Environment Protection Engineering

Vol. 44 2018 No. 4

DOI: 10.37190/epe180407

PAWEŁ WILK[1], PAULINA ORLIŃSKA-WOŹNIAK[1], JOANNA GĘBALA[1]

MATHEMATICAL DESCRIPTION OF A RIVER ABSORPTION CAPACITY ON THE EXAMPLE OF THE MIDDLE WARTA CATCHMENT

The paper presents a mathematical description of a module to determine the river absorption capacity (*RAC*), which is an extension of the Macromodel DNS/SWAT developed in IMGW-PIB. The balance equations of pollution loads are presented, as well as the mathematical description of the retention of pollutants, taking into account concentrations and loads of pollutants in selected river profiles. The developed mathematical module mRAC was tested in the Warta catchment between river calculation profiles Nowa Wieś Podgórna and Oborniki for total nitrogen (TN) and total phosphorus (TP).

1. INTRODUCTION

Maintaining a balance between human needs, economic growth and environmental protection is a key principle of sustainable development, and proper assessment of the ability to assimilate pollutants by surface waters in a given river stretch is now a key issue for the economic and ecological interests of the country [1]. Protecting waters and water resources is one of the most important objectives of EU water policy. The implemented Water Framework Directive (WFD) [2] treats water as a good and requires the introduction of a mandatory sustainable management of its resources, inter alia by preventing degradation, improving water resources and protecting water and aquatic ecosystems [3, 4]. The processes of transforming and transporting pollutants from the place of introduction into the environment into the inflow to the surface waters and further into the estuary, which is generally closing the calculation profiles, are complex and require analysis of physical, chemical and biological factors, as well as the knowledge and analysis of the degree of urbanization, the level of agricultural culture of the area and overlapping meteorological and hydrogeological phenomena [5]. The next step is

---

[1] Section of Modeling Surface Water Quality, Institute of Meteorology and Water Management, National Research Institute (IMGW-PIB), corresponding author P. Wilk, e-mil address: pawel.wilk@imgw.pl

to try to find mathematical formulas describing selected phenomena and thus to predict their development and possible changes. Today, mathematical models are used to solve such problems, combining a whole array of mathematical formulas that allow one to reproduce in varying degrees of detail the elements of the environment such as river catchments and their processes influencing the movement of pollutants. The basic mathematical model should fulfill the following two conditions. First of all, it should be simple enough to allow understanding and substantive interpretation of a phenomenon or a process, which is extremely difficult in the case of such complex processes as transport and conversion of pollutants into the environment. Secondly, it should be designed to accurately capture and describe the course of a phenomenon or a process [6, 7]. These models can be used to simulate the effects of long-term actions on a selected catchment area. Mathematical models also facilitate the simulation of the effects of implementing remedial programs to be implemented in the catchment area, for example as a result of the implementation of the WFD [8].

The general form of the model can be written:

$$Y = f\left(X_{D_i}, X_{D_j}, X_L\right) \tag{1}$$

where Y is a function that describes the characteristics of a feature, that is, a deterministic or random variable influenced by a researcher. f is a function of independent quantitative deterministic variables (X_{D_i}) and qualitative (X_{D_j}) and random variables (X_L). The paper presents a mathematical model for determining a parameter called river absorption capacity (*RAC*) [9, 10]. For analyzes, Discharge Nutrient Sea (DNS) Macromodel has been selected [5] using the soil and water assessment tool (SWAT) model [11, 12].

2. MATERIALS AND METHODS

2.1. MACROMODEL DNS/SWAT WITH A NEW MODULE – MRAC

The DNS macromodel has been designed in the Institute of Meteorology and Water Management, National Research Institute (Poland) for the analysis of processes taking place in a catchment such as water and matter cycles [5]. The macromodel is a unified tool combining existing and verified mathematical models and equations of hydrological transport process units. It allows us to simulate the long-term impact of land use on water quality and the impact of pollutant discharges to surface waters. It is a merger of data processing modules, data replenishment modules, water quantity models and water quality models.

Soil and water assessment tool (SWAT) [13] can be one of its modules. SWAT is a continuous long-term yield model. SWAT is a physically based model where processes associated with water and nutrient cycles are directly modeled by internal algorithms rather than incorporating regression equations to describe the relationship between input and output variables. Physical processes are simulated within hydrologic response units (HRU). HRUs are lumped land areas within the sub-basin that are comprised of unique land cover, soil and management combinations. To accurately predict the movement of pesticides, sediment or nutrients, firstly the hydrologic cycle is simulated. The simulation is divided into two major phases – a land phase which controls the amount of water (and nutrients) loading to the main channel and a routing phase which is the movement of water (and nutrients) through the channel network of the watershed to the outlet. Figure 1 shows the general sequence of processes used by SWAT to model the land phase of hydrologic cycle [11].

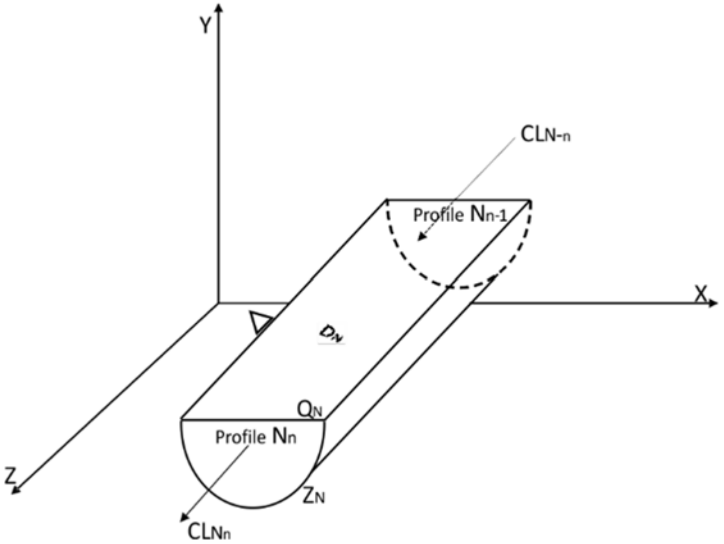

Fig. 1. Schematic diagram of the Macromodel DNS/SWAT enhanced with *RAC* module (based on [5])

Due to the fact that macromodel DNS/SWAT gives the possibility to extend it with additional modules and thus the ability to calculate additional environmental parameters (Fig. 1), it became the basis for the mRAC module for the selected homogenous surface bodies (JCWP) catchment area, using the results of the simulation.

