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USE OF THE MACROMODEL DNS/SWAT TO CALCULATE THE NATURAL BACKGROUND OF TN AND TP IN SURFACE WATERS FOR THE RAC PARAMETER

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Abstract
Total nitrogen (TN) and total phosphorus (TP) get into surface waters from both natural and anthropogenic sources. Anthropogenic sources have been relatively well recognised but the natural emmission of nutrients into the rivers, in the case of many catchments, remains a mystery. The paper describes the possibility of using a tool, the Macromodel DNS/SWAT (Discharge Nutrient Sea/Soil and Water Assessment Tool), to estimate the concentration and load of natural background (Natural Pollutant Concentration – NPC and Natural Pollution Load – NPL) for TN and TP and thus to specify the previously developed method of river absorption capacity – RAC. A variant scenario was developed allowing for a "virtual" change in the use of the area of an analysed catchment. This allowed the simulation of the amount of TN and TP in the waters of the main river, the Warta, in a situation where there was no anthropogenic phenomenon in the area. NPC and NPL results were obtained for six calculation profiles located on the central Warta main stream. On this basis, the total absorbency of the Total River Absorption Capacity – RACT River was calculated. The obtained results indicate an increasing pollution of the analyzed river on subsequent Surface Water Bodies (SWB). The values of RAC and RACt parameters for both TN and TP were reduced between the opening and closing profiles of the analyzed catchment by 2651 t/y (TN) and 86 t/y (TP), respectively.

Keywords: **Natural background; Total nitrogen; Total phosphorus, RAC parameter, Macromodel DNS/SWAT.**

1. INTRODUCTION

Biogenic compounds such as nitrogen and phosphorous occur naturally in almost all surface waters. Nitrogen is an element essential for cellular proteins, whereas phosphorus has a key role in energy transfer within a cell [1]. These elements are different essential for the proper functioning of aquatic ecosystems, and their natural amount in a river is called the natural background [2, 3]. Therefore, assuming that the emmission of nutrients to surface waters is a natural and inevitable process, and human activity only intensifies this process, the sources of biogenic compounds in surface waters can be divided into natural and anthropogenic ones. Natural sources include woods and wetlands, and are diffuse sources. Anthropogenic sources include urban, industrial and agricultural areas. Cities and industries can cause point source emissions of nutrients to rivers. Agriculture is diffuse source of TN and TP in rivers, through leaching or the runoff of fertilizers [4].

The high level of TP and TN in a watercourse does not necessarily immediately suggest problems with water quality. Unfortunately, the differentiation between anthropogenic causes and natural processes that take place in rivers is often very difficult [5, 6]. In recent years, there has been a significant increase in interest in the amount of nutrients of natural origin, due to reasons including the growing problem of water eutrophication [7].

As part of attempts to develop better and more effective criteria and standards for TN and TP in order to reduce the risk of eutrophication, information on the natural background of these pollutants can serve as a good reference system indicating the maximum achievable water quality [8, 9, 10]. A good example here is the US Environmental Agency (EPA), which recommends that individual US states use the 75th percentile values from regional distributions of background nutrient concentrations as the lower end of the appropriate range for choosing state criteria. In this case, the natural background of nutrients is calculated using data from long-term reference sites in these regions; these provide a potential source of information for developing regional background concentration distributions. The problem here is that such data often contain very large errors because in practice in industrialised countries there are no such things as reference sites.

As already mentioned, in both Europe and North America, there are practically no catchments deprived of anthropopressure, so it is not possible to determine the concentrations and loads of the natural background of TN and TP in surface waters based on monitoring studies. Therefore, one of the solutions to this problem is research in catchments in poorly industrialised or sparsely populated countries located in South America, Africa and Asia, where human influence is as minimal as possible [11]. Such studies have shown, inter alia, that the amount of TN in such catchments is closely correlated with the size of surface runoff and, for example, the type of vegetation occurring in an analysed area. The problem is that these studies were mainly carried out in tropical areas, and the results are hard to translate directly into conditions such as those in northern Europe [3]. Currently, more and more advanced mathematical models are becoming helpful here – apart from the simulation of catchment hydrology and pollution movement, they also allow for the introduction of variant change scenarios in the use of a catchment area [12, 13, 14, 15, 16].

Such scenarios allow for a "virtual" change in the use of any previously calibrated, verified and validated [17] river basin, allowing the simulation of the conditions that existed in the river basin in the past [18]. This allows, for example – in either a highly urbanised catchment area or one dominated by intensive farming – for a scenario in which the entire catchment area is occupied by forest or natural meadows to be introduced [19, 20].

