

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

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10 Abstract

In order to complete a thorough and systematic assessment of water quality it is useful to measure the absorption capacity of a 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 in the classification of water quality in the river profile. In order to implement the method, the Macromodel DNS / SWAT basin for the Middle Warta pilot (central Poland) was used to simulate nutrients loads. This enabled detailed analysis of water quality in each water body and the assessment of the size of the absorption capacity parameter, which allows to determine how many pollutions can be made to the river without compromising its quality class. Positive values of the calculated absorption capacity parameter mean that it is assumed that the ecosystem is adjusted in a way that means it can eliminate pollution loads through a number of self-purification processes. Negative values indicate that the load limit has been exceeded, and too much pollution has been introduced into the ecosystem for it to be able to deal with through the processes of self-purification. Absorption capacity thus enables the connection of environmental standards of water quality and water quality management plans in order to meet these standards.

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

1. Introduction

30 The Water Framework Directive (WFD) [Directive 2000/60 / EC] implemented in the European Union treats water as a common good and obligates the sustainable management of its resources, among other things, by preventing degradation, improving the state of water resources and protecting aquatic and water-dependent ecosystems [Orlińska-Woźniak et al., 2013; Boeuf and Fritsh, 2016]. The WFD determines the search for new and more effective solutions for the state of the aquatic environment and, consequently, the assessment of the effectiveness of actions plans in areas deemed polluted. What is

35 important here is that surface water pollution, in most cases, is not an irreversible state, so pollutant input to surface water will not always lead to irreversible contamination. Water has the ability to self-purify [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].

40 Generally, self-purification is a biochemical transformation of pollutants (containing mainly organic compounds) into simpler forms, often inorganic, that have microorganism activity; this is done at the expense of the consumption of oxygen from the air and water and through sedimentation processes that cause the physical elimination of water pollution [Jarosiewicz, 2007; Kowalewski, 2009; Elósegui et al., 1995; Vagnetti, 2003]. The most important factors influencing a river's self-purification ability include, among others, topography, soil type, vegetation, the hydraulic characteristics of the river, the retention time of water in the catchment, biodiversity and temperature [Spellman and Drinan 2001; Schulz et al., 45 2003; Vaikasas and Dumbrasukas, 2010; Marsili- and Giusti, 2008; Popek, 2011; Van der Lee et al., 2004]. To evaluate indirectly the possibility of a river performing self-purification – through the comparison of actual loads in the river to limit loads – the river absorption capacity (RAC) parameter is useful. The establishment of limits aims to determine a threshold below which there is a possibility of a 50 river's self-purification.

It should be noted that beyond a certain critical level of pollutants it may be impossible for an 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 ...", which referred to the process 55 of eutrophication. This work was motivated by attempts to improve water quality aimed at restoring ecosystems to their original conditions. Observations of many ecosystems were made and, despite the elimination of sources of pollution, they did not return to their original state, even after more than 30 years. Owing to this, the authors concluded that above a certain critical value of pollution, an ecosystem is not able to return to its original state. Understanding an ecosystem's response to multiple shifting 60 baselines is essential in setting 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, is led by the US Environmental Protection Agency (EPA) through the implementation of the Clean Water Act [Federal Water Pollution Control Act, 2002]. IMGW-PIB started studies on river the utilisation of the absorption capacity 65 parameter in water management in 2011 by proposing the calculation of absorption capacity on the basis of the advanced Macromodel DNS which has the ability to determine of the amount of point and nonpoint source of pollution in a given river section.

This paper presents a method of assessing the surface water state by determining the river absorption capacity parameter. Absorption capacity is defined as the maximum load that can be input into a river 70 without exceeding limit load and changing the water quality state class or, when the absorption capacity is negative, the load that should be removed to accomplish limit loads. The method assumes the use of mathematical modelling. The Macromodel DNS, developed at IMGW-PIB, was used [Ostojski, 2012]. It allows, inter alia, for daily flow simulations, as well as average daily loads of selected pollutants, which is essential for the determination of river retention. The simulation of these loads allows for the 75 calculation of river absorption capacity.

The proposed method of evaluating the status of surface water by using the river absorption capacity parameter is an alternative to the ratio commonly used by the EPA, defined as the assimilative capacity of the river, and 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].

80 This is defined as the maximum amount of a pollutant that can occur in a waterbody, designates the necessary reductions to one or more pollutant sources, allocates a planning tool and points out a 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 were first defined in 1992 and have been repeatedly revised and updated since then. This method is based on the identification of
85 point and nonpoint pollution and then the calculation of their sum for the river sections previously recognised as endangered by excessive pollution.

$$\text{TMDL} = \Sigma \text{WLAs} + \Sigma \text{ELAs} + \text{MOS}$$

WLAs - point source loads

LAs - nonpoint source loads

90 MOS - margin of safety

Knowledge of a river's absorption capacity enables the implementation of action plans aimed at preventing the degradation of water quality, and consequently that of aquatic and water-dependent ecosystems, which occurs as a result of human activity, that is, anthropopressure. Currently there is no
95 universal methodology to determine the absorption capacity of the river. In the few publications on the subject, only general equations are available [Chmielowski and Jarzabek, 2008; Monka, 2005; Tyszewski et al., 2008]. The general RAC equations in this publication for calculating this parameter are sufficient for their purpose. However, when a more in-depth analysis of both the calculations and the results is required, knowledge of the entire RAC methodology is required, taking into account the
100 pollutant load used for the calculation and a selected flow characteristic. There is also no information on the natural background of pollution identified as actual natural load (ANL), which should be taken into account when analysing the RAC parameter.

The aim of the study was to develop a method for the evaluation of the physico-chemical surface water state through the definition of the absorption capacity of a river. For this purpose, the Macromodel DNS / SWAT was used, which was calibrated, verified and validated for the Middle Warta pilot catchment.
105 The model was prepared to take into account the individual processes of pollutant transformation and transport, from the moment pollutants enter the environment until their discharge into the sea, and to allow the determination of nutrient 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
110 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 change the classification of water quality in the profile [Chmielowski and Jarzabek, 2008]. Afterwards the results of absorption capacity at river profiles were evaluated and the consequences of positive and negative values of absorption capacity for the analysed area were analysed, linking the reference of water quality
115 environmental standards with water quality management plans in order to meet these standards.

