

# The effect of selected inviolable flow characteristics on the results of environmental analysis using the example of river absorption capacity

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**Abstract:** The parameter River Absorption Capacity (RAC) is understood as the load of pollutants introduced into a given river section which will not cause permanent and irreversible changes in the aquatic ecosystem nor change the classification of water quality in a given river calculation profile. The paper presents a method of determining the RAC using the Macromodel DNS/SWAT developed at IMGW-PIB. The selection of an appropriate inviolable flow plays an important role in calculating RAC. Therefore, the article presents the calculations for the three different non-invasive flows: Mean low flow (MLF – the Kostrzewa method), 7Q10 and Tennant. The results obtained in these ways are different from each other. The concept of ‘environmental flows’ continues to evolve in response to these challenges, emphasizing aquatic and riparian ecosystems as legitimate water users within an Integrated Water Resources Management. The analysis has shown that the choice of relevant data for environmental computation is decisive and the use of purely statistical methods to protect biological life in rivers is insufficient. Thus, the use of environmental flows to better describe the specifics of the analyzed basins seems to be most beneficial.

## Introduction

The correct definition of the actual state of aquatic ecosystems and water dependency is critical in planning and for taking corrective actions. River Absorption Capacity (RAC) is understood as the load of pollutants introduced into a given river section which will not cause permanent and irreversible changes in the aquatic ecosystem or a change in the water quality classification in a given river calculation profile (Chmielowski et al. 2008, Wilk 2015). RAC is a parameter that determines the state, surface waters, and measures in order to prevent the deterioration of river water quality. In general, two types of data are needed to calculate the RAC – a limited pollutant load and an actual pollutant load. Limit load (LL) is the maximum load of a selected pollutant that may be in a selected river section of an analyzed river, which has been classified as having class II 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 the selected characteristic flow (CF). Actual load (AL) is the load of a selected pollutant measured at a given time in a selected calculation profile of an analyzed basin. To calculate these pollutant loads, you need to know the concentration of pollutants and the inviolable flow, i.e., the flow of the minimum amount of water needed to maintain biological life in a river. Inviolable flow is used for calculations to provide security buffers for RAC results. Inviolable flow is the least amount of water that has to be in a river to provide

optimum conditions for existing ecosystems. This allows the RAC to yield results for surface waters in the event of low flows. This provides the opportunity for the vulnerability of aquatic ecosystems on pollutants to be assessed. Choosing the appropriate representative of inviolable flow to calculate RAC is therefore crucial. The selection of too restrictive an inviolable flow (i.e., very low) may be unjustified from the point of view of the economic development of selected catchment areas. In the opposite case (i.e., choosing to open an inviolable flow), we will be faced with insufficient protection of the water against contamination. In either case, this will result in high economic costs incurred directly or indirectly by business entities using water. At present, in many environmental calculations in Poland, the Mean low flow (MLF) is used, which is a mean from the lowest annual flows from a multi-annual period. On the basis of this, the inviolable flow is calculated (Kostrzewa 1977, Operacz 2015). In the United States, to calculate a parameter which is very similar to RAC – the Total Maximum Daily Load (TMDL) (Williams et al. 2017) – the 7Q10 flow characteristic (lowest 7-day average flow that occurs, on average, once every 10 years) is commonly used (Verma et al. 2015). There is information on the need to move from average low flows to environmental flows. Environmental flows take into account much more information about a river's characteristics, such as width, depth, flow velocity, river bottom characteristics, land cover, fish migration, and more. Therefore, many of the current analyses and calculations use environmental flows (Matthews et al. 2014). Calculating the RAC parameter for main streams,

large catchments on which monitoring is conducted, is not a problem. The situation is worse when we want to calculate the RAC parameter for all Homogenous Surface Water Bodies (JCWP) in an analyzed catchment. On many tributaries, especially small ones with low flows, data on flow intensities and pollutant concentrations are lacking. In such cases, it is necessary to use mathematical tools to reproduce the missing data. Of course, not every mathematical model will be able to reproduce the data necessary to calculate the RAC parameter. The selected model should have the most accurate mapping of river basins, land use, point sources and nonpoint sources pollutants and meteorology. One of the best models is the Macromodel DNS/SWAT. The Macromodel DNS (Discharge-Nutrient-Sea) (Ostojski 2012) has been developed at the Institute of Meteorology and Water Management, National Research Institute, which has expanded the capabilities of one of the most popular and most advanced environmental models, the Soil and Water Assessment Tool (SWAT). Mathematical models have provided the opportunity for environmental analysis in many catchments, particularly in those which are not subject to constant environmental monitoring. The purpose of the study was to determine the impact of selected inviolable flows on the RAC of individual JCWPs in the Middle Warta River catchment. The results obtained from Macromodel DNS/SWAT and three different methods of calculating the inviolable flow – the MLF (the Kostrzewa method), the 7Q10 flow and the Tennant environmental flow – were used to achieve the goal.