At the same time, the model will generate water quality data on any selected calculation profiles for such a scenario. This method allows one to freely modify not only the use of the catchment area, but also the climatic conditions, which offers great opportunities. Since 2012, the DNS Macromodel [21], which employs the SWAT module and allows the simulation of natural and anthropogenic phenomena occurring in river basins, has been developed in the Section of Modeling Surface Water Quality of the Institute of Meteorology and Water Management. This model has been used in the past to develop the method of River Absorption Capacity (RAC) [22].

So far, however, this parameter has not directly taken into account the natural background of TN and TP in the river. The paper presents a universal method for expanding the RAC parameter. The extension consists in taking into account the natural background of pollution that we encounter in each river basin.

2. MATERIALS AND METHODS

2.1. River absorption capacity – RAC

Absorption capacity of a 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. The limit concentration is calculated based on monitoring data; the second is the actual load calculated based on the actual concentration at a selected river profile. Calculation profile is a plane created at the point of intersection of the river bed perpendicular to its current. When calculating both mentioned loads, the selected characteristic flow (flow values, based generally on a multi-year hydrogram flow – usually daily) is used. The absorption capacity of a river is calculated for each pollutant separately and should consider all potential sources of pollution (both point and nonpoint sources). Absorption capacity results are obtained for selected river profiles [22].

River absorption capacity RAC for a selected calculation profile is described with the equation:

$$RAC = LL - AL \quad (1)$$

where:

LL – limit load for selected pollutant – environmental standard (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 with the equation:

$$AL = AC \cdot CF \quad (2)$$

where:

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

CF – characteristic flow (m^3 s^{-1})

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

$$LL = LC * CF \tag{3}$$

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

2.2. Natural background

Natural pollutant concentration (NPC) and natural pollution load (NPL) reflect natural or near natural conditions in a selected river basin. NPC is also the basis for the classification of the ecological status of waters, which is usually a measure of deviation from the natural state – the absence of NPC, or a very slight deviation from this situation, means there is a very good ecological status. The assessment of the scale of changes in natural conditions as a result of anthropopressure is very difficult because in many areas anthropogenic factors have a multidirectional effect. Besides this, there is no reference to the background conditions determining a natural state. Among other things, it should be used in such analyzes to use advanced tools such as mathematical models composed of many modules that allow to reproduce in the digital space as many natural processes as occur on the river basin. As already mentioned, a large part of biogenic compounds in surface waters come from human activity, but nutrients are also washed out of the soil in natural conditions. NPL values are usually much lower in surface waters than anthropogenic load values (AL_{TH}). The Baltic Marine Environment Protection Commissio (HELCOM), using field studies and mathematical modeling, determined the values of the natural background of rivers' NPC in countries located in the Baltic Sea basin (Table 1).

Table 1.
NPC values in rivers of countries located in the Baltic Sea basin [23]

Country	TN (mg/l)	TP (mg/l)
Denmark	1.2	0.04
Finland	-	-
Estonia	1.1	0.04
Germany	1.0	0.25
Latvia	-	-
Lithuania	-	-
Poland	**0.3 – 1.2**	**0.04**
Russia	0.68	0.013
Sweden	0.2 – 0.9	0.01 – 0.02

The data presented by HELCOM (Table 1) are averaged values for areas of entire countries, and for example, for Poland or Sweden, the ranges for TN are very wide. On their basis, it is difficult to determine the actual share of the natural background of TN and TP for specific rivers, let alone for selected calculation profiles. In HELCOM, you can find general NPC data for the two largest Polish basins of the Vistula and Odra, but the ranges are still very wide. Therefore, it is necessary to use tools, such as the Macromodel DNS/SWAT, that allow for the NPL values to be defined with greater precision. This model allows to generate data with a daily time step for each selected calculation profile located on the analyzed catchment basing on monitoring data describing many catchment parameters.

The mathematical notation of the RAC parameter presented in Section 2.1 has been extended with the description of the actual load (AL), which is the sum of the NPL and the anthropogenic load (AL_{TH}) :

$$AL = NPL + AL_{TH} \tag{4}$$

The mathematical description of NPL in the Macromodel DNS is simple. It is determined on the basis of NPC and characteristic flow:

$$NPL = NPC * CF \tag{5}$$

This dependency should be maintained: $NPL < LL$

2.3. Total River Absorption Capacity – RAC_T

The methodology of the RAC parameter [22] has been confirmed as an effective tool for assessing the possibility of introducing a pollutant load to a given section of the river – a load which will not cause permanent and irreversible changes in the river ecosystem or change the water quality classification in the selected river's calculation profile. However, the analysis becomes more complicated when it is necessary to limit the pollutant load on a selected section of the river, i.e., when the RAC parameter is negative.

