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The river absorption capacity determination as a tool to evaluate state of surface water

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Abstract

In order to complete a thorough and systematic assessment of water quality it is useful to implement the concept of absorption capacity of the river. Absorption capacity is understood as a pollution load introduced into river water that will not cause permanent and irreversible changes in the aquatic ecosystem and will not cause a change of classification of water quality at the river profile. In order to implement the method the Macromodel DNS / SWAT basin for pilot Middle Warta (central Poland) was used to simulate nutrients loads. This enabled detailed analysis of water quality in each water bodies and assess the size of absorption capacity parameter, which determines what charge could be brought to a receiver without compromising its quality class. Positive values of calculated absorption capacity parameter means that it is assumed that the ecosystem is adjusted to eliminate the pollution loads introduced through a number of self-purification processes. Negative values indicate that the load limit was exceeded, and the ecosystem has been introduced too much pollution to deal with them in the processes of self-purification. Absorption capacity thus enables the connection of reference to water quality environmental standards and water quality management plans in order to meet these standards.

Keywords: river absorption capacity, nutrients, Macromodel DNS/SWAT,

1. Introduction

Water Framework Directive (WFD) [Directive 2000/60 / EC] implemented in the European Union treats water as a common good and obligates to the sustainable management of its resources, among other things, by preventing degradation, improving state of water resources and protection of aquatic and water-dependent ecosystems [Orlińska-Wozniak et al., 2013; Boeuf and Fritsh, 2016]. WFD determines searching for new and more effective solutions of the aquatic environment state evaluation and, consequently, effectiveness assessment of actions plans in areas deemed polluted. What is important, the surface water pollution, in most cases, is not an irreversible state, thereby pollutant input to the surface water not always lead to irreversible contamination. Water has the ability to self-purification [Dubnyak and Timchenko, 2000; Gorecki, 2007; Jancarkova et al., 1997; Karrasch et al., 2006; Jarosiewicz and Dalszewska, 2008; McColl, 1974; Vagnetti, 2003; Zagorc-Končan and Somen, 1999; Zalewski, 2003].

Generally, self-purification is a biochemical transformation of pollutants containing mainly organic compounds to simpler forms, often inorganic, with microorganisms activity, at the expense of consumption of oxygen from air and water and sedimentation processes causing physical elimination of water pollution [Jarosiewicz, 2007; Kowalewski, 2009; Elósegui et al., 1995; Vagnetti, 2003]. The most important factors influencing the river self-purification ability of nutrients include, among others, topography, soil type, vegetation, hydraulic characteristic of the river, the retention time of water in the catchment, biodiversity and temperature [Spellman and Drinan 2001; Schulz et al., 2003; Vaikasas and Dumbrauskas, 2010; Marsili-The vial and Giusti, 2008; Popek, 2011; Van der Lee et al., 2004]. To evaluate indirectly the possibility of self-purification of the river, by comparison of actual loads in the river to limit loads, the river absorbency capacity parameter is useful. Limits establishment aims to determine a threshold below which there is a possibility of river self-purification [lit przepisy prawne].

It should be noticed that beyond a certain critical level of pollutants it may be impossible for aquatic ecosystem to return to its original condition [Kowalkowski, 2009; Nixon 2009]. This was confirmed, inter alia, by [Duarte et al., 2009] in the article "Return to Neverland ..." referring to the process of eutrophication. This work was motivated by attempts to improve water quality aimed to restore ecosystems to the original conditions. Observations of many ecosystems were made and despite the elimination of the source of pollution they did not returned to the original state even for more than 30 years. Owing to that, authors concluded that above a certain critical value of pollution ecosystem is not able to return to its original state. Understanding ecosystem response to multiple shifting baselines is essential to set reliable targets for restoration efforts.

The most advanced work related to the determination of the, so-called, assimilative capacity of the river, which has similar assumptions to the river absorption capacity, leads US Environmental Protection Agency (EPA) by implementing Clean Water Act [Federal Water Pollution Control Act, 2002]. IMGW-PIB started studies on river absorption capacity parameter utilization in water

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management in 2011 by proposing the calculation of the absorption capacity on the basis of advanced Macromodel DNS which has an ability of determination of the amount of point and nonpoint source of pollution on a given river section.

Paper presents method of surface water state assessment by river absorption capacity parameter determination. Absorption capacity is defined as maximum load that could be input into the river without exceeding limit load and changing water quality state class or, when the absorption capacity is negative, load that should be remove to accomplish limit loads. Method assume utilization of mathematical modeling. Developed in IMGW-PIB Macromodel DNS was used [Ostojski, 2012]. It allows, inter alia, for daily flow simulations, as well as average daily loads of selected pollutants, what is essential for river retention determination. Simulation of this loads allows for calculations of river absorption capacity.

The proposed method of evaluating the status of surface water by using river absorption capacity parameter is an alternative to commonly used by the EPA ratio defined as assimilative capacity of the river, which is called the Total Maximum Daily Load (TMDL) [Bulsathaporn et al., 2013; Magley and Joyner, 2008; Mohlar, 2011; Radcliffe et al., 2009; Reckhow and Wostl, 2001].

It is defined as the maximum amount of a pollutant that can occur in a waterbody and allocates the necessary reductions to one or more pollutant sources, a planning tool and potential starting point for restoration or protection activities with the ultimate goal of attaining or maintaining water quality standards [EPA, 2016]. Procedures for determining the TMDL formed in 1992 and have been repeatedly revised and updated. This method is based on identification of point and nonpoint pollution and summing them for the river sections previously recognized as endangered by excessive pollution.

$$TMDL = \Sigma WLAs + \Sigma LAs + MOS$$

WLAs - point source loads
LAs - nonpoint source loads
MOS - margin of safety

Knowledge of the river absorption capacity enables to implement action plans aimed to prevent water quality degradation, and consequently aquatic and water-dependent ecosystems, occurring as a result of human activity, that is, anthropopressure. Currently there is no universal methodology to determine the absorption capacity of the river. In the few publications [Chmielowski and Jarząbek, 2008; Monka, 2005; Tyszewski et al., 2008] only general equations are available.

The aim of the study was to develop a method of the physico-chemical surface water state evaluation through the definition of absorption capacity of the river in the profile. For this purpose a Macromodels DNS / SWAT was used, which was calibrated, verified and validated for pilot catchment Middle Warta. The model was prepared to take into account the individual processes of pollutants transformation and transport from the moment they enter the environment until their discharge into the sea, and to allow the determination of nutrients loads at estuary profiles of water bodies. Using data from the simulation the method of calculating the absorption capacity of the river was implemented. The absorption capacity is understood as pollution load entered into a section of river that will not cause permanent and irreversible changes in the aquatic ecosystem and will not

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change the classification of water quality in the profile, but also carries information about what charge should be remove in case of exceeding environmental standards [Chmielowski and Jarząbek, 2008]. Afterwards the results of absorption capacity at the river profiles was evaluated along with identifying the consequences of positive and negative values of absorption capacity for the analyzed area and linking the reference of water quality environmental standards with water quality management plans in order to meet these standards.