2. Materials and methods

2.1. Absorption capacity

The phenomenon of absorption capacity is described by the schematic impact of pollutant discharges originating from human activity on the ecosystem of the basin presented in Fig. 1. When a natural river devoid of anthropopressure has only natural background 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), while the maximum pollution load in the river can be called ANL. This is a very rare situation and in Europe there are virtually no basins without human pressure. Some such basins are in the northern parts of Scandinavia and Russia [Helsinki Commission, 2004]. Therefore, the only way to determine the natural background is to use a mathematical model which allows the creation of a scenario in which the entire human pressure on a catchment is removed. At the moment \ anthropogenic discharge appears in a catchment, an ecosystem changes and enters a state of adaptation (zone II). This means that the pollution introduced to the basin will interfere with the balance of the ecosystem, but not cause permanent changes in it. An ecosystem adapts to pollution's "elimination" through a series of processes collectively called the self-purification of the river. Generally, it is assumed that after the removal of a pollution source, an ecosystem will return to a state of equilibrium (or close to it). In river ecosystems in zone II, retention is can be up to 30% of the total amount of nitrogen [Dziopak, 2007; Neverova-Dziopak, 2009]. Therefore, the pollution discharged into a stream at any point will not be equal to 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). CL can't be defined as the critical size of load in practice is impossible to determine. Of course, it is possible to try to estimate the critical load value for selected catchment fragments, but this will always be approximate. The critical load can also be defined as the limit beyond which a return to good status is no longer possible. The amount of pollutants in a river then is so great that the previous self-cleaning processes are permanently impaired and no longer function. To prevent irreversible consequences of exceeding the CL, the concept of limit load LL is introduced, and its value is defined as the limit of good water status set by administrative decisions in accordance with the WFD and the regulation of the Minister of the Environment [Regulation of the Minister of the Environment, 2011]. Limit load (LL) is the maximum load of a selected pollutant, which may be in a selected river section of an analysed river, which has been classified in class II of clean water (good water status). This load was calculated on the basis of the limit concentration (LC), which is determined in Poland by the ordinance of the Minister of the Environment, and also the selected characteristic flow (CF). A good water status is defined as waters that meet, for most water quality indicators, the requirements for surface waters used to supply the population with water for consumption. As well as the values of biological water quality. indicators show little indication of anthropogenic impact.

Fig. 1

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 the extreme value of water levels observed in the analysed period (1.1).

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

Critical load CL is difficult to determine in practice, 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 an ecosystem. Therefore, it is preferred that the limit load LL is determined 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. It is the difference between LL and CL that defines whether we are dealing with a positive or negative RAC parameter (Fig. 2). In addition, the load limit (LL) along with the critical load (CL) define the so-called area of uncertainty (Fig.1). The size of this area will be different for each water body, and its precise definition is very difficult because it is practically impossible to determine the critical load value beyond which a catchment will be permanently and irreversibly polluted.

Absorption capacity of the river is the difference between two loads: the first of these 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]; the second is the actual load calculated based on the actual concentration at a 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 sources of pollution (both point and nonpoint sources). The results of absorption capacity are obtained for selected river profiles.

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

$$RAC = LL - AL \quad (1.2)$$

where:

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

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

The actual load at a control profile is described by equation:

$$CL = AC * CF \quad (1.3)$$

where:

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

CF – characteristic flow ($\text{m}^3 \text{ s}^{-1}$)

While the limit load at a control profile is described by equation:

$$LL = LC * CF \quad (1.4)$$

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

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

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

195 where:

n – the number of elements in the analysed set

2.2. Absorption capacity cases

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

Fig. 2

Values of river absorption capacity RAC:

- 205
- Positive – means that actual load AL at the profile is lower than limit load LL of selected pollutant:

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

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

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

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

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

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

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

Therefore, there is an exceedance of the limit value for environmental standards for a good water state at the profile and there is an obligation to take action aimed at reducing pollutant loads

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discharged into the river. If the critical load is not exceeded, in the case of negative absorption capacity, the reduction of pollutant loads should cause a spontaneous return of the ecosystem to its original state, understood as a state before a change caused by anthropopressure.

225 2.3. Macromodel DNS/SWAT

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

The Macromodel DNS (Discharge-Nutrient-Sea) was designed at 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 the simulation of 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). The Macromodel DNS defines the actual load AL description at a control profile as:

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

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

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

245 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

250 The values of the individual components of equation (1.9) were obtained by using the Macromodel DNS in conjunction with the SWAT module. The possibility of introducing detailed catchment data allows for modelling data on both point and nonpoint pollutants (L_{POINT} , L_{NON}), pollutant loads entering the river along with infiltration waters (L_{INF}) and retention (R). Data on atmospheric deposition (L_{DEP}) was obtained from the Norwegian Meteorological Institute, whose mathematical models cover the area of Poland.

SWAT (Soil and Water Assessment Tool) [Neitsch et al. 2004, Neitsch et al. 2005] can be one of modules of the 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 a 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 a watershed to the outlet [Neitsch et.al.2011]. The Macromodel DNS containing SWAT model as an integral module was called the Macromodel DNS/SWAT, (Fig. 4).

Fig. 4

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

2.3.1. Research area

The methodology proposed in the article for calculating absorption capacity of a river have been implemented on the example of a fragment of the catchment of the Warta (the Middle Warta). The Warta is the third longest river in Poland. The selected basin has an area of 6039 km² 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 were 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 at the end the profile – Oborniki was chosen (Fig. 5). The analysed part of the catchment is characterised by a significant amount of area exposed to nitrogen pollutants of an agricultural origin. The area is characterised by a high proportion of nitrate vulnerable zones – areas particularly vulnerable to nitrogen pollution from agricultural sources (NVZ) [Directive 91/676/EEC]. The main 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 as well as surface runoff from agricultural areas. In the basin area is the largest metropolitan area of Warta catchment – Poznań, which is the fifth most populous city in Poland and has a very rapidly growing suburban area. Monitoring research which has been conducted for many years on the water state of the Warta indicates that the quality of its waters is strongly differentiated into individual river sections and pollution flowing into the river can affect locally the process of eutrophication, among other aspects.

