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 phosphorous 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 back-
ground nutrient concentrations as the lower end of
the appropriate range for choosing state criteria. In
this case, the natural background of nutrients is cal-
culated using data from long-term reference sites in
these regions; these provide a potential source of
information for developing regional background con-
centration 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 natur-
al background of TN and TP in surface waters based
on monitoring studies. Therefore, one of the solu-
tions 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 vege-
tation 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 condi-
tions 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 qual-
ity 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 cli-
matic 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 con-
sists 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 deter-
mined 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 cur-
rent. When calculating both mentioned loads, the
selected characteristic flow (flow values, based gen-
ernally 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 calcu-
lation profile is described with the equation:
\[ RAC = LL - AL \]
where:
LL – limit load for selected pollutant – environmental
standard (10³ kg·yr⁻¹)
AL – actual load for selected pollutant (10³ kg·yr⁻¹)
The actual load at a control profile is described with the
equation:
\[ AL = AC \cdot CF \]
where:
AC – actual concentration of selected pollutant (mg L⁻¹)
CF – characteristic flow (m³ s⁻¹)
While the limit load at a control profile is described with the equation:

\[
LL = LC \times CF \tag{3}
\]

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>
<thead>
<tr>
<th>Country</th>
<th>TN (mg/l)</th>
<th>TP (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>1.2</td>
<td>0.04</td>
</tr>
<tr>
<td>Finland</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Estonia</td>
<td>1.1</td>
<td>0.04</td>
</tr>
<tr>
<td>Germany</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>Latvia</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lithuania</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Poland</td>
<td>0.3 – 1.2</td>
<td>0.04</td>
</tr>
<tr>
<td>Russia</td>
<td>0.06</td>
<td>0.013</td>
</tr>
<tr>
<td>Sweden</td>
<td>0.2 – 0.9</td>
<td>0.01 – 0.02</td>
</tr>
</tbody>
</table>

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:

\[
NPL = NPC \times CF \tag{5}
\]

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 des-
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 km² and constitutes 11% of all acreage of the Warta Basin (54.5 thousand km²). 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...
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 analyzed catchment has grown from 20% to over 99% [34].

<table>
<thead>
<tr>
<th>Land use types</th>
<th>real conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial surfaces</td>
<td>6.2</td>
</tr>
<tr>
<td>Agricultural areas</td>
<td>72.8</td>
</tr>
<tr>
<td>Forest</td>
<td>20</td>
</tr>
<tr>
<td>Wetland areas</td>
<td>0.1</td>
</tr>
<tr>
<td>Water bodies</td>
<td>0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Land use types</th>
<th>scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>99</td>
</tr>
<tr>
<td>Wetland areas</td>
<td>0.1</td>
</tr>
<tr>
<td>Water bodies</td>
<td>0.9</td>
</tr>
</tbody>
</table>
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.

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-
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 anthropopressure 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 RACT 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 RACT. Of course, one must remember that the value of RAC and RACT 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 RACT 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 is occupied by the city of Poznań. A similar tendency is noticeable when comparing the values of the RAC parameter with \( \text{RAC}_T \). The \( \text{RAC}_T \) 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 \( \text{RAC}_T \). The analyzed river is particularly sensitive to an excessive amount of TP below profile No. 60. \( \text{RAC}_T \) 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;
- \( \text{RAC}_T \) 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;

REFERENCES


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