2. Materials and methods

2.1. Absorption capacity

Absorption capacity phenomenon can be described by schematic impact of pollutant discharges originating from human activity on the ecosystem of the basin presented in fig. 1 . Natural river devoid of anthropopressure has only natural background of pollution [Brodie et al., 2009; Helsinki Commission, 2004; Henriksson and Milijokonsulter, 2007], then we talk about the state of balance in the river (zone I) and maximum pollution load in the river can be called a actual natural load ANL. This is a very rare situation and in Europe there is virtually no basins without human pressure. Some of such basins could be find in the northern part of Scandinavia and Russia [Helsinki Commission, 2004]. Therefore, the only way to determine the natural background is utilization of a mathematical model allowing to create a scenario of removal of the entire human pressure from the catchment. At the moment when anthropogenic discharge appears in the catchment, ecosystem changes into the state of adaptation (zone II). This means that the pollution introduced to the basin will interfere the balance of the ecosystem, but do not cause permanent changes in it. Ecosystem adapts to their "elimination" through a series of processes generally called the self-purification of the river. This process is also understood as the retention of pollutants defined as an extension of the circulation of pollutants in the basin and thereby increase of the possibilities of self-purification in the selected area. Generally, it is assumed that after the removal of the pollution source ecosystem will return to state of equilibrium or close. In river ecosystems in zone II retention is able to retain up to 30% of the total amount of nitrogen [Dziopak, 2007; Neverova-Dziopak, 2009]. Therefore, the pollution discharged into the stream at any point will not be equal the load of these pollutants registered at the control profile located below this discharge. Moreover, if there is too much pollution introduced into the ecosystem, the critical load CL can be exceeded, which will cause irreversible changes in the ecosystem. This causes an "overload" of the ecosystem (zone III). In this case, even the removal of sources of pollution will not cause spontaneous return of the ecosystem to its original state, understood as a state before changes caused by anthropopressure. To prevent irreversible consequences of exceeding the CL the concept of limit load LL is introduced, its value is defined as the limit of good water status set by administrative decisions in accordance with the WFD.

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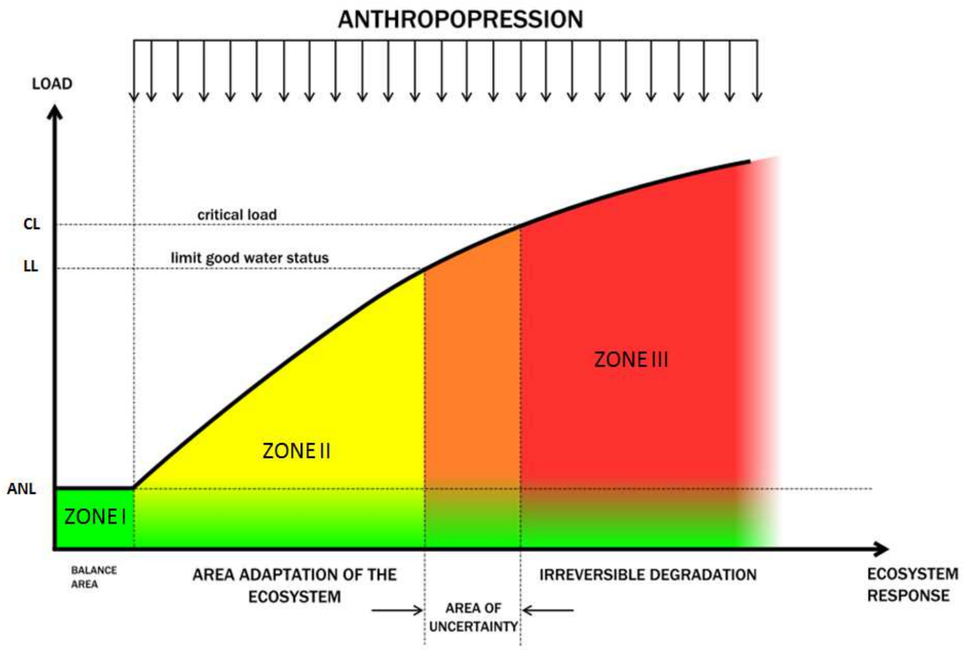

Fig. 1. The impact of anthropopressure on the ecosystem surface water at the profile [source: self research]

Actual natural load (background pollution) ANL is determined based on the concentration of pollutants in the river without the anthropopressure impact ANC and characteristic flow CF, which is extreme value of water levels observed in the analyzed period (1.1).

$$ANL = ANC * CF \qquad (1.1)$$

Critical load CL in practice is difficult to determine, mainly because there is an area of uncertainty between the limit load value and the critical load value (fig.1). It is impossible to determine the boundaries of the area. Incorrect determination of CL can lead to erroneous conclusions and consequently actions taken on this basis could result in irreversible changes in the ecosystem. Therefore, it is preferred to determine the limit load LL on the basis of limit concentration LC of good water status [Regulation of the Minister of the Environment, 2011] and the characteristic flow CF. Limit load LL should be lower than the critical load CL.

Absorption capacity of the river is the difference of two loads of which the first is the limit load calculated on the basis of a limit concentration determined in Poland for different types of water by the Regulation of the Minister of the Environment [Regulation of the Minister of the Environment, 2011], while the second is the actual load calculated based on the actual concentration at selected river profile. When calculating both mentioned loads the selected characteristic flow is used. Absorption capacity of the river is calculated for each pollutant separately and should consider all potential

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sources of pollution (both point and nonpoint sources). Results of absorption capacity are obtained for selected river profiles.

River absorption capacity RAC for selected control profile is described by the equation:

$$\mathrm{RAC} = \mathrm{LL} - \mathrm{CL} \quad (1.2)$$

where:

LL - limit load for selected pollutant (10^3 kg yr^{-1})

CL - actual load for selected pollutant (10^3 kg yr^{-1})

Actual load at control profile is described by equation:

$$\mathrm{CL} = \mathrm{AC} * \mathrm{CF} \quad (1.3)$$

where:

AC - actual concentration of selected pollutant (mg L^{-1})

CF - characteristic flow (m^3 s^{-1})

While limit load at control profile is described by equation:

$$\mathrm{LL} = \mathrm{LC} * \mathrm{CF} \quad (1.4)$$

LC - limit concentration of selected pollutant (mg L^{-1})

In the research average low flow SNQ was chosen an a characteristic flow, which is arithmetic mean of lowest yearly flows.

$$Q_{\mathrm{SNQ}} = SNQ = \frac{\sum_{i=1}^{n} NQ_i}{n} \quad (1.5)$$

where:

n - the number of elements in the considered set of major flows

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2.2. Absorption capacity cases

Analysis of relation between limit load LL and actual load AL of selected pollutant at control profile shows that absorption capacity RAC of river section can have positive, negative and theoretically equal to zero values. These cases are shown in fig. 2.