Fig. 5

2.3.2. Data

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

300 The DEM remains the national, central geodesic and cartographic 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 analysed catchments at a scale of 1:50 000 was used. Data concerning wastewater treatment plants located in the
305 area of the analysed 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 $\text{m}^3 \text{yr}^{-1}$, total suspended solids (mg L^{-1}), total nitrogen (mg L^{-1}) and total phosphorus (mg L^{-1}). Meteorological input data had a daily time step and included solar radiation, wind speed, precipitation, relative moisture,
310 and maximum and minimum temperatures. Soil maps at a scale of 1: 100,000 with the soil types 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

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

Tab. 2

Input data used to calculate phosphorus loads from manure and mineral fertilizers were obtained from the Polish Local Database (BDL) and included information regarding livestock and the surface area of
320 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-basins in line with 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

325 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, the 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 were 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 modelling 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 with the OAT method (one-at-a-time), a repeated iterative loop. The values of parameters received during the sensitivity analysis (Tab.4) were successively changed in ranges with a high probability of occurrence 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 recognised that such a calibration method enables the 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 R^2 , PBIAS and NSE were 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 1 January 2003 to 31 December 2007, with the daily time step for Poznań – Most Rocha measuring point, located at 241.76 km (150.22 miles). The verification of the models was conducted from 1 January 2008 to 31 December 2009 with the daily time step for Poznań – Most Rocha measuring point. As for validation, this was conducted from 1 January 2003 to 31 December 2006 with a daily time step for the Oborniki measuring point located at 205.2 km (127.5 miles). In the mentioned periods, the full range of daily data for flow was available, as was 3% to 7% of data for both total nitrogen loads and total phosphorus loads (Tab. 3). The flow rate data were derived from the Hydrology System conducted by the Institute of Meteorology and Water Management (IMGW). Total nitrogen and total phosphorus data were from the SEM database.

The monitoring data we used to calibrate, validate and validate the mathematical model come from the years 2003-2009. It was decided that calibration and validation of the mathematical model for this period would be made, as IMGW was conducting its own parallel SEM monitoring of the Middle Warta then. Therefore, for this period of time, we have the largest possible database to better match modelling results to observations (especially for general nitrogen). The monitoring measures currently underway have confirmed that the values of general nitrogen concentrations in the Middle Warta basin remain at a similar level. In a revised version of the article, we will make a description of the data so that it is clear to every reader why this time period has been used. For each of these processes, robust statistics were used to calculate the winsorized robust statistical measures [Ostojski et al. 2016].

Tab. 3

3. The modelling results

For the pilot catchment model Middle Warta and Rega, within the functionality of SWAT, which is in this case a DNS Macromodel module, sensitivity analysis of parameters associated with the flow, total nitrogen and total phosphorus was 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

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

Fig. 6

Fig. 7

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 modelling conducted using robust statistics and winsorized L-estimators were used [Ostojski et al. 2016].

Tab. 5

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] results of model fit. For calibration and verification of total nitrogen, "very good" and "good" fit results of the

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

3.1. Absorption capacity results

After the 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 calculation of the precise absorption capacity at closing profiles of all 70 Water Bodies located in the analysed 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 sub-catchments 56 to 60 (values of up to 3 500 t / year). A clear drop in absorption capacity on the main stream was noted from the closing profile of 61 water bodies where absorption reached 880 t / year, that is, on water bodies located directly behind the city of Poznań. The lowest, but still positive, values of absorption capacity were at the closing profiles of small streams characterised by low flows.

Negative absorption capacity values for total nitrogen only occurred 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 about 55 t / year and 2 t / year, respectively. Basin 63 is the last section of the main stream of the analysed catchment where absorption capacity obtained the value of 880 t / year.

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

Fig.8

Tab. 6

Total phosphorus

The value of absorption capacity for most closing profiles of water bodies (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 Poznań – these were up to 130 t / year. There is a clearly visible negative

435 impact of the city of Poznań on absorption capacity of profiles located on the main stream below the
agglomeration (60, 61, 62, 63). There, negative values of absorption capacity were up to -1500 t / year.
Other water bodies that obtained negative values of absorption are nos. 10, 27, 38, 43, 64, 69, 50 and
51. Most of these are located in the southern part of the analysed catchment area. Graphic results of the
absorption capacity of total phosphorus load, based on a characteristic flow of QSNQ, are shown in Fig.
9. A summary of the results for all analysed closing profiles of water bodies are presented in Table 7.

440 Fig. 9

Tab. 7

4. Summary

445 The Macromodel DNS/SWAT developed at the Institute of Meteorology and Water Management
(Poland) is an effective tool for the determination river absorption capacity. The utilisation of
mathematical modelling for the calculation of absorption capacity allowed the precise determination of
total nitrogen and total phosphorous overloads at each river profile, according to limit values, as well as
the determination of the disposal capacity of the reach when the absorption capacity has positive values.

450 Research results show, simply but precisely, the water state at the estuarine profiles of selected basins.
The method assumes the performance of the analysis at closing profiles of water bodies. For the analysed
pilot catchment, 95% of estuarine profiles of water bodies have a 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 generally
referred to as the self-purification of the river. In such cases, it is assumed that after the removal of
455 pollution sources, an ecosystem returns to a state of equilibrium, or close to it (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, to the north of the city of Poznań (water bodies 56 to 59).
This area is characterised by low population density and low industrialisation, although there are a large
number of large-scale farms. It should also be taken into account that the main reach of the Warta River
is characterised by a high flow (average $195 \text{ m}^3 \text{ s}^{-1}$), which has a direct impact on the dilution of
460 contaminants in the water mass. It may thus be concluded that major streams characterised by low time
variability of flow are more resistant to contamination and higher values of absorption can be expected
there. Negative absorption capacity for total nitrogen was noted for three water bodies (10, 63, 64),
which 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 characterised by very low flows (they sometimes
465 dry up in the summer) and industrial plants and numerous illegal sewage discharges are located in their
territory. A small reservoir characterised by a high concentration of nitrates is also located in water body
10. The third case of negative absorption capacity for total nitrogen is the last control profile of the main
stream – estuarine profile 63 of the pilot Middle Warta catchment. There is a problem here related to the
rapid expansion of the city of Oborniki and the insufficient development of sewage system; there is also
470 intensive agriculture in this area. A large number of leaking septic tanks are responsible for a significant
load of nutrients in surface waters in the area.