## Materials and methods

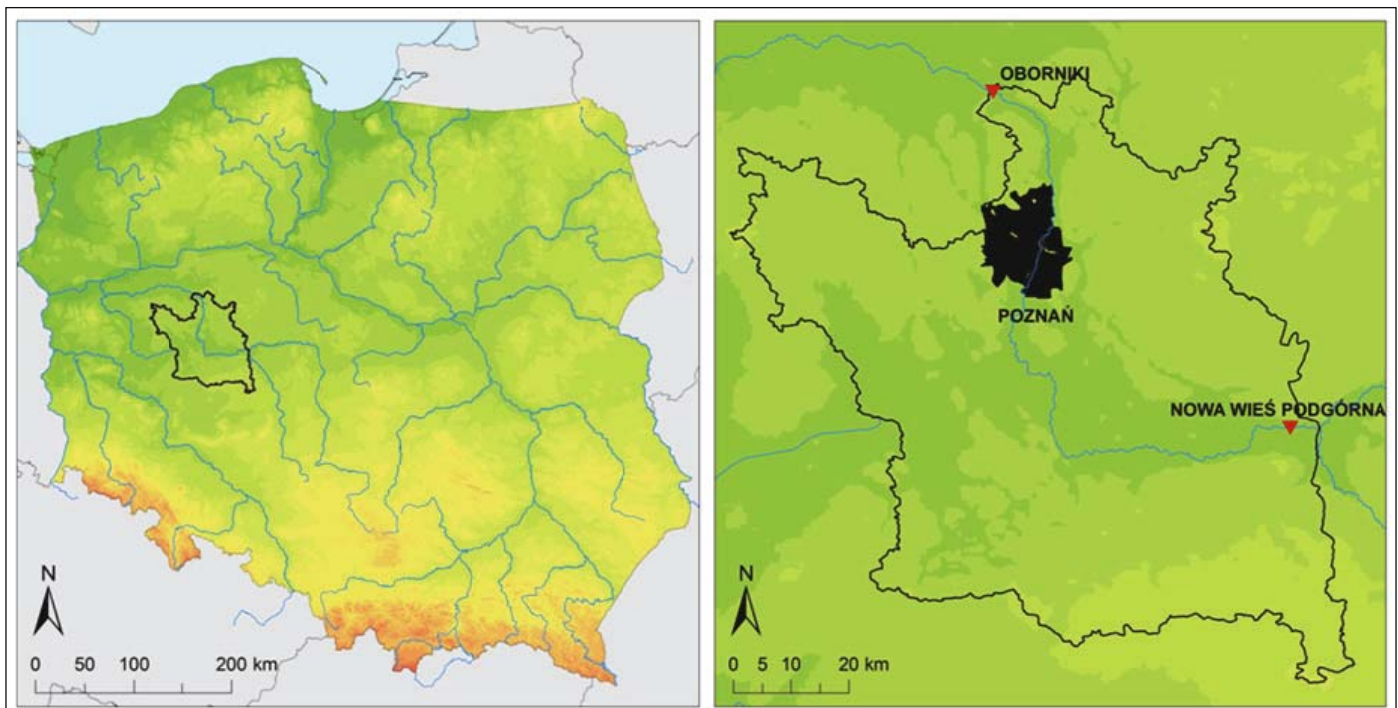
### *The Macromodel DNS/SWAT*

Macromodel DNS (Discharge-Nutrient-Sea) was designed at The Institute of Meteorology and Water Management – National Research Institute, Poland for the analysis of processes that take 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 us to simulate the long-term impact of land use on water quality and the impact of pollutant discharges to surface waters. It is a merger of data processing modules, data replenishment modules, water quantity models and water quality models.

SWAT (Soil and Water Assessment Tool) (Neitsch et al. 2011) can be one of the Macromodel DNS modules. SWAT is a continuous long-term yield model, and is a physically based model where processes associated with water and nutrient cycles are directly modeled by internal algorithms rather than by incorporating regression equations to describe the relationship between input and output variables. Physical processes are simulated within hydrologic response units (HRU). HRUs are lumped land areas within a sub-basin that are comprised of unique land cover, soil and management combinations. HRUs are the basic units in the SWAT model. They are determined by applying a land cover map, a soil map, and a drop map in each sub-basin. In order to divide HRUs, it is necessary to classify the demarcation map. 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 an outlet. Figure 1 shows the general sequence of processes used by SWAT to model the land phase of a hydrologic cycle.

SWAT tracks the movement and transformation of nutrients in a watershed. Nutrients may be introduced to the main channel and transported through surface runoff and lateral subsurface flow. The SWAT module, as an element of the Macromodel DNS, enables us to analyze the processes of the water cycle and organic matter in the catchment. This



**Fig. 1.** Location of the Middle Warta River catchment along with the location of the city of Poznań and the profile opening and closing the analyzed river catchment

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 to surface waters. This module uses the hydrologic transport model, which is based on, inter alia, meteorological data, the quantity of surface runoff and the amount of soil fertilization, enabling us to carry out the analysis of the phenomena and processes connected with the transportation of nutrient loads in the catchment.