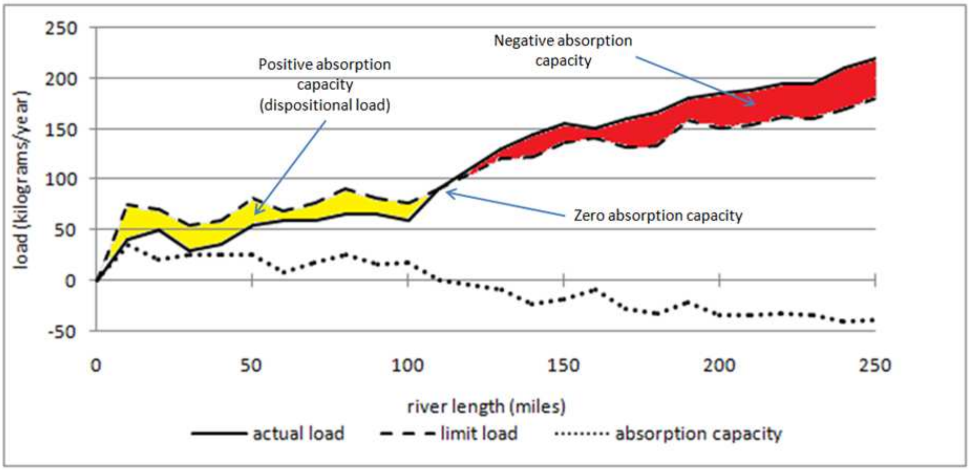

Fig. 2 Possible cases of absorption capacity values for selected section of the river [source: self research]

Values of river absorption capacity RAC:

- Positive - means that actual load AL at the profile is lower than limit load LL of selected pollutant:

$$AL < LL \qquad (1.6)$$

  Thus there is a possibility of addition load input to the river section equal to difference between actual load AL and limit load LL without causing environmental limits exceedance

- Equal to zero - means than actual load AL and limit load LL at the profile are equal:

$$AL = LL \qquad (1.7)$$

  It is a hypothetical situation when there is no possibility of input of any load of pollutant although there is still no necessity of of making radical steps to purify river water. In practice, the absorption equal to zero is difficult to determine.

- Negative - means that at the profile actual load AL is greater than limit load LL of selected pollutant:

$$AL > LL \qquad (1.8)$$

  Therefore, there is a exceedance of the limit value for environmental standards for good water state at the profile and it is obliged to take actions aimed to reduce pollutant loads discharged into the river. If the critical load is not exceeded, in the case of negative absorption capacity reduction of pollutant loads should cause spontaneous return of the ecosystem to its original state, understood as a state before the change caused by anthropopressure.

2.3. Macromodel DNS/SWAT

Appropriate amount of monitoring data covering a sufficiently long period of time is pivotal to surface water pollution state analysis. When monitoring data are limited, what is a common situation, it becomes essential to use supplemental tools as mathematical models. They provide an opportunity not only of spatial and temporal resolution data complementation but also allow to carry out analysis on, inter alia,. processes responsible for self-purification of the river. Utilization of correctly chosen and adapted mathematical model to absorption capacity determination enables to obtain extensive knowledge about the state of surface water and simulate the selected scenarios of action programmes to improve water quality on a selected river section.

Macromodel DNS (Discharge-Nutrient-Sea) was 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 **[**Ostojski, 2012**]**. The Macromodel is a unified tool combining existing and verified mathematical models and equations of hydrological transport process units. It allows 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. fig. 3 and fig..4. Macromodel DNS allows the actual load AL description at control profile as:

$$AL = L_{POINT} + L_{NON} + L_{INF} + L_{DEP} + AL_{-1} - R \qquad (1.9)$$

L_{POINT} - the sum of load discharged from point sources

L_{NON} - the sum of load discharged from nonpoint sources

L_{INF} - the sum of load discharged from infiltration

L_{DEP} - the sum of load discharged from atmospheric deposition

AL_{-1} - load flowing from upper river profile

R - section retention

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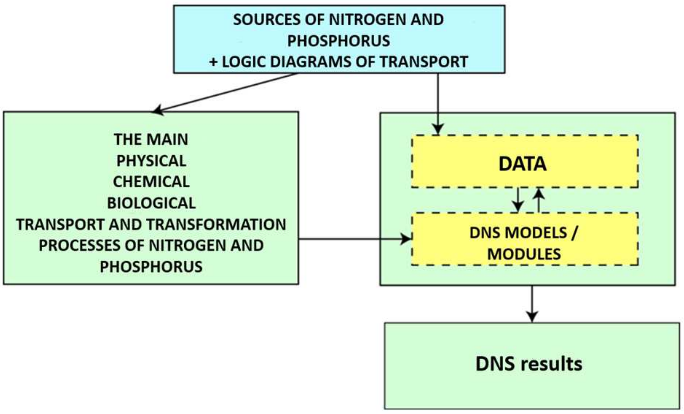

Fig. 3. Macromodel DNS scheme [source: Ostojski, 2012]

SWAT (Soil and Water Assessment Tool) [Neitsch at.al. 2004, Neitsch at.al. 2005] can be one of modules of Macromodel DNS. 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 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 ... shows the general sequence of processes used by SWAT to model the land phase of hydrologic cycle [Neitsch at.al.2011]. Macromodel DNS containing SWAT model as integral module was called Macromodel DNS/SWAT, (fig. 4).

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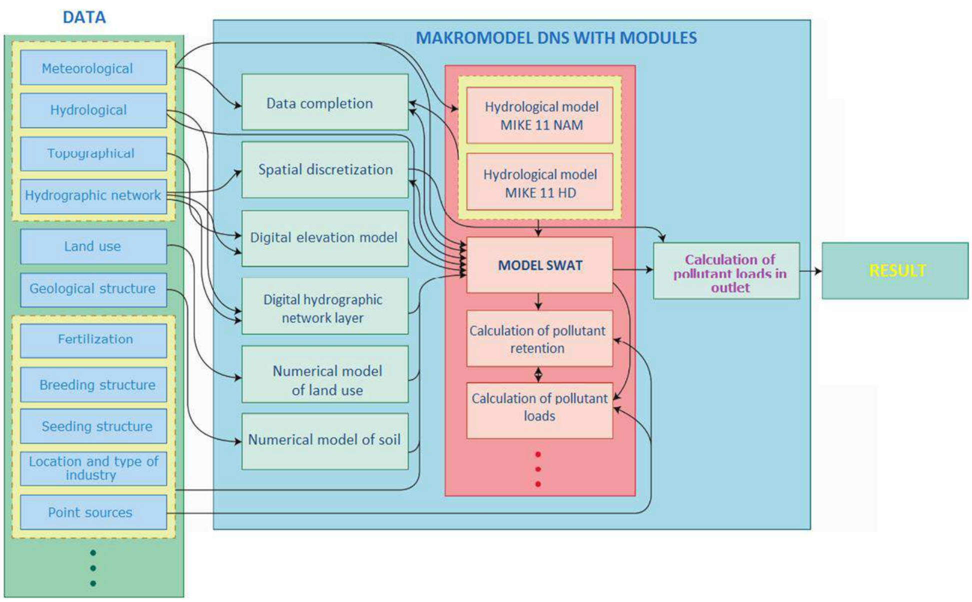