For total phosphorous, twelve water bodies were obtained with 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 characterised by low flows; their territories feature 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 noted at closing profiles of water bodies on the main reach located south of the city of Poznań (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. The results of the proposed method coincide with previous field research conducted by the Voivodeship Inspectorate for Environmental Protection.

5. Discussion

Data on the analysed Middle Warta catchment obtained with the use of the calibrated, verified and validated Macromodel DNS/SWAT were used to calculate the absorption capacity of the river. The results of general phosphorus calibration using the Macromodel DNS / SWAT are worse than for general nitrogen. This is due to the high daily and seasonal volatility of this element in river waters and the relatively small amount of monitoring data needed to calibrate, verify and validate the model. In spite of this, results of the statistical measures identified as "unacceptable" were obtained mainly for the NSEs, so the authors decided to use the obtained model data for general phosphorus. The obtained RAC results for general phosphorus largely coincide with the actual state occurring in the basin; the water bodies that have been negatively affected by the RAC parameter are located in, among other areas, the main watercourse south of the city of Poznań, which has a negative impact on the waters of the Warta. The remaining water bodies, which had negative RAC values for total phosphorus, are small watercourses in the southern part of the analysed basin, characterised by low flow rates and the location of sewage treatment sites and other points of wastewater discharges. Discussion of the results in the article will be extended with information on this subject. The use of mathematical modelling was intended to simulate daily loads of pollutants at any selected river profile and then to classify the sources of pollution occurring in the basin. The absorption capacity determined on this basis for individual water bodies enables detailed knowledge of the condition of the aquatic environment and the possibility of its adaptation to pollution to be obtained. This is key information for assessing whether the intended water management has a significant impact on the state of a water body. The obtained information concerns the location of polluted areas as well as areas not currently at risk of pollution and where reserves of absorption capacity occurred; this is important during the development of management plans for water in basins, as well as in other contexts.

The article presents the possible response of the river ecosystem to the pollutant load conveyed to it (Fig. 1). In addition to the three zones marked I, II and III, there is one more area of uncertainty. Its width defines the difference between CL and LL, but only the LL value is known in this case. As previously described, it is not possible to determine the CL value beyond which it will no longer return to good water status. The actual volume of CL loads is influenced by a number of processes occurring in surface waters; these vary with the intensity of the river flow and the seasons. It is not known how wide the zone, defined as the area of uncertainty, is. Knowledge of the existence of the area of uncertainty and CL is important in various contexts, including for governmental authorities dealing with

the definition of LL load which should be designed to guarantee the protection of the aquatic environment.

515 The knowledge of actual natural load (ANL) is important information for the proper determination of pollutant loads in rivers. Much of the biogenic compounds in surface waters are found there as a result of human activity, but nutrients are also leached from the soil under natural conditions. Estimating ANL is difficult because in Europe there are no longer virtually any anthropogenic drainage basins that could become a benchmark for determining ANL. The Macromodel DNS / SWAT can be used to help create
520 scenarios for the use of catchments. This allows you to "remove" the anthropopressure from the analysed basin and estimate the amount of naturally occurring pollutants. This will be the subject of further research.

In this study, river absorption capacity was calculated for seventy estuarine profiles of individual water bodies for the pilot catchment. This enabled the identification of those water bodies which need urgent
525 actions aimed at reducing the amount of nutrients entering the surface water from point and nonpoint sources. On the other hand, there were areas identified 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 not changing its class of quality state. In both cases exploitation of the Macromodel DNS/SWAT does not have to be limited only to determine the amount of pollutant loads
530 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 analysed. Primarily, the TMDL ratio, described in Chapter 1, were analysed. However, this
535 parameter is based only on the identification of pollution sources in the catchment without the utilisation of limit loads. In Poland, limit loads are placed in acts of national law. As well as this, 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 is
540 especially suitable for nutrients due to the fact that it is based largely on the Macromodel DNS / SWAT adapted to the modelling of nutrients, and this refers to the load limit of pollutants for a specific class of water quality, as described in this article. Both the parameter TMDL and river absorption capacity are parameters related to the determining of the assimilative capacity of the river; however, the calculation of these parameters is based on different assumptions.

545 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 is 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 environmental calculations. More and more often in publications [Dyson et al., 2003; European Commission, 2015]
550 the question is being raised concerning the use of environmental flows (taking into account the meaning of medium and high flows in maintaining a 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 related to Polish catchments, this type of

555 analysis for all estuarine profiles of water bodies is impossible to implement. This is one of the reasons
why in Poland, similarly to in the United States, characteristic flows commonly used are those
emphasising only low flows (SNQ, 7Q10). The 7Q10 parameter (the lowest flow of a 7-day period for
a decade) statistically has a predisposition for often achieving zero values; this is a clear disadvantage
of using 7Q10 in environmental analysis. It also requires a 10-year measurement series. For the purposes
560 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
565 from the river in order to achieve environmental standards. However, the use of either SNQ or 7Q10 is
a hydrological approach characterised by the simplicity of calculations and the possibility of its
utilisation at uncontrolled reaches due to the revised method of handling this type of statistic between
the profiles. It is assumed that, in the case of research described in the paper, hydrological conditions
reflect biological needs.