2.2. RIVER ABSORPTION CAPACITY (*RAC*)

RAC between river calculation profiles N_{n-1} and N_n, for the *k*th pollution $(RAC_{N_n,k})$ is described as the maximum permissible flow of *k*th pollution into the river section, which will not cross limit load in the river calculation profile $N_n(LL_{N_n,k})$ based on the values of limits concentration $LC_{N_n,k}$ for good water status and characteristic flow of the river $Q_{Ch,N}$. We can write it using a mathematical formula:

$$RAC_{N_n,k} = LL_{N_n,k} - CL_{N_n,k} \tag{2}$$

where $LC_{N_n,k}$ means the actual load of *k*th of pollution in the N_n profile written with the formula:

$$LC_{N_n,k} = AC_{N_n,k} Q_{C,N_n} \tag{3}$$

where $AC_{N_n,k}$ means the actual concentration of *k*th pollution in the calculation profile N_n, and Q_{C,N_n} actual flow rate in this calculation profile. $LL_{N_n,k}$ is defined according to the formula:

$$LL_{N_n,k} = LC_{N_n,k} Q_{Ch,N} \tag{4}$$

2.3. BALANCE OF POLLUTANT LOADS FLOWING INTO RIVER CALCULATION PROFILE

RAC is a parameter describing the process that takes place over the whole length of the analyzed section of the river. Individual river calculation profiles provide control profiles that allow analysis of river flow processes influencing the absorption capacity. To be able to talk about the mathematical description of the river section absorption capacity, start by describing the pollution load at the point located at the profile calculation N_n, as shown in Fig. 2.

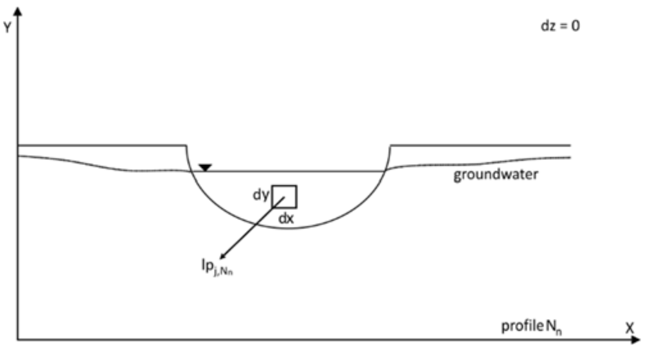

Fig. 2. N_n profile with marked surface *dx dy* and pollution load lp_{j,N_n}

The surface P_{N_n} of the calculation profile can be divided into squares of dimensions *dx*, *dy* and surface p_{j,N_n}, where:

$$PN_{N_n} = \int_1^j p_{j,N_n}(x,y)\,dxdy \tag{5}$$

It is assumed that the square *dxdy* is the wall of the cube *dx*, *dy*, *dz* and the cube is characterized by a constant concentration of *k*th pollution $a_{p_j,N_n,k}$ and constant flow q_{p_j,N_n} at time *dt*. It can be assumed that the load of *k*th pollution $l_{p_j,N_n,k}$ flowing through the square *dx*, *dy* at time *dt* is given by the formula:

$$l_{p_j,N_n,k}(x,y,z,t) = a_{p_j,N_n,k}(x,y,z,t)\,q_{p_j,N_n}(x,y,z,t) \tag{6}$$

In the following, only the *k*th pollution will be analyzed, so in Eq. (6) for the sake of clarity, the subscript *k* can be omitted and the equation takes the form:

$$l_{p_j,N_n}(x,y,z,t) = a_{p_j,N_n}(x,y,z,t)\,q_{p_j,N_n}(x,y,z,t) \tag{7}$$

For the so-called indications, the actual load for pollution flowing through the surface of the *P* calculation profile N_n (Fig. 2), marked $CL_{N_n,k}$ (Eq. (3)), depends on the time T_{N_n}, i.e., the flow time Q_N in the river bed length Δ*l* being the distance between the profiles N_{n-1} and N_n, and can be described by the equation:

$$\begin{aligned} CL_{N_n,k} &= \int_0^{T_{N_n}} \int_{P_{N_n}} l_{p_j,N_n}(x,y,z,t) \\ &= \int_0^{T_{N_n}} \int_{P_{N_n}} \left(a_{p_j,N_n}(x,y,z,t)\,q_{c,N_n}(x,y,z,t)\right) dxdydz \end{aligned} \tag{8}$$

where the unit load of pollutants entering the N_n profile denoted as l_{p_j,N_n} is the actual unit load of pollutants.

Figure 3 shows schematically the section of the closed river Δ*l* of the N_{n-1} and N_n profiles and the surface $D_N \cup Z_N$ along with the actual load of the pollutant $CL_{N_n,k}$ entering the calculation profile N_n.

