis of the modelled and measured runoff the results of verification were considered satisfactory. The model can, therefore, be applied for the longer-term time intervals in Polish climatic conditions over the lowland and lake district areas.

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