6. Conclusion

- 570 1. To assess the quality of surface water, it is useful to use the concept of a river's absorption
capacity. This is understood as the maximum load of a 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, this is the load that must be removed from the water in order meet
575 environmental standards. Knowledge of the river absorption capacity enables the planning of
actions that prevent the degradation of water quality in the river and, consequently, damage to
aquatic and water-dependent ecosystems that occurs due to anthropogenic pressure.
- 580 2. Calculations of absorption capacity of a river segment are based on pollutant loads from the
nearest profiles, however, it is not equal to a load introduced directly into the surface water on
that segment due to the self-purification processes of the river water on the way from the
introduction of the pollutant into the river to the control profile. The dynamics of self-
585 purification processes affect absorption capacity.
- 585 3. Positive values of absorption capacity mean that an ecosystem adapts to the elimination of
introduced pollution loads through a number of self-purification processes. It is assumed that
pollution already introduced does not cause permanent change and after the elimination of the
source of the pollution, the ecosystem will return to equilibrium, or close to a state of balance.
Positive values of absorption capacity allow the disposable load of pollutant in the catchment
to be determined.
- 590 4. Negative values of absorption capacity indicate areas where anthropogenic activities –
agricultural or municipal – are responsible for excessive pollution of nutrients. This means that
the limit load has been exceeded, and too much pollution for the possibility of the river's self-
purification has been introduced to the ecosystem. There is an amount of load that must be
removed from the river segment to attain water quality standards, however, this is not

- 595 tantamount to a complete return to the initial state of the ecosystem, especially for nutrients, and this may affect many processes in the catchments. It is also unknown whether the critical load has been exceeded or not. Nevertheless, in this case, the excessive pollution should be reduced and methods should be implemented to revitalise the ecosystem.
5. The Macromodel DNS/SWAT can be an effective tool for the analysis of the absorption capacity of a river segment, as was shown with the example of the Middle Warta basin for average daily loads of nitrogen and total phosphorus.
 - 600 6. Information on the river absorption capacity can be a good basis for the creation of action scenarios which could help in determining the impact of the realisation of land development plans or investment 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 considered.
 - 605 8. To summarise, 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 modelling techniques. This enables the consideration within the modelling of many hydrological, geological and soil conditions, weather and water quality parameters, and then the implementation of the obtained results during mathematical calculations. Absorption capacity of a river segment explains the relationship between the load of pollutants in the river, limit values of environmental standards and water quality assessment along with the identification of sources of pollution and possibilities for improving water quality and the state of aquatic and water-dependent ecosystems.
 - 610 9. The analysis of absorption capacity using QSNQ as a characteristic flow has proven to be efficient and useful. However, at the stage of practical implementation of this parameter in order for in-depth assessment of nutrient pollution (e.g. in terms of eutrophication), the utilisation of characteristic flow based on low flows may not be sufficient. Therefore, it is necessary to continue research on the utilisation of environmental flows which additionally takes into account medium and high flow, as well as the 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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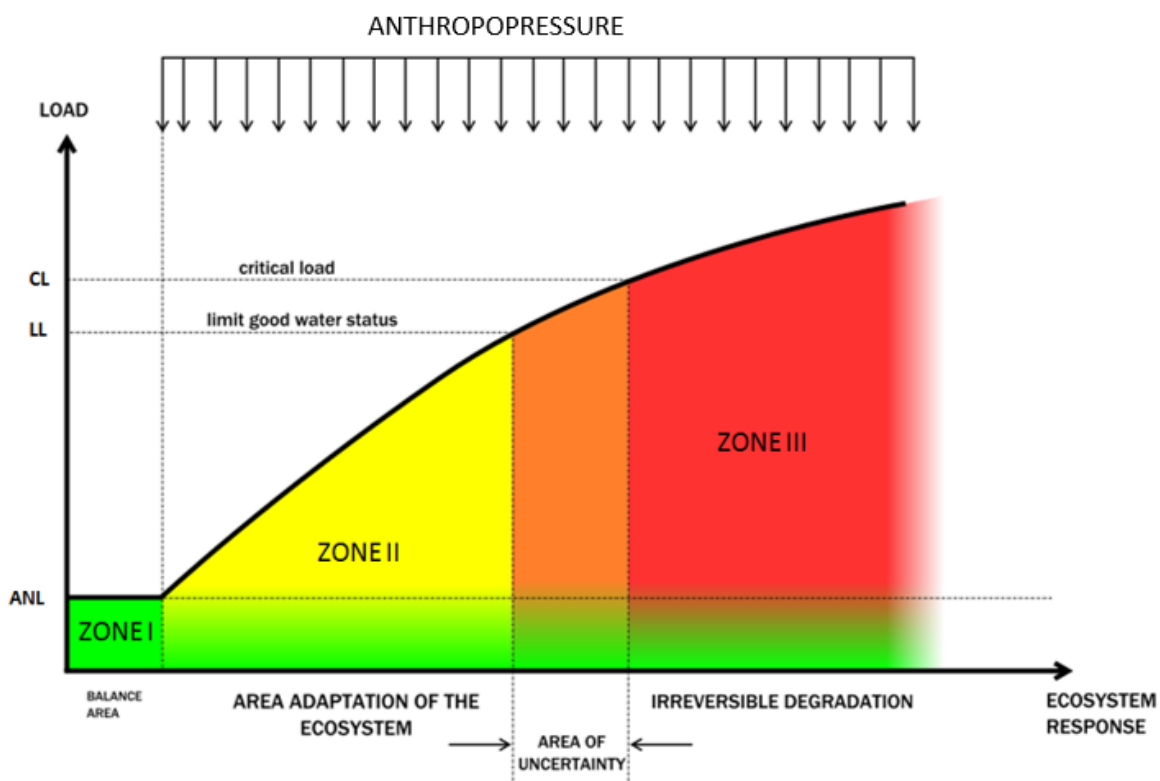
Author contribution:

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

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

Mieczysław S. Ostojki - development of the Macromodel DNS

The authors declare that they have no conflict of interest.