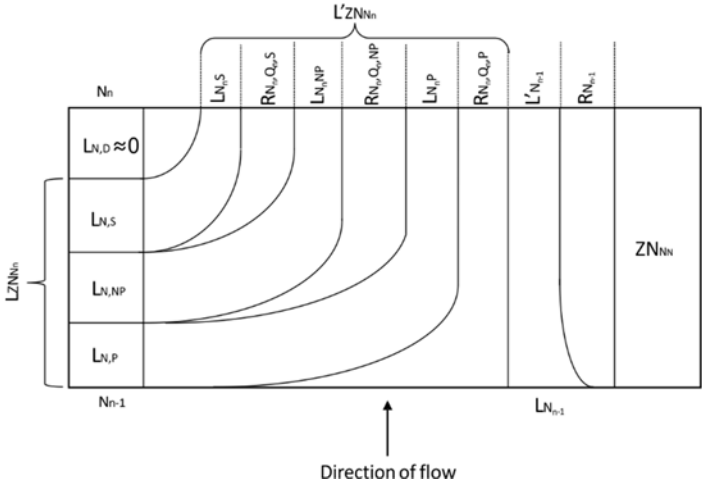

Fig. 3. River section diagram Δl, closed calculation profiles N_{n-1} and N_n and surface $D_N \cup Z_N$

At the time T_{N_n} on the segment Δl, the river reaches the pollution load $L_{ZN_{N_n}}$ fed to the volume of water Q_N by the contact surface of water with soil Z_N and the contact surface of water with atmosphere D_N $(D_N \cup Z_N)$. In the calculation profile N_n, this load is smaller by its retention R_{N_n} on the way from the input of load to the water Q_N to the calculation profile N_n:

$$L'_{ZN_{N_n}} = L_{ZN_{N_n}} - R_{N_n} \tag{9}$$

$L_{N_{n-1}}$ led to calculation profile N_{n-1}. In the N_n profile calculation, this load is reduced by its retention $R_{N_{n-1}}$ at the distance from the N_{n-1} to N_n:

$$L'_{N_{n-1}} = L_{N_{n-1}} - R_{N_{n-1}} \tag{10}$$

Pollutions actual load CL_{N_n} arriving into the calculation profile N_n can be defined as the sum of:

$$CL_{N_n} = L'_{h_{N_n}} + L'_{N_{n-1}} \tag{11}$$

detailing:

$$CL_{N_n} = L_{h_{N_n}} + L_{N_{n-1}} - R_{N_n} - R_{N_{n-1}} \tag{12}$$

marking:

$$R_{N_n,\,N_{n-1}} = R_{N_n} + R_{N_{n-1}} \tag{13}$$

Equation (12) can be written as:

$$CL_{N_n} = L_{h_{N_n}} + L_{N_{n-1}} - R_{N_n,N_{n-1}} \tag{14}$$

From this equation it follows that the sum of the pollutant loads entering the calculation profile N_n is not equal to the sum of the loads entering the river between the N_{n-1} and N_n profiles, including the pollution load flowing through the N_{n-1} profile. This difference resulting from the self-cleaning process is called retention of the $R_{N_n,N_{n-1}}$ river between the N_{n-1} and N_n calculation profiles and will be taken into account when assessing river absorption capacity in this section.

2.4. EQUATION OF RETENTION POLLUTANTS

There is no full agreement on the definition of river retention [14]. Some authors [15, 16] clearly distinguish between two concepts related to retention, that is, storage and removal. The former one refers to the temporary storage of biomass or sediment, while the latter is to the long-term elimination of pollution from the aquatic ecosystem. Still, it is common practice to use the term retention to describe the complete removal of both temporary and permanent pollution from the river. In this paper, retention is understood as self-purification of the river and is defined as the detention of pollutants in the river or their removal outside the catchment area. It is a very effective process until the opportunities for pollution reduction across the river are not exceeded.

The retention R_{N_n} on river section Δl (Eq. (9)), can be generally written as:

$$R_{N_n} = \int_0^{T_{N_n}} \int_{Q_N} r_{N_n}\left(x, y, z, t\right) dxdydz \tag{15}$$

where r_{N_n} means the unitary retention of pollutant loads brought to surface water Q_N by the surface $D_N \cup Z_N$ on the distance from their introduction to surface water Q_N to the supply to the calculation profile N_n.

The retention R_{N_n} is the sum of the retention of pollutant loads, delivered:

- from point sources $R_{N_n,Q_N,\,P}$,
- from nonpoint source $R_{N_n,Q_N,\,NP}$,

- with infiltration waters $R_{N_n,Q_N,S}$,
- to Q_N as a result of deposition directly on the D_N surface $R_{N_n,Q_N,D}$.

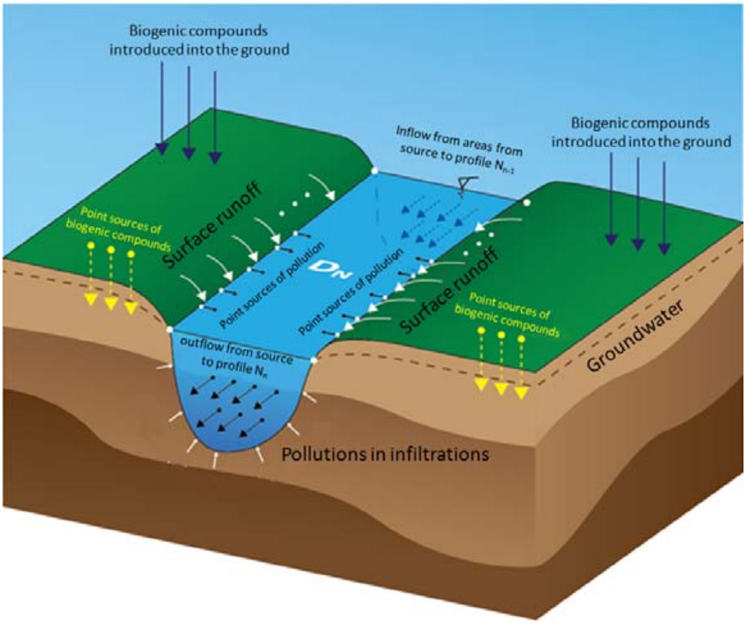

Fig. 4. Scheme of pollutions sources introduced into surface water from catchment area h_{N_n} between calculations profiles N_{n-1} and N_n [5]