In this case, the knowledge about NPL becomes essential, because it will enable the preparation of appropriate programs of activities dedicated to each basin and the taking into account of its specificity. In order to introduce the concept of the natural background of pollutants to the existing RAC methodology, the concept of the total river absorption capacity parameter – RAC_T – should be introduced for ease of reference.

The RAC_T parameter is the difference between LL and NPL:

$$RAC_T = LL - NPL \tag{6}$$

it describes the total load of anthropogenic pollution that can be absorbed in river water between two designated calculation profiles, not exceeding the water purity class in this section described as limit charge (LL) (Figs. 1 and 2). This parameter allows, inter alia, the determination of what would be the absorption of the river if it were to be deprived of anthropogenic stress.

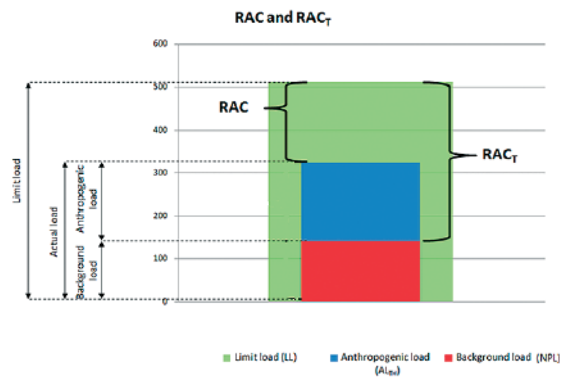

Figure 1.
RAC and RAC$_T$ on a selected calculation profile of a river

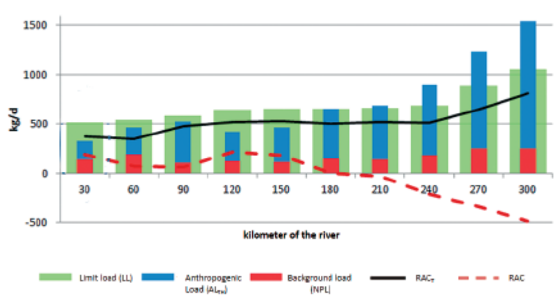

Figure 2.
An example distribution of RAC and RAC$_T$ along a river

2.4. DNS/SWAT Macromodel

The Macromodel DNS/SWAT was designed by the Institute of Meteorology and Water Management – National Research Institute for the analysis of processes taking place in a basin, such as water and matter cycles. It allows for the simulation of the long-term impact of land use on water quality and the impact of pollutants discharged into surface waters. The SWAT module uses the hydrological transport model which is based on meteorological and hydrological data, the size of surface runoff and fertilizer amount to analyse phenomena and processes related to the transport of nutrients in the watershed [1, 24].

The SWAT module is an element of the Macromodel DNS and is used the processes of water cycles and organic matter in the basin. This allows us to carry out simulations of the long-term impact of land use management on water quality, and to examine the amount of pollutants discharged from particular Surface Water Bodies (SWB) to surface waters. This module uses a hydrological transport model, which is based on, inter alia, meteorological data, the quantity of surface runoff and the amount of soil fertilization, and enables us to carry out the analysis of phenomena and processes connected with the transportation of nitrogen loads in a sub-basin. With the use of the Macromodel DNS/SWAT, all the elements form a homogenous, numerical sub-basin model that enables us to analyse different scenarios of sub-basin exploitation in different meteorological and hydrological conditions [25, 26]. The SWAT module has been used many times to create scenarios of land use change [27, 28, 29]; in most cases these scenarios were used to predict future events and their impact on the water quality of a catchment.