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

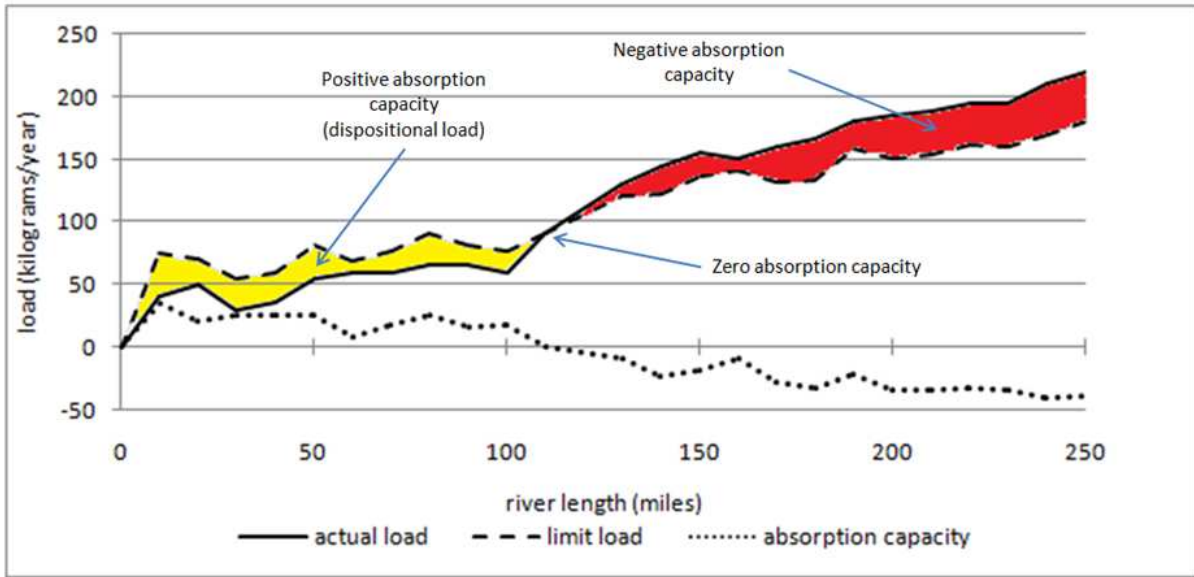


Fig. 2 Possible cases of absorption capacity values for selected section of the river [source: own research]

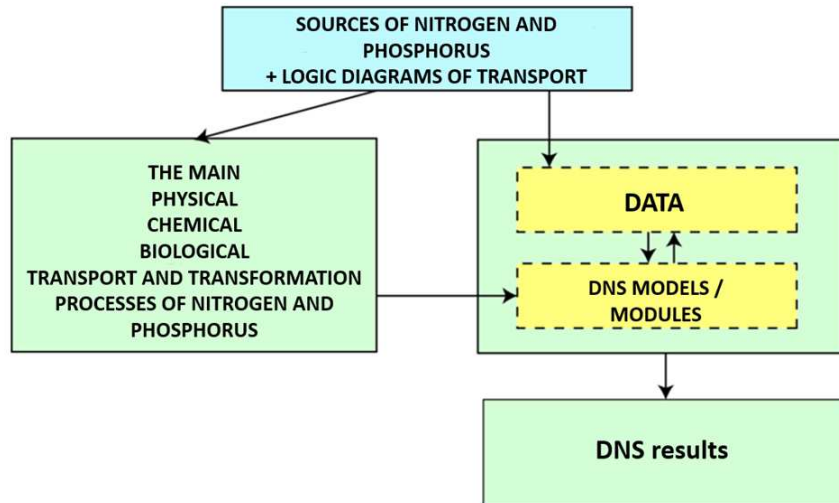


Fig. 3. Macromodel DNS scheme [source: Ostojski, 2012]

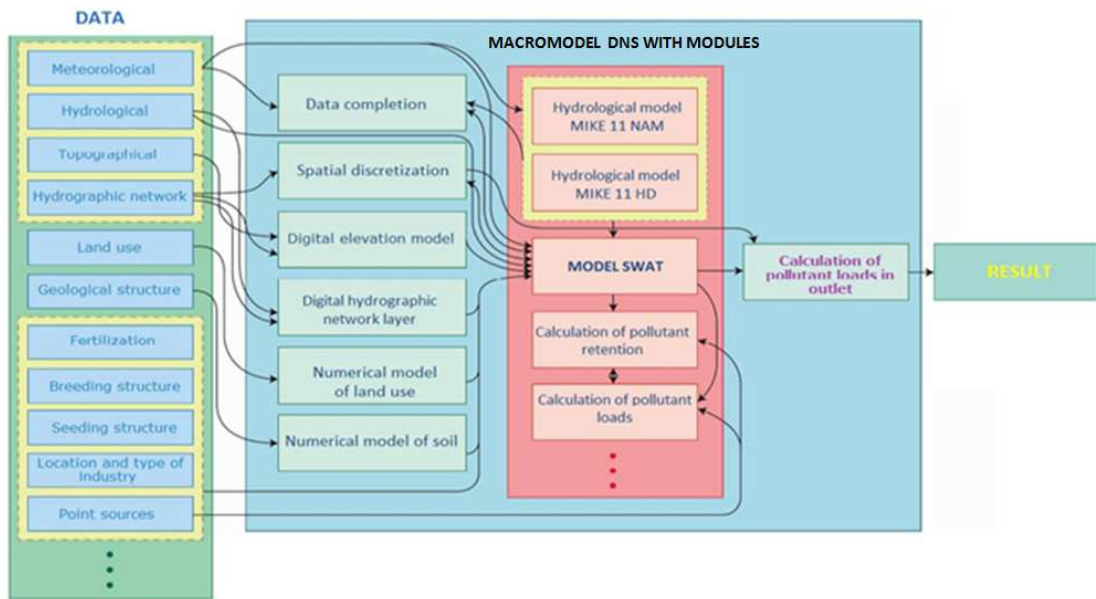
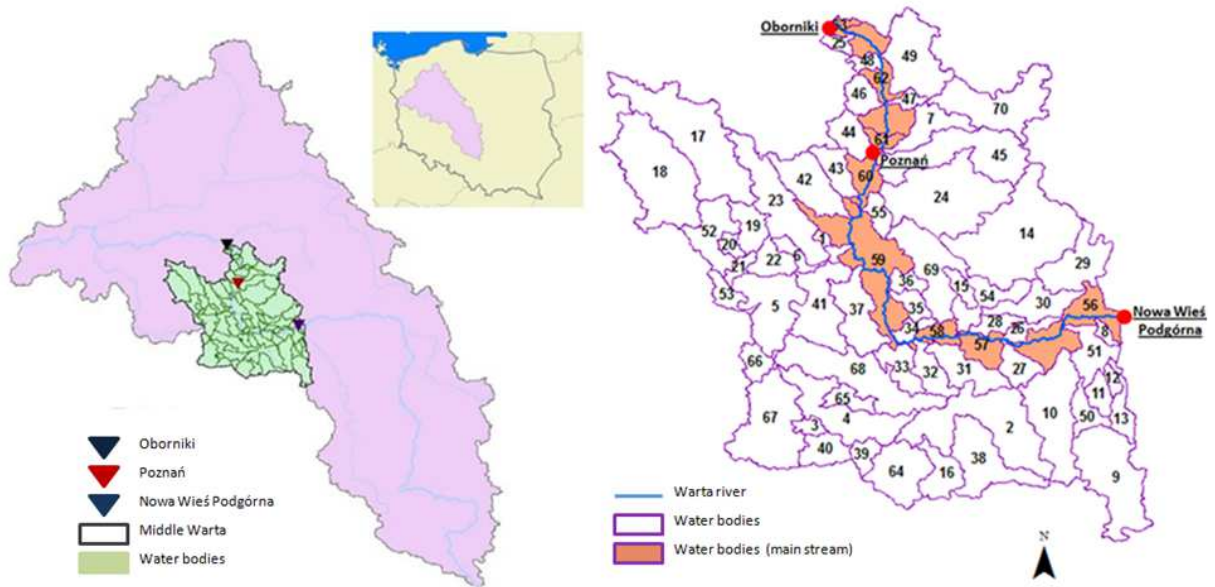