Fig. 4 . Macromodel DNS/SWAT schematic diagram [source: Ostojski, 2012]

With the use of the Macromodel DNS/SWAT all the elements form a homogenous, numerical catchment model that enables to analyze different scenarios of catchment exploitation in different meteorological and hydrologic conditions. The Macromodel DNS/SWAT can be used to analyze the loads of nutrients at any selected control points **[**Gębala at.al. 2014**;** Ostojski, 2012]

2.3.1. Research area

Methodology of calculating absorption capacity of the river proposed in article have been implemented on the example of a fragment of the catchment of the Warta (Middle Warta). Warta is the third longest river in Poland. The selected basin has an area of 6039 km^2 which represents approximately 11% of the entire Warta catchment. The study area was divided into Water Bodies that are the basic unit of water management in the EU. Numbers was assigned from 1 to 70 to each water body, water bodies located in the main stream received numbers from 56 to 63. As the beginning of the basin Nowa Wies Podgórna profile was selected, and as the end the profile Oborniki (fig. 5). The analyzed part of the catchment is characterized by a significant amount of area exposed to nitrogen pollutants of an agricultural origin. The area is characterized by a high proportion of nitrate vulnerable zones - areas particularly vulnerable to nitrogen pollution from agricultural sources (NVZ) [Directive 91/676/EEC]. Mail soils type on the selected catchment area are light and very light soils. The major sources of pollution are constant and seasonal discharges of domestic, economic and industrial sewage from cities located near the river and surface runoffs from agricultural areas. At the basin area is located the largest metropolitan area of Warta catchment - Poznan city, which is the fifth most populous city in Poland with a very rapidly growing suburban area. Conducted for many years, monitoring research of the Warta River water sate indicate that the quality of its waters is strongly differentiated into individual river sections and pollution flowing into the river can affect locally, among other things, the process of eutrophication.

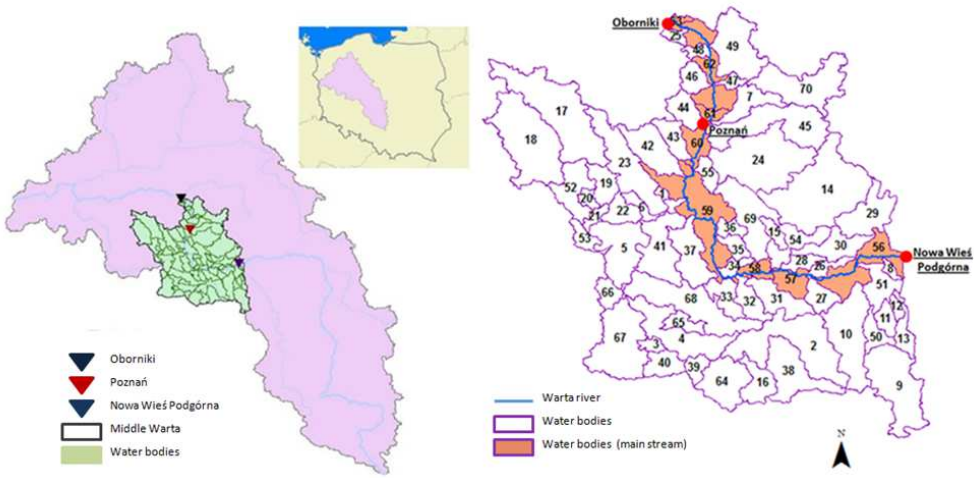

Fig. 5. Location of catchments in Poland the Middle Warta catchment with an indication of profiles for calibration and verification (Poznań) and validation (Oborniki) [source: MPHP 2009]

2.3.2. Data

For the pivotal river catchments and for the use of the Macromodel DNS/SWAT, the input data has been prepared, that is: digital elevation model (DEM), hydrology map, soil map, land use map, data concerning wastewater treatment plant, the daily meteorological and hydrological data as well as the amount of fertilizers. The gathered data was developed in a form of a database required by the model [Abbaspour 2008, Srinivasan 2006, Srinivasan 2011].

The DEM remains the national, central geodesic and cartographic level resource and is created on the basis of aerial photographs within a flat and rectangular system of coefficients. The Map of Hydrographical Divisions of Poland [MPHP 2009] is the basis for the information system of water management. The map containing the details of river networks and water bodies within the boundaries of the analyzed catchments in a scale of 1:50 000 was used. Data concerning wastewater treatment plants located in the area of the analyzed catchments were obtained from the National Water Management Authority in Poland. The data contained detailed information, including the geographic coordinates of a given wastewater treatment plant, the amount of public wastewater treated within a year in thousands $m^3\ yr^{-1}$, total suspended solids ($mg\ L^{-1}$), total nitrogen ($mg\ L^{-1}$) and total phosphorus ($mg\ L^{-1}$). Meteorological input data with a daily time step and included solar radiation, wind speed, precipitation, relative moisture, and maximum and minimum temperatures. Soil maps at a scale of 1: 100,000 with the types of soil: very light, light, average, and heavy (Tab. 1) were obtained from the Institute of Soil Science and Plant Cultivation National Research Institute [IUNG 2009].

Tab. 1 Soil class with the percentage of participation in the catchment area [source: IUNG 2009]

Catchment / Soil class	Middle Warta
very light	32.9
light	30.6
average	33.9
heavy	2.4

Land use maps of the Middle Warta catchment were created based on the CORINE Land Cover information system [Bossard 2000, CORINE 2009] which divides land use into five classes attributing to it relevant abbreviations acceptable and readable by the model (Tab. 2).

Tab. 2. Land use types with the percentage of participation in the catchment area [source: CORINE 2009]

Catchment / Land use types	Middle Warta
Artificial surfaces	6.17
Agricultural areas	72.82
Forests	20.04
Wetland areas	0.1
Water bodies	0.85
Meadows	-

Input data used to calculate phosphorus loads from manure and mineral fertilizers were obtained from the Polish Local Database (BDL) including information regarding livestock and the surface area of arable lands in hectares at the provincial level. The average dose of nitrate fertilizers was 158.5 kg N/ha and phosphate fertilizers 47.08 kg P/ha. The Middle Warta river catchment has been divided into 70 sub-basin according to the boundaries of water bodies which are the basic unit of water management in Poland, according to [Directive 2000/60/EC].

2.3.3. Sensitivity analysis and calibration

Sensitivity analysis demonstrates the impact that change to an individual input parameter has on the model response and can be performed using a number of different methods. The method in the ArcSWAT Interface combines the Latin Hypercube (LH) and One-factor-At-a-Time (OFAT) sampling. During sensitivity analysis, SWAT runs (p+1)*m times, where p is the number of parameters being evaluated and m is the number of LH loops. For each loop, a set of parameter values is selected such that a unique area of the parameter space is sampled. That set of parameter values is used to run a baseline simulation for that unique area. Then, using one-at-a-time (OAT), a parameter is randomly selected, and its value is changed from the previous simulation by a user-defined percentage. SWAT is run on the new parameter set, and then a different parameter is randomly selected and varied. After all the parameters have been varied, the LH algorithm locates a new sampling area by changing all the parameters.