Figure 4 shows schematically the sources of pollutions introduced into surface water Q_N and to the catchment area h_{N_n}. So we can write that:

$$R_{N_n} = R_{N_n,Q_N,P} + R_{N_n,Q_N,NP} + R_{N_n,Q_N,S} + R_{N_n,Q_N,D} \tag{16}$$

The load of pollutant entering the profile N_n by the surface Z_N, D_N from the catchment h_{N_n}, denoted by L_{h_N}, is the sum of the load coming from point sources discharged directly into surface waters Q_N designated as $L_{N_n,P}$

$$L_{N_n,P} = \sum_{i=1}^{l_{p,N_n}} \int_0^{T_{N_n}} c_i(t)\, q_{i,w}(t)\, dt \tag{17}$$

where: l_{p,N_n} is the number of point sources of pollution from N_{n-1} to N_n, $i = 1, 2, ..., lp,_{N_n}$, $c_i(t)$ – concentration of pollutants at time t discharged from ith source of pollutants to surface waters at section Δl, $q_{i,w}$ – the intensity of wastewater drainage at time t, discharged at the ith spot source of pollutants to the surface waters at section Δl, the load coming from nonpoint sources flowing into surface water Q_N, designated as $L_{N_n,NP}$

$$L_{N_n,NP} = \int_0^{T_{N_n}} \int_{P_N} l_{NP}\left(x, y, z, t\right) dxdydz \tag{18}$$

where: l_{NP} is the unit concentration of impurities entering the surface waters due to surface runoff between the N_{n-1} and N_n calculation profiles by the P_N contact line of the D_N surface to the ground where the P_N is the sum of the lengths of the left $P_{N,L}$ and the right $P_{N,R}$ shoreline.

The load flowing into Q_N surface water with infiltration waters through the surface of the Z_N, designated as $L_{N_n,S}$

$$L_{N_n,S} = \int_0^{T_{N_n}} \int_{Z_{N,M}} z_{M,N}\left(x, y, z, t\right) dxdydz \tag{19}$$

where: $z_{M,N}$ – load of pollutants entering the surface water by a ground water contact between the calculation profiles N_{n-1} and N_n

The load falling on the surface of the water D_N due to deposition from the atmosphere designated as $L_{N_n,D}$

$$L_{N_n,D} = \int_0^{T_{N_n}} \int_{D_N} d_{N,D}\left(x, y, z, t\right) dxdydz \tag{20}$$

where: $d_{N,D}$ – deposition of pollutants from the atmosphere directly per unit area of water D_N between profiles N_{n-1} and N_n.

Thus we can rewrite Eq. (9):

$$L'_{ZN_{N_n}} = L_{N_n,P} + L_{N_n,NP} + L_{N_n,S} + L_{N_n,D} - R_{N_n} \tag{21}$$

Load of pollutants from atmospheric deposition L_{N_nD} was omitted due to the small surface area of water D_N relative to the catchment area.

$$L_{N_n,D} \approx 0 \tag{22}$$

Actual pollutant load. The actual pollutant load CL_{N_n} (Eq. (14)) entering the calculation profile N_n is the sum of the loads from the computational profiles located above and the contamination loads entering the Q_N waters at the section between the calculation profiles N_{n-1} and N_n minus the total retention of the pollutants $R_{N_n,N_{n-1}}$ (Eq. (13)) by way of their introduction into the surface water to the tributary to the N_n profile. Finally Eq. (13) is given the form:

$$CL_{N_n} = L_{N_n,P} + L_{N_n,NP} + L_{N_n,S} + L_{N_{n-1}} - R_{N_n,N_{n-1}} \tag{23}$$

where $R_{N_n,N_{n-1}}$ is defined by Eq. (13), and graphical interpretation of Eq. (23) is shown in Fig. 5.

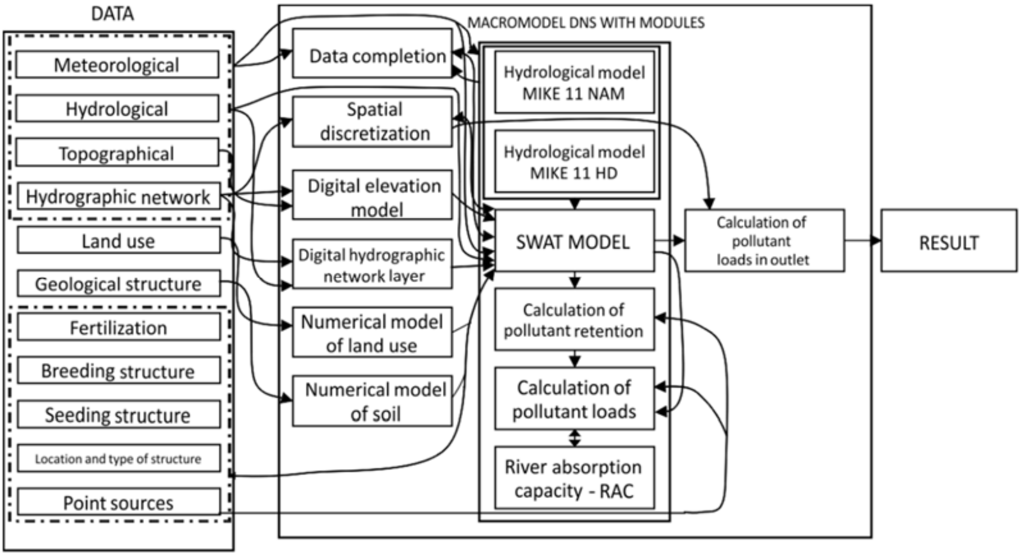

Fig. 5. Schematic diagram of the pollutant inflow for the calculation profile N from surface waters between calculation profiles N_{n-1} and N_n (based on [5])