Fig. 4- Macromodel DNS/SWAT schematic diagram- [source: Ostojcki, 2012]



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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]

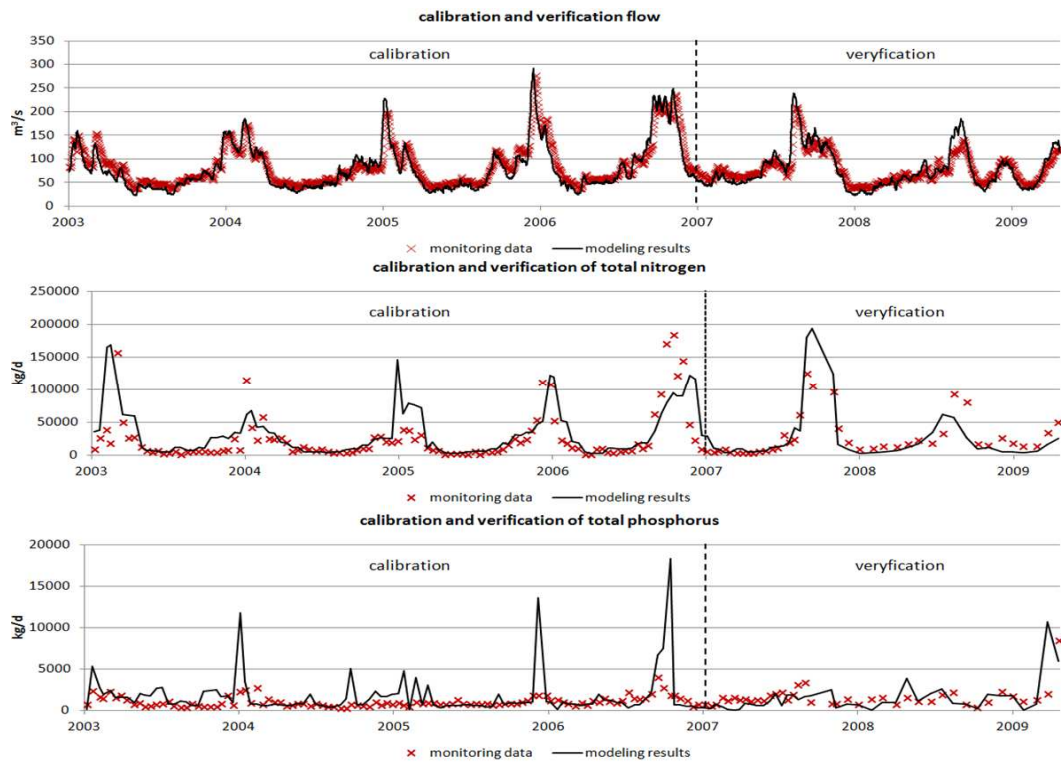


Fig. 6. Matching of modeling results and monitoring results for the period of calibration and verification

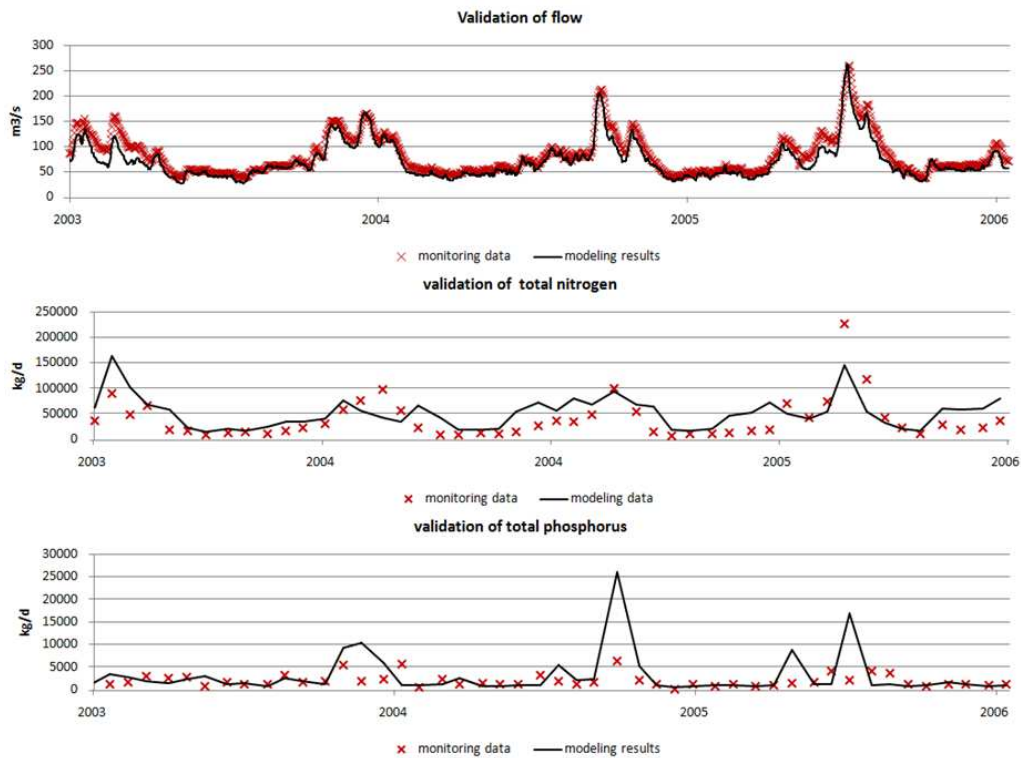


Fig. 7. Matching of modeling results and monitoring results for the period of validation