In further work sensitivity analysis of the parameters in the model was carried out. The main purpose of applying 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 phosphorus load in the analyzed profile of the river. The parameters have been developed for ranges typical for 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. The values of paramiters received during the sensitivity analysis (tab.4) were successively changed in ranges with a high probability of occurance in a given area. These values were based on 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.It was recognized that such a calibration method enables fitting of the appropriate model to real conditions, especially for general phosphorus, for which automatic calibration is problematic due to the small amount of observational data. To evaluate model matching with observation in subsequent iterations of the loop three statistical measures R2, PBIAS and NSE was used [Moriasi and Arnold, 2007, Ostojski et al. 2016].

The calibration of the flow, total nitrogen and total phosphorus loads was carried out for the data derived from multi-year analyses from January 1. 2003 to December 31. 2007 with the daily time step for Poznań – Most Rocha measuring point located on 241.76 km (150.22 miles). The verification of the models was conducted from January 1. 2008 to December 31. 2009 with the daily time step for Poznań – Most Rocha measuring point. As for validation, this was conducted from January 1. 2003 to December 31. 2006 with a daily time step for the Oborniki measuring point located on 205.2 km (127.5 miles). In the mentioned periods, the full range of daily data for flow was available, and 3% to 7% of data for both total nitrogen loads and total phosphorus loads (tab. 3). For each of these processes, robust statistics were used to calculate the winsorized robust statistical measures [Ostojski et al. 2016].

Tab. 3. The amount of data available from the State Environmental Monitoring and IMGW for selected catchments

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Process	Total Data Quantity (TDQ)	Flow		Total N		Total P	
		Data Quantity	Percentage of TDQ	Data Quantity	Percentage of TDQ	Data Quantity	Percentage of TDQ
Calibration	**1826**	1826	**100%**	120	**7%**	120	**7%**
Veryfication	**731**	731	**100%**	25	**3%**	25	**3%**
Validation	**1461**	1461	**100%**	48	**3%**	48	**3%**

3. The modeling results

For pilot catchment model - Middle Warta and Rega - within the functionality of SWAT, being in this case a DNS Macromodel module, a sensitivity analysis of parameters associated with the flow, total nitrogen and total phosphorus were conducted according to the description in chapter 3.3.3. The results of this sensitivity analysis are presented in table 4. There are 14 parameters presented which are most sensitive and associated with the flow in the control point. For total nitrogen loads, from a range of parameters that may be manipulated during the calibration of the model, 4 parameters obtained the highest sensitivity and 7 parameters for total phosphorus loads. The parameters selected during the sensitivity analysis were used during the model calibration.

Tab. 4. The most sensitive parameters obtained from the sensitivity analysis in SWAT model for the analyzed catchments [source: Gębala 2015, Wilk 2015]

Parameter	Parameter description
	Flow parameters
ALPHA_BF	Baseflow alpha factor [days]
CANMX	Maximum conopy storage [mm H_2O]
CH_K(1)	Effective hydraulic conductivity in tributary channel alluvium [mm/hr]
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 facor
ESCO	Soil evaporation compensation factor
GWQMN	Threshold depth of water in the skallow 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/hr]
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 [$10m^3/Mg$]
PPERCO	Phosphorus percolation coefficient [$10m^3/Mg$]
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 [$10m^3/Mg$]
SOL_NO3	Initial NO3 concentration in the soil layer [mg N/kg soil]
CMN	Rate factor for humus mineralization of active organic nutrients (N and P)

Charts showing the matching of results of modeling and monitoring results for the period of calibration and verification are shown in Fig. 6 and validation in Fig. 7.

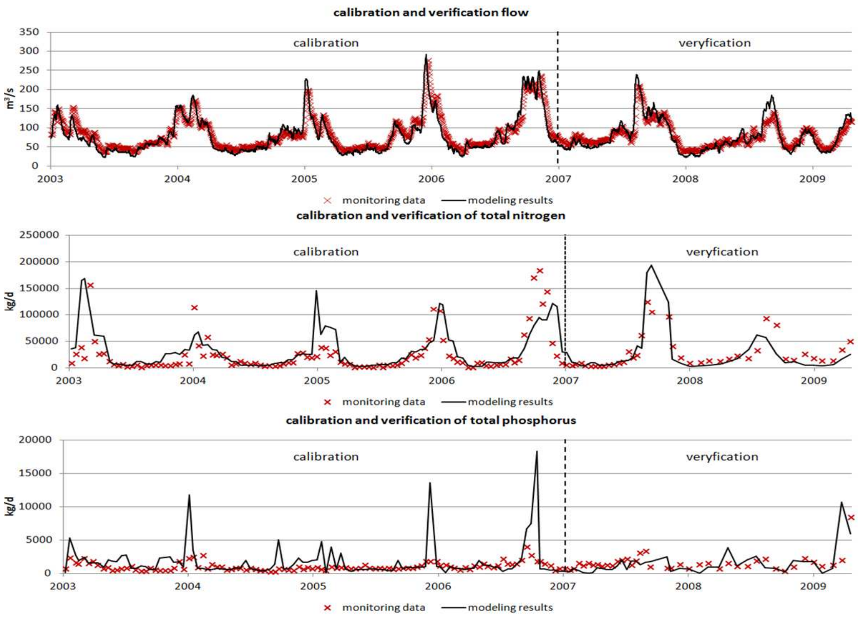

Fig. 6. Matching of modeling results and monitoring results for the period of calibration and verification

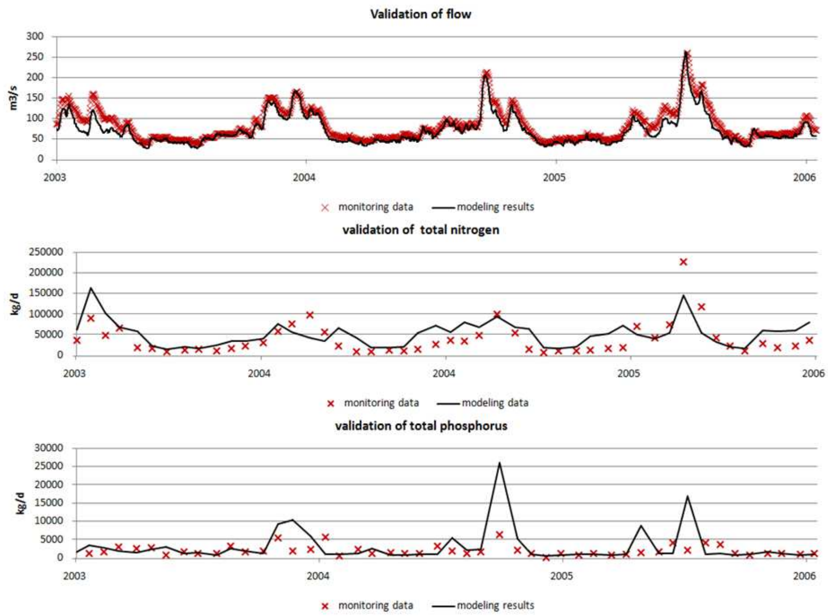

Fig. 7. Matching of modeling results and monitoring results for the period of validation

To describe the results of the calibration, verification and validation three statistical measures were used: the coefficient of determination (R^2), the percent bias (PBIAS) and Nash Sutcliffe efficiency (NSE), [Alansi et al., 2009; Bosch et al., 2011; Chu et al., 2004; Pai et al., 2011; Rathjens and Oppelt, 2012]. The results are presented in table 5. An assessment of the modeling you and conducted using robust statistics and winsorized L-estimators were used [Ostojski et al. 2016].