2.4.1. Research area

The same catchment was used for NPL and RAC$_T$ analysis, which was chosen for testing the methodology of the RAC parameter. The Middle Warta Basin (Fig. 3 and 4) constitutes a part of the Warta Basin and is closed by two profiles: Nowa Wieś Podgórna and Oborniki. The acreage of the basin equals 6039 km^2 and constitutes 11% of all acreage of the Warta Basin (54.5 thousand km^2). There are a few tributaries on the studied part of the river, out of which the most important are the Lutynia River, the Mosiński Canal and the Mogilnica River. The analysed part of the basin is characterised by a significant amount of area exposed to nitrogen pollutants of an agricultural origin. There is also the largest agglomeration of the basin – Poznań city. The parent rocks of the basin area are post-glacial sediments, mainly sandy and loamy soils, with a majority of brown and podzolic soils. The long-term observation studies of the Warta River indicate that the water quality differs in particular sections. The major source of pollution comes from the constant and seasonal discharges of domestic, economic and industrial sewage from cities located near the river as well as from surface runoff from agricultural areas [30].

2.4.2. Baseline and variant scenario

The authors were interested in the comparison of results obtained from the prepared scenario of changes in land use with the results obtained in the past for the RAC parameter. For analysis, the Macromodel DNS/SWAT – built at Institute of Meteorology and Water Management – National

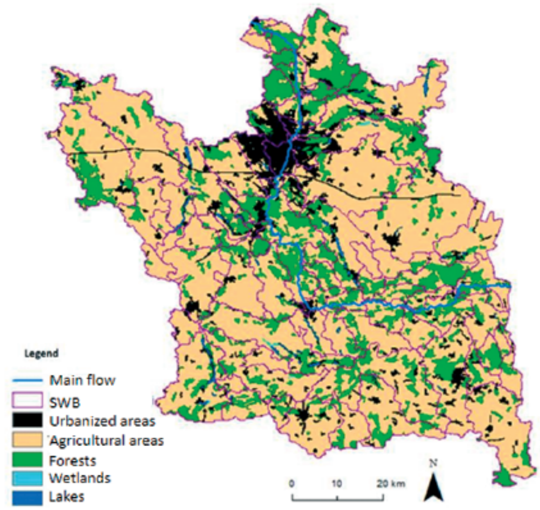

Figure 3.
The Middle Warta catchment

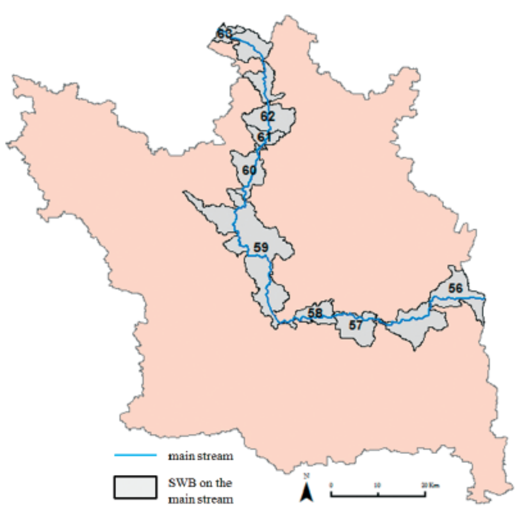

Figure 4.
SWB located on the main stream of the central Warta catchment

Research Institute (IMGW-PIB) in 2015 to develop the RAC methodology described in detail in [22] – was used. This model was recognized as a baseline scenario, also referred to as a reference or control. This scenario is a simulation of a model that has successfully passed the calibration, verification and validation procedures. Such a simulation should include an uninterrupted period of at least a few years, including years with different hydrological characteristics (dry, average, wet). The processes affecting the outflow of nitrogen and phosphorus loads from the catchment may be completely different, depending on the hydrological characteristics of a given year. The model employed met all the requirements of the baseline scenario, while taking into account a whole range of input data allowing for precise simulation of natural and anthropogenic processes taking place in the basin. The next stage was the creation of a variant scenario, which made it possible to answer the question: what was the concentration and load of TN and TP on the main stream of the Warta River before the appearance of humans in the area? The variant scenario consists in performing simulations for the same period of time as in the base scenario with changed parameter values representing the selected module in the model (fertilization, land use, meteorology). All other parameters, except those related to the module selected for changes, must have the same values as in the base scenario. In order to make it possible to build a variant scenario, it was first necessary to identify, using the available research, what the use of the analyzed catchment looked like in the period before the emergence of anthropopression in the area. It is known that in ancient times and the Early throughout central Europe, including in most areas Poland, mixed forest dominated [1, 31, 32, 33]. Using this information, in the model acting as a variant scenario, land use was modified by replacing urban areas and agricultural areas with areas occupied by mixed forest (Table 2, Figure 5). Thus, the share of forests in relation to the entire area of the analysed catchment has grown from 20% to over 99% [34].