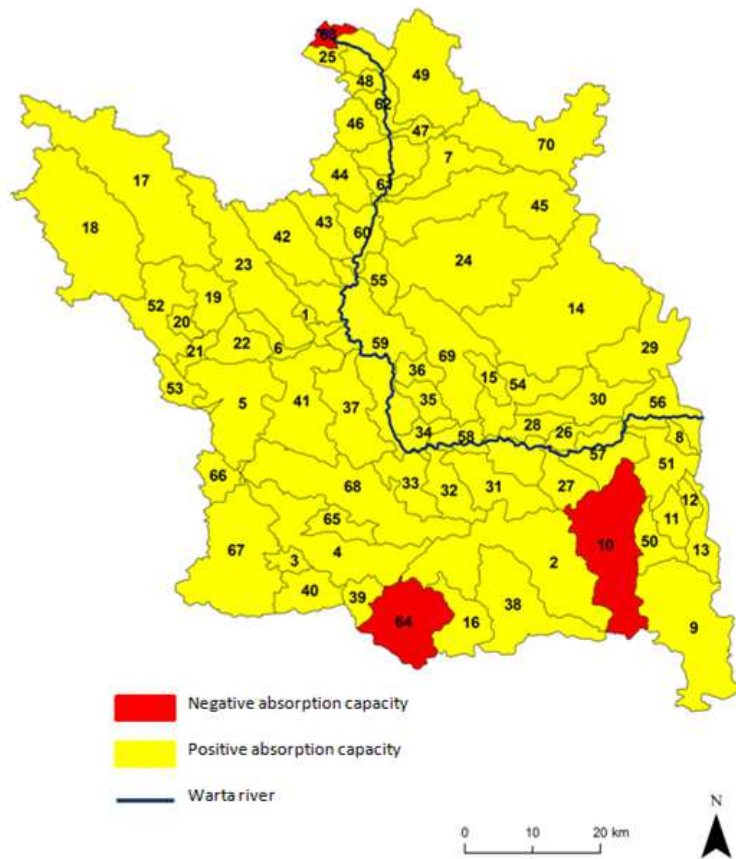
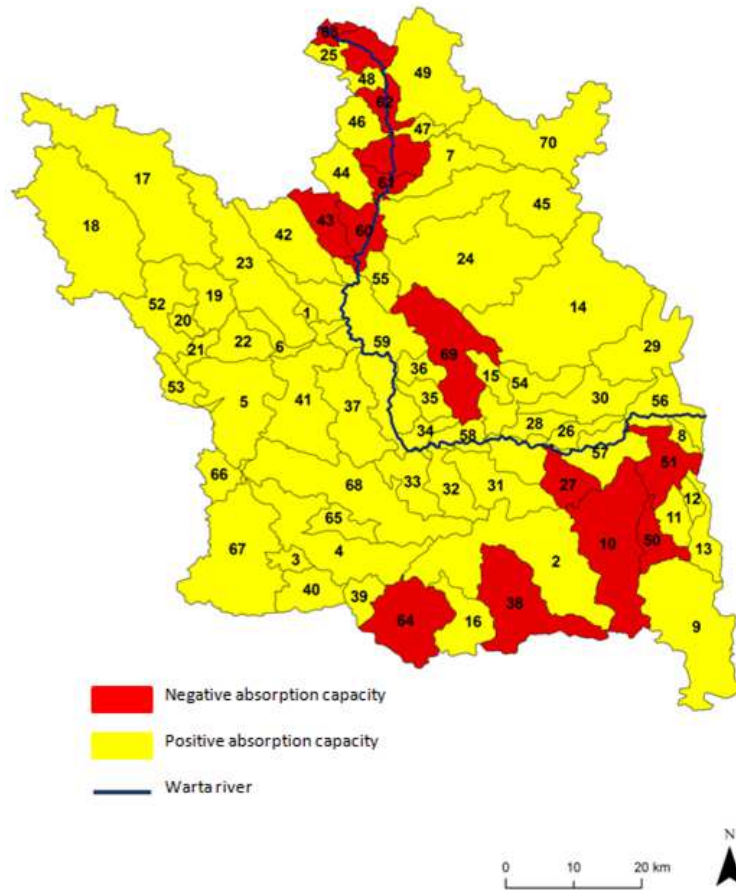


Fig. 8 Actual absorption capacity for each water body of the Middle Warta for total nitrogen based on characteristic flow SNQ [source: own studies]



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

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

| Catchment | Middle Warta |
|------------|--------------|
| Soil class | |
| Very light | 32.9 |
| Light | 30.6 |
| Average | 33.9 |
| Heavy | 2.4 |

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

| Catchment | Middle Warta |
|---------------------|--------------|
| Land use types | |
| Artificial surfaces | 6.17 |
| Agricultural areas | 72.82 |
| Forests | 20.04 |

| | |
|---------------|------|
| Wetland areas | 0.1 |
| Water bodies | 0.85 |
| Meadows | - |

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

| 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% |
| Verification | 731 | 731 | 100% | 25 | 3% | 25 | 3% |
| Validation | 1461 | 1461 | 100% | 48 | 3% | 48 | 3% |

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 canopy storage [mm H ₂ O] |
| 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 factor |
| ESCO | Soil evaporation compensation factor |
| GWQMN | Threshold depth of water in the shallow aquifer required for return flow to occur [mm H ₂ O] |
| 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 NO ₃ concentration in the soil layer [mg N/kg soil] |
| CMN | Rate factor for humus mineralisation of active organic nutrients (N and P) |

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

| Parameter | Flow | | | Total nitrogen | | | Total phosphorus | | |
|--------------|----------------|-------|------|----------------|-------|------|------------------|-------|-------|
| | 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 |

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

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| water body number | tons/year | water body number | tons/year | water body 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 |
| 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 | - | - |

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

| water body number | tons/year | water body number | tons/year | water body 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 | - | - |