Tab. 5. The results of the calibration, verification and validation for flow, total nitrogen and total phosphorus

Parameter	Flow			Total nitrogen			Total phosphorus		
Coefficient \ phases	R^2	PBIAS	NSE	R^2	PBIAS	NSE	R^2	PBIAS	NSE
Calibration	0.93	6.07	0.91	0.65	0.14	0.57	0.41	-0.36	-2.49
Verification	0.92	-0.84	0.81	0.81	0.14	0.56	0.01	0.36	-1.05
Validation	0.94	14.51	0.85	0.47	-0.58	0.06	0.65	-0.22	-5.91

In the case of calibration, verification and validation of flow all statistical measures obtained "very good" and "good" [Alansi et al., 2009; Chiang et al., 2012; Krause, 2005; Moriasi et al., 2007] the results of model fit. For calibration and verification of total nitrogen "very good" and "good" fit results

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of the model were obtained, only in the case of validation for the coefficient of determination R^2 and the Nash Sutcliffe efficiency coefficient NSE results achieved "satisfactory". As expected, the biggest difficulty during calibration, verification and validation made total phosphorus loads, among other things this was due to the high volatility of daily and seasonal concentrations of this parameter in the environment and a limited amount of monitoring data. The coefficient of determination R^2 at the stage of calibration and verification of received values respectively "satisfactory" and "unsatisfactory", PBIAS in all cases obtained values classifying it as "very good" as opposed to the NSE values in all cases were "unsatisfactory". Due to lack of methodology enabling joined assessment of these three coefficients, R^2 was prioritized and results of total phosphorous calibration was evaluated as satisfactory.

3.1. Absorption capacity results

After calibration, verification and validation processes of the SWAT module daily loads of nitrogen and total phosphorus for the selected period of time were obtained. This database has enabled the precise absorption capacity calculation at closing profiles of all 70 Water Bodies located in the analyzed basin. Absorption capacity was calculated for total nitrogen and total phosphorus where for the characteristic flow average low flow QSNQ was used.

Total nitrogen

Absorption capacity values of total nitrogen for individual water bodies in the vast majority (67 water bodies) obtained positive values (Fig. 8). The highest positive values of absorption capacity were observed at closing profiles of the individual water bodies located in the main stream of the Middle Warta subcatchments 56 to 60, of values to 3 500 t / year. A clear drop of absorption capacity on the main stream was noticed from the closing profile 61 water bodies where absorption reached 880 t / year, on water bodies located directly behind the city of Poznan. The lowest but still positive values of absorption capacity were at closing profiles of small streams characterized by low flows.

Negative absorption capacity values for total nitrogen occurred only at three water bodies (10, 63 and 64). Two of them (10 and 64) are small reaches with low flows which should limit the amount of total nitrogen by respectively about 55 t / year and 2 t / year. The basin 63 is the last section of main stream of analyzed catchment where absorption capacity obtained value - 880 t / year.

Graphically results of absorption capacity of total nitrogen load based on a characteristic flow of QSNQ were shown in figure 8. A summary of the results for all analyzed closing profiles of water bodies are presented in Table 6.

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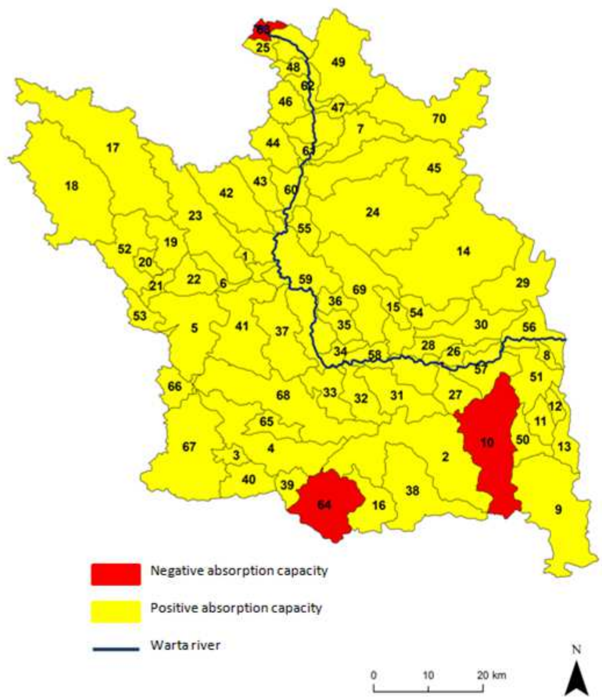

Fig. 8 Actual absorption capacity for each water body of Middle Warta for total nitrogen based on characteristic flow SNQ [source: self studies]

Tab. 6. Total nitrogen absorption capacity for each profile of Middle Warta water bodies based on characteristic flow SNQ

water bodies number	tons/year	water bodies number	tons/year	water bodies number	tons/year
1	2.4	25	4.7	49	7.3
2	85.4	26	6	50	3.1
3	4.1	27	2.7	51	3.3
4	344.3	28	7.1	52	32.3
5	909.1	29	42.8	53	20.6
6	1065	30	59.8	54	21.4
7	142.4	31	22.8	55	32.2
8	1.3	32	16.1	56	2981
9	44.4	33	28.6	57	2203.4
10	-54.6	34	2.8	58	2009.5

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11	2.1	35	6.7	59	2345.3
12	1.2	36	13.4	60	3041.4
13	3.6	37	71.9	61	879.8
14	135.6	38	18.4	62	588.3
15	9.8	39	0.1	63	-883.3
16	4.8	40	0.4	64	-1.9
17	274.3	41	6.1	65	0.9
18	95.6	42	3.9	66	2.4
19	67.9	43	11	67	2.4
20	14.3	44	14.2	68	13.9
21	62	45	19.5	69	7.1
22	17.3	46	0.1	70	7.4
23	137.5	47	0.2	-	-
24	285.1	48	0.2	-	-

Total phosphorus

The value of absorption capacity for most of water bodies closing profiles (58) for total phosphorus were positive, as shown in (Fig. 9) The highest values were obtained for water bodies located between Nowa Wieś Podgórna and the city of Poznan, up to 130 t / year. There is clearly visible negative impact of the city of Poznan on absorption capacity of water bodies profiles located on main stream below the agglomeration (60, 61, 62, 63), there were negative values of absorption capacity were up to -1500 t / year. Other water bodies, which obtained negative values of absorption are no. 10, 27, 38, 43, 64, 69, 50 and 51. Most of them are located in the southern part of the analyzed catchment area. Graphically results of absorption capacity of total phosphorus load based on a characteristic flow of QSNQ were shown in Figure 9. A summary of the results for all analyzed closing profiles of water bodies are presented in Table 7.