Table 2.
Land use for the base and variant scenario

Land use types	real conditions	Land use types	scenario
Artificial surfaces	6.2		
Agricultural areas	72.8	Forest	99
Forest	20		
Wetland areas	0.1	Wetland areas	0.1
Water bodies	0.9	Water bodies	0.9

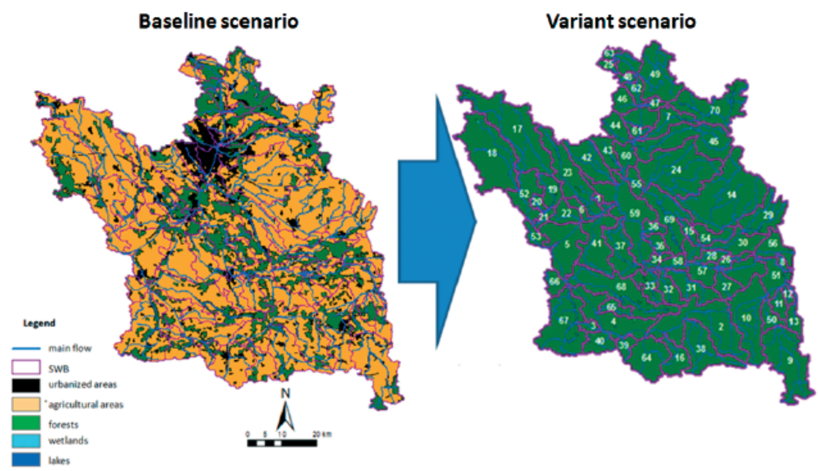

Figure 5.
Changing the use of catchments in the Macromodel DNS/SWAT – baseline and variant scenarios

Table 3 presents the most important parameters of the Macromodel DNS/SWAT along with the adopted values that were applied for catchment areas covered with mixed forest. The almost total change of use in the whole catchment area caused simultaneous changes in model processes simulated by the model (e.g. retention), which had a direct impact on the amount of TN and TP penetrating into surface waters.

Table 3.
Parameters of the Macromodel DNS/SWAT for forest areas

parameter	description	value
BLAI	maximum potential leaf area index	5
FRGRW1	fraction of the plant growing season of total potential heat units	0.05
CHTMX	maximum canopy height	6
RDMX	maximum root depth (m)	3.5
T_OPT	optimal temperature for plant growth (°C)	30
T_BASE	minimum temperature for plant growth (°C)	10
CPYLD	normal fraction of phosphorus in yield (kgP/kg)	0.0003
CNYLD	normal fraction of phosphorus in yield (kgN/kg)	0.0015
BIOEHI	biomass energy ratio	16
RSDCO_PL	plant residue decomposition coefficient	0.05
BMX_TREES	maximum biomass for a forest (tons/ha)	1000
MAT_YRS	number of years required for tree species to reach full devel-opment	50
BIO_LEAF	fraction of tree biomass accu-mulated each year that is con-verted to residue during dor-mancy	0.3

3. RESULTS AND DISCUSSION

The variant scenario allowed a multi-year database allowing for new calculations to be obtained. First, the focus was on the calculation of the percentage share of the natural pollution background on the eight calculation profiles of the Middle Warta main watercourse. The results are summarised in Table 4.

In the central water course of the Middle Warta, the mean NPL for TN is 14% and for TP it is 21%. The background load varies significantly along the length of the watercourse; the maximum NPL values for both TN and TP were obtained for the calculation profile No. 60.

Using the received data, RAC_T values for eight calculation profiles closing SWB located on the main watercourse were calculated as shown in Table 5.

Due to the fact that RAC_T talks about the total absorption of a selected section of the river, considering only NPL, its value always takes positive values.

The development of the existing methodology of the RAC parameter made it possible to take into account the concentration and load of the natural background of contaminants (NPC and NPL) in further analysis. Due to the lack of European catchments where there is no anthropogenic phenomenon on which it would be possible to conduct reliable analysis of the amount of the background and its variability over time, it was necessary to use new tools such as mathematical models. The use of mathematical models to deter-

Table 4.
List of received TN and TP loads for the base and variant scenarios and percentage share of NPL

	TN			TP		
Number of water bodies (main stream)	Baseline scenario (AL) (t/y)	Variant scenario (NPL) (t/y)	NPL participation (%)	Baseline scenario (AL) [t/y]	Variant scenario (NPL) [t/y]	NPL participation (%)
56	11314	1122	10	471	136	29
57	13232	1577	12	509	132	26
58	13141	2232	17	512	128	25
59	13070	2237	17	532	124	23
60	11271	2209	20	405	121	30
61	15193	2177	14	582	118	20
62	15611	2156	14	715	116	16
63	19357	2167	11	938	114	12
average	**14024**	**1985**	**14**	**583**	**124**	**21**