Construction and implementation of the macromodel DNS/SWAT with mRAC. Loads of pollutants entering the river catchment separated by calculation profiles N_{n-1} and N_n as well as point sources of these loads on the river section are possible to determine or estimate based on monitoring measurements and simulation calculations. Estimated based on these data retention refers only to the meteorological conditions and the manner of use of the catchment h_{N_n}. So it does not provide the basis for forecasting retention even in the same catchment area for other scenarios of its use or other meteorological conditions.

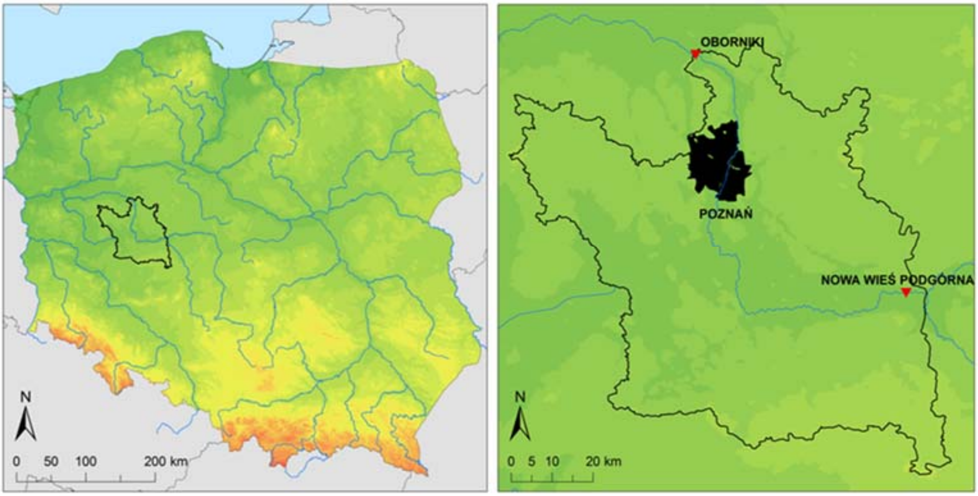

Fig. 6. Location of the Middle Warta catchment and Poznań agglomeration

Research area. The river catchment area of the Middle Warta was used for the analysis of the river profiles from the calculation profiles of Nowa Wieś Podgórna–Oborniki. The area of the analyzed catchment is 6039 km^2 [17] which accounts for approximately 11% of the total area of the Warta catchment and is located in the whole Wielkopolska region (Fig. 6). On the studied stretch of the river, several tributaries flow into the river bed. The selected catchment area is characterized by significant nitrate vulnerable zones (NVZ). In the selected area, also the largest agglomeration is located in the Warta catchment, which is the city of Poznań. The monitoring of the Warta for many years has shown that the quality of its water varies from one to the other. The river pollution can affect, inter alia, the eutrophication process. The main source of pollution is the permanent and periodic discharge of domestic and industrial waste water from cities located near the river and surface runoff from agricultural land [18]. The Middle Warta catchment was divided into 70 JCWP (Fig. 7) and the calculations were made for each calculation profiles JCWP.

The data used were:

- Input data such as digital evaluation model (DEM), 1:50 000, and the map of hydrographical divisions of Poland [17].
- Data on discharges of pollutants from sewage treatment plants, containing geographical coordinates of discharge points, amount of municipal waste water treated, total suspended soil, total nitrogen and total phosphorus (mg/dm^3) [19].

- Meteorological data on precipitation, temperature, humidity, sunlight and wind speed and direction derived from historical database IMGW-PIB.
- Digital maps for soil classes, scale 1: 100 000 divided into very light, light, medium and heavy soils.

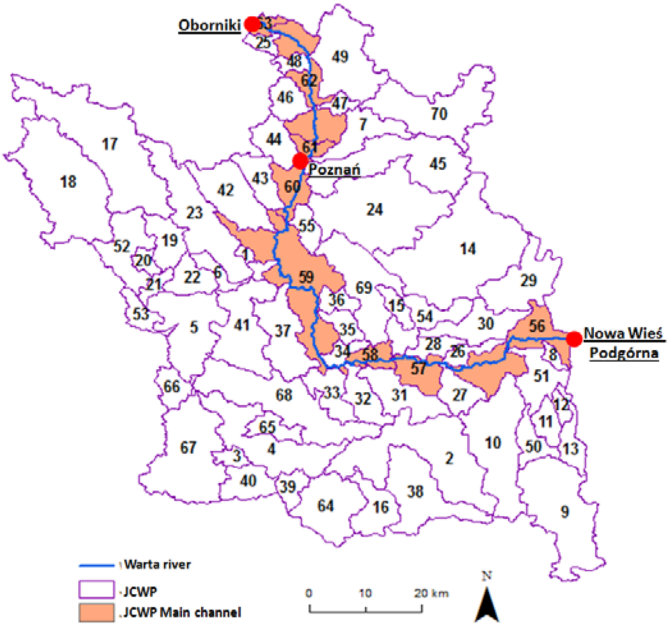

Fig. 7. Division of the Middle Warta catchment on JCWP

- Land use maps developed on the basis of CORINE LAND COVER. Maps dividing the catchment area into urbanized, agricultural, forested, wetlands, and water bodies. The agricultural land was further divided into specific crops.
- Fertilizer data from the Local Data Bank about the amount of TN (47.08 kg N/ha) and TP (16.46 kg P/ha).