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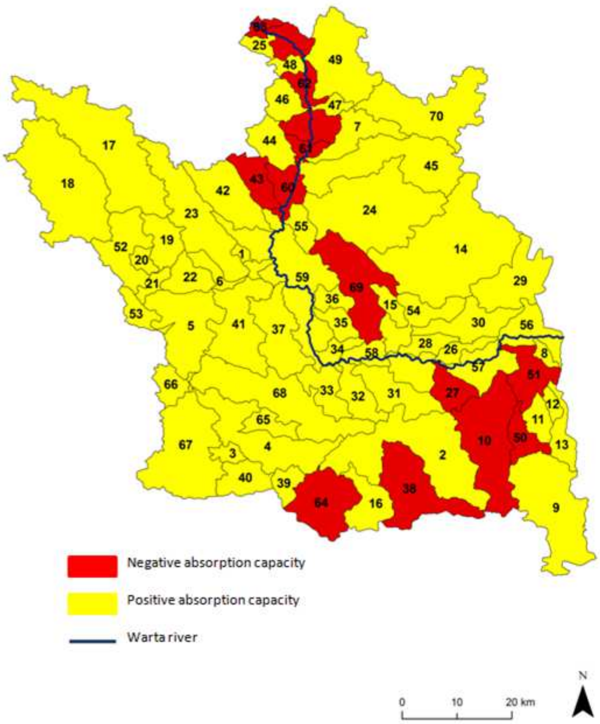

Fig. 9 Actual absorption capacity for each water body of Middle Warta for total phosphorous based on characteristic flow SNQ [source: self studies]

Tab. 7. Total phosphorous absorption capacity for each profile of Middle Warta water bodies based on characteristic flow SNQ

water bodies number	tons/year	water bodies number	tons/year	water bodies number	tons/year
1	0.098	25	0.189	49	0.292
2	0.983	26	0.241	50	-0.016
3	0.165	27	-0.215	51	-3.218
4	5.304	28	0.283	52	1.136
5	16.128	29	0.843	53	0.669
6	8.014	30	1.315	54	0.444
7	3.476	31	0.913	55	0.663
8	0.05	32	0.644	56	129.257
9	0.484	33	1.146	57	123.965

10	-15.519	34	0.113	58	104.055
11	0.082	35	0.269	59	79.82
12	0.049	36	0.538	60	-151.807
13	0.145	37	2.881	61	-592.318
14	5.01	38	-1.234	62	-1069.137
15	0.393	39	0.005	63	-1485.195
16	0.193	40	0.014	64	-1.008
17	10.239	41	0.095	65	0.035
18	3.692	42	0.124	66	0.096
19	1.285	43	-0.484	67	0.096
20	0.572	44	0.568	68	0.519
21	0.736	45	0.782	69	-0.035
22	0.693	46	0.004	70	0.15
23	3.096	47	0.007	-	-
24	8.823	48	0.01	-	-

4. Summary

Effective tool to river absorption capacity determination is a Macromodel DNS/SWAT developed in Institute of Meteorology and Water Management (Poland). Utilization of mathematical modeling to absorption capacity calculation allowed the precise determination of total nitrogen and total phosphorous overloads at each river profile according to limit values as well as determination of disposal capacity of the reach when the absorption capacity has positive values.

Research results show, simply but precisely, water state at estuarine profiles of selected basins. The method assumes to perform the analysis at closing profiles of water bodies. For the analyzed pilot catchment 95% of estuarine profiles of water bodies have positive absorption capacity for the load of total nitrogen and 80% for a load of total phosphorus, which means that in these areas the ecosystem is able to adapt to the "elimination" of these pollutants by a series of processes called generally self-purification of the river. In such cases, it is assumed that after the removal of the pollution sources ecosystem returns to state of equilibrium or close (Fig. 1). The highest values of absorption capacity for both total nitrogen and total phosphorus were observed at profiles of water bodies located within the main stream, upper to the city of Poznan (water bodies from 56 to 59). This area is characterized by low population density and low industrialization, although a large number of large-scale farms. It should also taken into account that the main reach of Warta river is characterized by a high flow (average 195 m^3 s^{-1}), what have a direct impact on the dilution of contaminants in the water mass. It may thus be concluded that major streams characterized by low time variability of flow are more resistant to contamination and there can be expected the higher values of absorption. Negative absorption capacity for total nitrogen was noticed for three water bodies (10, 63, 64) what means that limit load was exceeded there. Two profiles belong to two water bodies located in the southern part of the basin (10, 64). These basins are characterized by very low flows (sometimes dry up in the summer) and on their area are located industrial plants and numerous illegal sewage discharges. In water body with number 10 is also located a small reservoir characterized by a high concentration of nitrates. The third case of negative absorption capacity for total nitrogen is the last control profile of the main stream - estuarine profile of pilot catchment Middle Warta (63). There is a problem there of the rapid expansion of the city Oborniki and insufficient sewage system development as well as intensive agriculture. A large number of leaking septic tanks is responsible for a significant load of nutrients in surface waters in the area.

For total phosphorous twelve water bodies obtained negative values of absorption capacity (10, 27, 38, 43, 50, 51, 60, 61, 62, 63, 64, 69). Half of them are located in the southern part of the study area and are water bodies of small streams characterized by low flows and located on their area large-scale farms, industrial plants, sewage treatment plants, and, as has already been mentioned, numerous illegal discharges of wastewater (water bodies no.: 10, 27, 38, 50, 51, 64). Negative values of absorption capacity for total phosphorus were also noticed at closing profiles of water bodies on the main reach located lower than the city of Poznan (water bodies no.: 60, 61, 62, 63), which proves that high loads of pollutants are discharged from the area of this agglomeration to the waters of the Warta river. The results of the proposed method coincide with previous field research conducted by Voivodeship Inspectorate for Environmental Protection.

5. Discussion

Data on the analyzed Middle Warta catchment obtained by utilization of calibrated, verified and validated Macromodel DNS/SWAT were used to calculate the absorption capacity of the river. Using mathematical modeling aimed to simulate daily loads of pollutants at any selected estuarine river profile and then to classify the sources of pollution occurring in the basin. The absorption capacity determinate on this basis for individual water bodies enable to obtain detailed knowledge of the condition of the aquatic environment and the possibility of its adaptation to pollution which is key information for assessing whether the intended water management have a significant impact on their state. Obtained information concerns localization of polluted areas as well as areas not currently at risk of pollution and where reserves of absorption capacity occurred what is important for, inter alia, during developing management plans for water in basins.