Table 5.
Comparison of the RACT parameter value with the RAC parameter

Number of SWB (main stream)	RAC for TN (t/y)	RACT for TN (t/y)	RAC for TP (t/y)	RACT for TP (t/y)
56	2981	10775	129	437
57	2203	10286	124	418
58	2009	9803	104	400
59	2345	9451	80	387
60	3041	8996	-152	370
61	880	8937	-592	370
62	588	8392	-1069	349
63	-883	8124	-1485	351

mine the background of pollution in the environment is currently practiced, for example, by HELCOM. The fact is that these models are calibrated based on actual monitoring data from the analyzed catchments, and the results of the model regarding the natural background are difficult to verify due to the lack of anthropogenic depletion in Europe and very limited access to data from the catchment deprived of anthroporesia in the world. Nevertheless, previous experience indicates that mathematical models are the best possible choice for this type of analysis. The catchment ecosystem and the processes occurring in it resemble a system of connected vessels, so the chosen model must be detailed enough to include as many of these processes, and dependencies between them, as possible. Selected for analysis, the Macromodel DNS/SWAT met all the requirements and although it is not possible to directly simulate NPL, it allows for the construction of a variant scenario allowing for the "removal" of the anthropopressure in its entirety from the basin and the recreation of the NPL values on any chosen calculation profile of the river. This allows the calculation of RAC_T on the profiles in question. The Macromodel DNS/SWAT allows for simulation with any time step, so the variant scenario can provide results for each year, month or even every day selected for multi-year analysis. Determining the variability of concentration and the load of the natural background of contaminants becomes possible. The analysis of the value the natural background of contaminants, as described in the paper, was used to calculate the total absorbency of RAC_T. Of course, one must remember that the value of RAC and RAC_T is dependent on LL, which may change in the future. However, using the Macromodel DNS / SWAT, new data and value conversion are possible at any time. This is only an illustrative value, but it is very helpful, for example, when setting standards for individual water purity classes. Only a comparison of the values of RAC and RAC_T gives full knowledge of the analysed basin from the point of view of its assimilation capacity. The analyses were carried out on eight computational profiles located on the main stream of the central Warta River. The variant scenario that was applied allowed for the generation of load volumes TN and TP in the absence of anthropopressure in the basin. These results were compared with the values of TN and TP charges obtained from the baseline scenario and on this basis the percentage share of NPL was calculated. HELCOM states that in general for the entire Odra River Basin, of which the Warta River Basin is a part, the percentages of NPL for TN and TP are approximately 20% and 18%, respectively. The research presented indicates the opposite tendency – namely, the average NPL value for TP is higher compared to TN. The variability of NPL values was also observed, depending on the location of individual calculation profiles. Both for TN and for TP, the NPL value decreases from calculation profile No. 60. At the same time, in the baseline scenario, the charges

TN and TP grow rapidly, starting from calculation profile No. 60, which is caused by the fact that the entire SWB area with computing profile No. 60 closing it is occupied by the city of Poznań. A similar tendency is noticeable when comparing the values of the RAC parameter with RAC_T. The RAC_T of the Warta catchment for both TN and TP is largest in the first two calculation profiles (56 and 57), and subsequent profiles are already characterized by a systematic decrease of RAC_T. The analyzed river is particularly sensitive to an excessive amount of TP below profile No. 60. RAC_T is much lower there than in the sections located above, and large amounts of pollutants coming from point sources from the growing metropolis are emitted into the river. They far exceed the acceptable standards, and this has a direct impact on the negative values of the RAC parameter in the baseline scenario.

4. CONCLUSION

- the use of mathematical modeling allowed the determination of the concentration and load of natural background (NPC and NPL) for TN and TP on selected profiles of the Middle Warta;
- the data obtained in this way made it possible to expand the existing RAC methodology by expanding its capabilities. Until now, only the total value of pollutant load was analyzed without analyzing what part of it is naturally occurring TN and TP;
- RAC_T allowed the determination of the total assimilation capacity of the river for anthropogenic pollution;
- the results obtained can be used to clarify the set limit values for selected pollutants and to prepare effective remedial programs on particularly polluted sections of rivers;

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