2.5. SENSITIVITY ANALYSIS

- The main purpose of the sensitivity analysis is to define a set of parameters with the highest sensitivity, meaning those which have the greatest impact on the parameters affecting flow and nutrient load in the analyzed profile of the river. The parameters have been developed for ranges typical of Polish conditions. After conducting the sensitivity analysis, the next stage of study was the model calibration. Model calibration was performed through an iterative value selection process of a single parameter of the model, in order to achieve the greatest possible modeling accuracy in regard to observational data. The estimation of model parameters in the assumed conditions, in order to achieve the highest convergence of the simulation and observation results, was carried out by the OAT method (one-at-a-time), a repeated iterative loop.

Table 1

Parameters received during the sensitivity analysis

Parameter	Description
Flow parameters	
ALPHA_BF	baseflow alpha factor, days
CANMX	maximum canopy storage, mm H_2O
CH_K(1)	effective hydraulic conductivity in tributary channel alluvium, mm/h
CH_K(2)	effective hydraulic conductivity in main channel alluvium, mm/h
CN2	initial SCS runoff curve number for moisture condition II
EPCO	plant uptake compensation factor
ESCO	soil evaporation compensation factor
GWQMN	threshold depth of water in the shallow aquifer required for return flow to occur, mm H_2O
GW_REVAP	groundwater “revap” coefficient
RCHRG_DP	deep aquifer percolation factor
SOL_ALB	moist soil albedo
SOL_K	saturated hydraulic conductivity, mm/h
SURLAG	surface runoff lag coefficient
TIMP	snow pack temperature lag factor
Nitrogen and phosphorus parameters	
ERORGP	phosphorus enrichment ratio for loading with sediment
PHOSKD	phosphorus soil partitioning coefficient, m^3/Mg
PPERCO	phosphorus percolation coefficient, m^3/Mg
PSP	phosphorus availability index
P_UPDIS	phosphorus uptake distribution parameter
SOL_ORGN	initial organic N concentration in the soil layer, mg N/kg soil
SOL_ORGP	initial organic P concentration in the soil layer, mg P/kg soil
NPERCO	nitrogen percolation coefficient, m^3/Mg
SOL_NO3	initial NO_3^- concentration in the soil layer, mg N/kg soil

Parameters received during the sensitivity analysis (Table 1) were successively changed in ranges with a high probability of occurrence in a given area. These values were based on an expertise gained from analysis and consulting in the field of hydrology as well as the sources and dynamics of phosphorus change in surface waters in the area of the pilot catchment. Such a calibration method enables fitting of the appropriate model to real conditions, especially for total phosphorus, for which automatic calibration is problematic due to the small amount of observational data.

It was built and then calibrated to verify and validate the mathematical model[20]. Properly calibrated, verified and validated models have prognostic capabilities that allow mapping of the behavior of the actual ecosystem. In the case of the Middle Warta model, calibration was performed for monitoring data with the Poznań–Roch Bridge calculation profile, and verification and validation for the Oborniki calculation profile.

Three statistical measures were used for the correct description of the results of the model calibration:

- coefficient of determination (R^2) [21],
- percent-bias (PBIAS) [22],
- the Nash–Sutcliffe efficiency (NSE) [23].

Table 2

The results of the calibration, verification and validation for flow, total nitrogen and total phosphorus for the Middle Warta catchment

	Flow			Total nitrogen			Total phosphorus		
	R^2	PBIAS	NSE	R^2	PBIAS	NSE	R^2	PBIAS	NSE
Calibration	0.93	4.94	0.91	0.37	–31.03	0.17	0.41	–0.36	–2.49
Verification	0.94	2.21	0.85	0.73	6.57	0.27	0.00	0.36	–1.05
Validation	0.95	9.4	0.87	0.43	–33.28	0.30	0.65	–0.22	–5.91

No shade – very good, light grey – good and satisfactory, dark grey – not satisfactory.

In Table 2, the results of calibration, verification and validation were obtained for the Middle Warta catchment, taking into account the criteria of statistical measures [24, 25].

3. RESULTS AND DISCUSSION

The calibrated, verified and validated Macromodel DNS/SWAT with mRAC was used to calculate the *RAC* parameter in all 70 closure profiles of the JCWP of the analyzed catchment using the developed mRAC module. The SNQ characteristic flow was used for the calculation. For TN, three JCWPs received negative *RAC*s (10, 63 and 64). JCWP Nos. 10 and 64 located in the southern part of the catchment area are small streams with low flow values, most of which occupy agricultural land. The highest *RAC* values were obtained for JCWP 56–62 located on the main channel. A negative value of the *RAC* for *TN* after the Poznań agglomeration (Table 3) is visible on the last JCWP main channel in the calculation profile – Oborniki (63).

Similarly, the *RAC* values clearly indicate a high negative impact of the city of Poznań on the water quality of the catchment area. Beginning with JCWP No. 60 up to 63, the *RAC* values remained negative and the quality of water declined. A total of twelve JCWPs had negative *RAC* values for TP (10, 27, 38, 43, 50, 51, 60, 61, 62, 63, 64, 69). Except for the JCWP main channel located below the city of Poznań, the most polluted areas are located in the southern part of the analyzed catchment area.