In this study river absorption capacity were calculated for seventy estuarine profiles of individual water bodies for pilot catchment. This enabled the identifications of those water bodies which need urgent actions aimed to reduce the amount of nutrients entering the surface water from point and nonpoint sources. At the other hand there were identified areas where acceptable limits of pollution are not exceeded and, moreover, it was possible to accurately determine the pollutant load, which, if necessary, can even lead to the river without changing its class of quality state. In both cases exploitation of Macromodel DNS/SWAT does not have to be limited only to determine the amount of pollutant loads but can also allow the assessment of the impact of planned activities on the catchment. In the case of the described studies a division of the basin into water bodies was used, but if necessary it is possible to split pilot catchment into any selected basin areas.

During planning the research described in the paper similar methods used in other regions of the world were analized. Primarily the TMDL ratio, described in chapter 1, were analized. However, this parameter is based only on identification of pollution source in the catchment without utilization of limit loads. In Poland limit loads are placed in national law acts. Besides, developing Total Maximum Daily Loads (TMDLs) for nutrients is also difficult because nitrogen and phosphorus can come from any number of sources, e.g., a significant amount of nitrogen can come from agricultural or atmospheric sources. Therefore, the proposed method of determining the absorption capacity, suitable especially for nutrients due to the fact that it is based largely on Macromodel DNS / SWAT adapted to the modeling of nutrients, and that refers to the load limit of pollutants for a specific class of water quality, as described in this article. Both parameter TMDL and river absorption capacity are parameters related to determining the assimilative capacity of the river, however, the calculation of these parameters are based on different assumptions.

For both TMDL and absorption capacity one of the most important elements for calculations is the proper selection of characteristic flow. If the absorption capacity of the river was a parameter on the basis of which decisions of water quality improvement could be made, the choice of characteristic flow becomes crucial. Depending on the country different characteristic flow are used for the environmental calculations. More and more often in publications [Dyson et al., 2003; European Commission, 2015] the question is raised about the use of environmental flows (taking into account the meaning of medium and high flows in maintaining good state of river ecosystems). However, the determination of environmental flows requires field and computation research of hydraulic and ecological characteristics. At the current stage of knowledge and research made on polish catchments, this type of analysis for all estuarine profiles of water bodies are impossible to implement. This is one of the reasons why in Poland, like also in the United States, characteristic flow commonly used are ones emphasizing only on low flows (SNQ, 7Q10). The 7Q10 parameter (the lowest flow of 7-day period for a decade) statistically has a predisposition for achieving zero values often what is a disadvantage of using 7Q10 in environmental analysis. It also requires the 10-year measurement series. For the purposes of research conducted on the possibility of using the absorption capacity as a parameter to control the quality of water in the catchment the SNQ flow was chosen as adequate. The proposed designation of absorption capacity include water quality standards in accordance with the law acts [...], which also recommend the use of SNQ to calculate the environmental calculation. In addition, for basins with a negative absorption, the use of flow lower than SNQ results in lowering the load that should be removed from the river in order to achieve environmental standards. However, using of either SNQ or 7Q10 is a hydrological approach characterized by the simplicity of calculations and the possibility of its utilisation at uncontrolled reaches due to the revised method of handling this type of statistics between the profiles. It is assumed that, in the case of research described in the paper, hydrological conditions reflect the biological needs.

6. Conclusion

1. To assess the quality of surface water is useful to use the concept of absorption capacity of the river. It is understood as the maximum load of pollutant which can still enter the river without exceeding the limit load and, consequently, without changing its quality class or when the load limit is exceeded, it is the load that must be removed from the water in order meet environmental standards. Knowledge of the river absorption capacity enable to plan actions

that prevent the degradation of water quality in the river and, consequently, aquatic and water-dependent ecosystems, occurring due to anthropogenic pressure.

2. Calculations of absorption capacity of the river segment are based on pollutant loads from nearest profiles, however, it is not equal to load introduced directly into the surface water on that segment due to processes of self-purification of the river water on the way from introduction of pollutant into the river to the control profile. Dynamics of self-purification processes affects absorption capacity.

3. Positive values of absorption capacity means that ecosystem adapts to the elimination of introduced pollution loads through a number of self-purification processes. It is assumed that pollution already introduced do not cause permanent change and after elimination of the source of pollution ecosystem will return to equilibrium or close to balance state. Positive values of absorption capacity allow to determine a disposable load of pollutant in the catchment.

4. Negative values of absorption capacity indicate areas where anthropogenic activities, agricultural or municipal, are responsible for excessive pollution with nutrients. This means that the limit load was exceeded, and to the ecosystem has been introduced too much pollution for possibility of self-purification of the river. This is the amount of load that must be removed from the river segment for attaining the water quality standards, however, this is not tantamount to a complete ecosystem return to the initial state, especially for nutrients which may affect many processes in the catchments. It is also unknown whether the critical load was exceeded or not. Nevertheless, in this case, the excessive pollution should be reduce and methods of ecosystem revitalization should be implement.

5. Macromodel DNS/SWAT can be a effective tool for absorption capacity analysis of river segment what was shown on the example of Middle Warta basin for an average daily loads of nitrogen and total phosphorus.

6. Information on the river absorption capacity can be a good basis for creation of action scenarios which could help in determining the impact of realization of land development plans or investments planning on surface water and aquatic and water-dependent ecosystems.

7. For a more detailed analysis of water quality for selected catchments hydrological units smaller than water bodies should be consider.

8. To summarize, the developed absorption capacity parameter is a valuable element of the assessment of water quality. It allows the connection of water quality according to reference values of environmental standards and water quality management plans in order to meet these standards. This parameter is designated by detailed mathematical calculations in combination with precise modeling techniques. This enable to consider in the modeling many hydrological, geological and soil conditions, weather and water quality parameters, and then the implementation of obtained results during mathematical calculations. Absorption capacity of river segment explains the relationship between the load of pollutants in the river, limits values of environmental standards and water quality assessment along with the identification

of sources of pollution and possibilities of improving water quality and state of aquatic and water-dependent ecosystems.

9. Analysis of absorption capacity using QSNQ as a characteristic flow has shown to be efficient and useful. However, at the stage of practical implementation of this parameter in order to in-depth assessment of nutrient pollution (eg in terms of eutrophication) the utilization of characteristic flow based on low flows may not be sufficient. Therefore, it is necessary to continue research on utilization of environmental flows which takes into account additionally medium and high flow, as well as a number of elements affecting the hydrological regime such as the size, time of occurrence, duration and frequency of floods and low waters.

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Author contribution:

Paweł Wilk - development of a method for calculating the river absorption capacity using the Macromodel DNS / SWAT, calibration, veryfication and validation of the model.

Paulina Orlińska-Woźniak, Joanna Gębala - preparation of data necessary to build the Macromodel DNS / SWAT

Mieczysław S. Ostojski - development of the Macromodel DNS

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