Table 3

RAC values for TN and TP for JCWP main channel Middle Warta

No JCWP main channel	*RAC* parameter TN (t/year)	*RAC* parameter TP (t/year)
56	2980.9	129.26
57	2203.3	123.97
58	2009.4	104.05
59	2345.3	79.82
60	3041.4	–151.81
61	879.7	–592.32
62	588.2	–1069.14
63	–883.2	–1485.20

The *RAC* values for TN and TP clearly indicate the problem with the amount of biogenic compounds introduced to the waters of the river section from Poznań to Oborniki, which closes the analyzed catchment. This is particularly evident in TP (Fig. 8), which mainly comes from point source water pollutions. JCWP from 60 to 63 is an area that currently has been experiencing very intense development with insufficient expansion of the sewerage network. In addition, the continued dominance of land throughout the Middle Warta area is the intensive farming that supplies significant quantities of nitrogen to surface waters. This was the cause of many NVZs in this area.

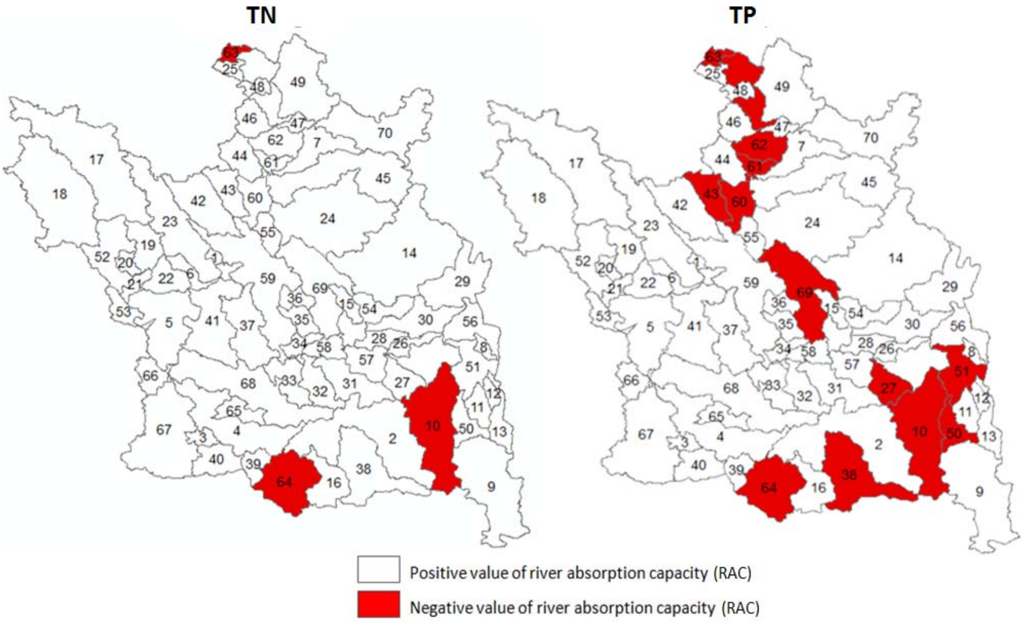

Fig. 8. Results of the *RAC* parameter for all JCWP Middle Warta catchment

The remaining JCWPs, with negative *RAC* values (10, 27, 38, 43, 51, 59) are characterized by low flow values while dominating the share of agriculture in land use and often located in their wastewater treatment plants. This is particularly the case of the Lubieszka River (10), which is heavily burdened with domestic and agricultural waste water, on which a retention reservoir is located, whose waters are also heavily polluted.

For a defined concept of river absorption capacity, a mathematical description of this process has been developed, taking into account the individual processes of transforming and transporting biological, chemical and physical impurities from their introduction into the catchment basin into the input to the assumed calculation profile. The paper presents balance equations of pollution loads that flow into the calculation profile taking into account the concentrations and loads of pollutants at each point of the river profile and the length of the selected river section bounded by two calculation profiles. A mathematical description of pollution retention is also presented, which is closely related to the river self-cleaning process, taking into account all possible sources of contamination in the catchment area.

Based on the mathematical description of these processes, the models that best reflect the processes of transformations of biogenic compounds were analyzed. This was accomplished by upgrading the Macromodel DNS/SWAT to the mRAC module described in the article, which met the requirements. By combining the mRAC module with the Macromodel DNS/SWAT, we have the opportunity to evaluate the *RAC* parameter of individual river sections for selected pollutants based on the statistical quality balance of surface waters. Using a mathematical model for this type of calculation allows one to obtain a set of data, even for areas where monitoring has never been conducted, such as single small flows, which greatly expands the spectrum of possibilities and opens new fields of activity.

An extensive Macromodel DNS/SWAT with mRAC module was tested for the middle Warta catchment between the calculation profiles Nowa Wieś Podgórna and Oborniki. Results obtained for the analyzed catchment indicated the catchment areas with excessive amounts of biogenic compounds with which the aquatic environment is unable to cope. Using the parameter *RAC*, a detailed TN and TP loads have been calculated which should be removed from surface waters in selected areas or loads of nutrients that the river can still receive without deteriorating its cleanliness class. The results obtained are consistent with data from past field trials and laboratory experiments in the analyzed area. This confirms that the developed model has proved useful. The next stages of investigations should include:

- developing of an improved macromodel DNS/SWAT matching indicators for TP,
- utilization of extended macromodel for suspended sediments and chlorophyll a,
- implementation of the DNS/SWAT macromodel with the mRAC module for the Słupia River catchment, in which the runway profile was fitted with an autosampler from continuous tests of TN, TP and organic carbon.

4. CONCLUSIONS

The value of the *RAC* parameter is not equivalent to the charge introduced directly into the surface water due to self-cleaning of surface waters, whose dynamics affect the *RAC* value on a given river section.

The macromodel DNS/SWAT after its extension to the mRAC module may be a good tool for *RAC* analysis of a given river segment as shown in the example of the Middle Warta catchment.

REFERENCES

[1] PEARCE D., BARBIER E., MARKANDYA A., *Sustainable development. economics and environment in the Third World*, Routledge, London 2000.

[2] D 2455/2001/WE. Decision of the European Parliament and of the Council. Establishing the list of priority substances in the field of water policy and amending Directive 2000/60/EC, 2001.

[3] GROMIEC M., SADURSKI A., ZALEWSKI M., ROWIŃSKI P., *Hazards related to water quality*, Nauka, 2014, 1, 99–122 (in Polish).

[4] DURKOWSKI T., JARNUSZEWSKI G., *Changes in quality of surface and ground waters during implementation of nitrates directive in selected agricultural river basin of western Pomerania*, Ecol. Eng., 2015, 43, 122–130.

[5] OSTOJSKI M.S., *Modeling of the processes of discharge of nutrients to the Baltic Sea on the example of nitrogen and total phosphorus*, PWN, 2012 (in Polish).

[6] HAIMES Y.Y., *Risk modeling, assessment, and management*, Wiley, 2015.

[7] JI Z.G., *Hydrodynamics and water quality. Modeling rivers, lakes, and estuaries*, Wiley, 2017.

[8] YEN H., WHITE M.J., JEONG J., ARABI M., ARNOLD J.G., *Evaluation of alternative surface runoff accounting procedures using SWAT model*, Int. J. Agric. Biol. Eng., 2015, 8 (3), 64–68.

[9] CHMIELOWSKI W.Z., JARZĄBEK A., *Exercises and projects in the field of water management*, Wyd. Politechniki Krakowskiej, Krakow 2008 (in Polish).

[10] WILK P., *The method of calculating river absorption capacity as a tool to assess the physicochemical state of surface waters*, PhD Thesis, IMGW-PIB, Warsaw 2015 (in Polish).

[11] ABBASPOUR K.C., ROUHOLAHNEJAD E., VAGHEFI S., SRINIVASAN R., YANG H., KLØVE B., *Calibration and uncertainty of a high-resolution large-scale SWAT model*, J. Hydrol., 2015, 524, 733–752.

[12] CIBIN R., TRYBULA E., CHAUBEY I., BROUDER S.M., VOLENEC J.J., *Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model*, GCB Bioen., 2016, 8 (4), 837–848.

[13] NEITSCH S.L., ARNOLD J., KINIRY R., WILLIAMS J.R., *Soil and water assessments tool theoretical documentation*, Blackland Research Center, Texas Agricultural Experiment Station, 2011.

[14] DE KLEIN J.J.M., *From ditch to delta. Nutrient retention in running waters*, PhD Thesis, PhD-thesis Wageningen University, Wageningen, The Netherlands, 2008.

[15] KRONVANG B., LAUBEL A., LARSEN S.E., FRIBERG N., *Pesticides and heavy metals in Danish streambed sediment in the interactions between sediments and water*, Springer, 2003, 93–101.

[16] LA NOTTE A., MAES J., DALMAZZONE S., CROSSMAN N.D., GRIZZETTI B., BIDOGLIO G., *Physical and monetary ecosystem service accounts for Europe: A case study for in-stream nitrogen retention*, Ecosyst. Serv., 2017, 23, 18–29.

[17] *MPHP. The Map of Hydrographical Divisions of Poland*, http://www.kzgw.gov.pl/index.php/pl/materialy-informacyjne/rastrowa-mapa-podzialu-hydrograficznego-polski Polish Waters, KZGW, 2009.

[18] GĘBALA J., ORLIŃSKA-WOŹNIAK P., WILK P., *Poland's surface waters pollution with nitrogen compounds originating from agriculture. Selected issues related to the water quality assessment*, Gospodarka Wodna, 2013, 11, 424–430 (in Polish).

[19] AKPOŚ. Update of the National Sewage Treatment Program. National Water Management Authority, http://www.kzgw.gov.pl

[20] OSTOJSKI M.S., GĘBALA J., ORLIŃSKA-WOŹNIAK P., WILK P., *Implementation of robust statistics in the calibration, verification and validation step of model evaluation to better reflect processes concerning total phosphorus load occurring in the catchment*, Ecol. Model., 2016, 332, 83–93.

[21] NAKAGAWA S., SCHIELZETH H., *A general and simple method for obtaining R2 from generalized linear mixed-effects models*, Meth. Ecol. Evol., 2013, 4 (2), 133–142.

[22] YESUF H.M., MELESSE A.M., ZELEKE G., ALAMIREW T., *Streamflow prediction uncertainty analysis and verification of SWAT model in a tropical watershed*, Environ. Earth Sci., 2016, 75 (9), 806.

[23] BONUMÁ N.B., ROSSI C.G., ARNOLD J.G., REICHERT J.M., MINELLA J.P., ALLEN P.M., VOLK M., *Simulating landscape sediment transport capacity by using a modified SWAT model*, J. Environ. Qual., 2014, 43 (1), 55–66.

[24] VERMA A.K., JHA M.K., *Evaluation of a GIS-based watershed model for streamflow and sediment-yield simulation in the upper Baitarani river basin of Eastern India*, J. Hydrol. Eng., 2015, 20 (6), 13–144.

[25] SARGENT R.G., *Verification and validation of simulation models*, J. Sim., 2013, 7 (1), 162–176.