Using the SWAT model as a Macromodel DNS module has greatly expanded the capabilities of the macromodel and allowed the RAC to be calculated. The use of SWAT has allowed for the division of the analyzed basin into individual JCWPs and then for the introduction of very detailed river basin data into the model. Macromodel DNS/SWAT has been able to obtain concentration and pollutant load data for all seventy JCWP shutdown profiles. Without access to such a tool, it would be very difficult, or even impossible, to calculate the RAC for the entire catchment area.

### Research area

A part of the Warta river basin was selected for the study, in the section between the calculation profiles of Nowa Wieś Podgórna and Oborniki in central Poland. The area of the analyzed catchment is 6039 km<sup>2</sup> (MPHP 2013), which accounts for about 11% of the total area of the Warta catchment area (Fig. 2). On the studied section of the river, several tributaries flow into the main stream. The selected catchment area is characterized by a significant share of areas designated as Nitrate Vulnerable Zones (NVZs) (Directive 91/676 / EWG). The agglomeration of the city of Poznań is located in the analyzed Warta basin. There are 287 water reservoirs in the catchment area. Due to the granulometric composition that affects both the fertility of the soil and the degree of nutrient leaching and water capacity, this area has mainly light and very light soils (IUNG 2016). The monitoring of the Warta River for many years has shown that the quality of the water varies from one part of the river to the other, and that contaminants entering the river can affect the eutrophication process.

The main source of pollution is the permanent and temporary discharge of domestic and industrial waste water from cities and surface runoff from agricultural land. (Michałkiewicz et al. 2011). The catchment area, as determined by the National Water Management Authority (KZGW) for Polish Homogenous Surface Water Bodies (JCWP), was divided into 70 JCWPs. (Fig. 3).

### Data used for modeling

For the use of the Macromodel DNS/SWAT, the following input data has been prepared for the Middle Warta catchments: a digital elevation model (DEM), a hydrology map, a soil map, a land use map, data concerning wastewater treatment plants and the daily meteorological and hydrological data as well as the amount of fertilizers. The gathered data were developed in the form of a database required by the model (Abbaspour 2008).

The DEM remains the national, central geodesic and cartographic level resource, and is created on the basis of aerial photographs within a flat and rectangular system of coefficients. The Map of Hydrographical Divisions of Poland (MPHP 2009) is the basis for the information system of water management. The map, at a scale of 1:50 000 and containing the details of river networks and bodies of water within the boundaries of the analyzed catchments, was used. Data

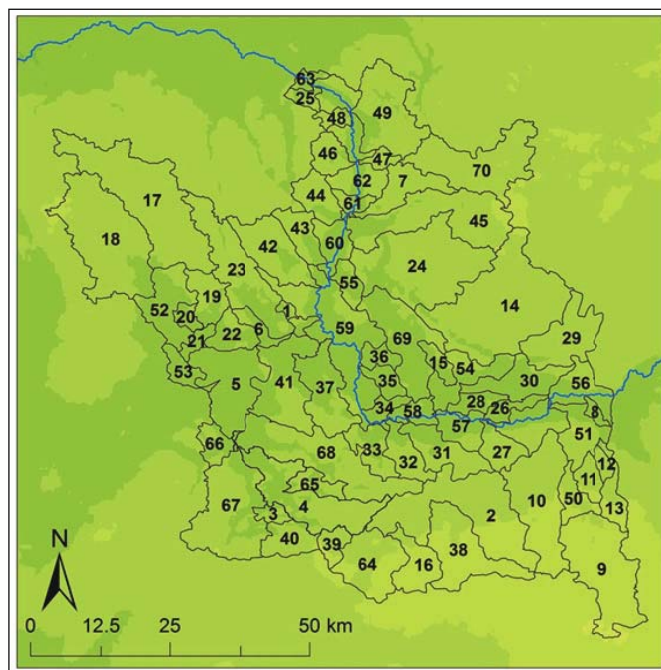


Fig. 2. The Middle Warta River catchment, divided into 70 JCWP

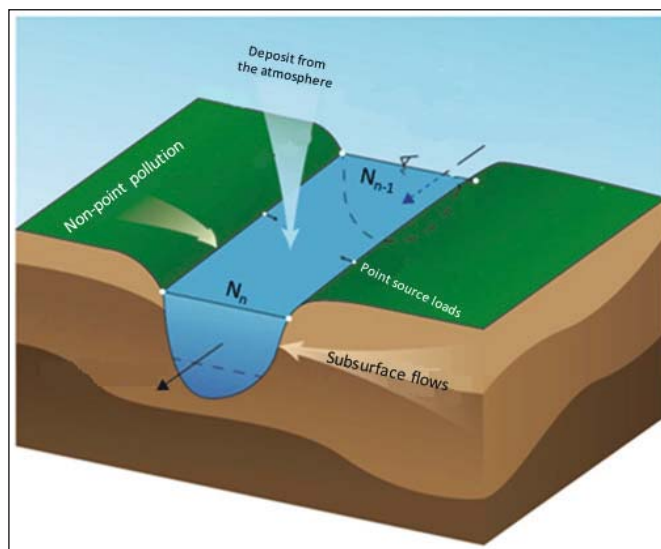


Fig. 3. Catchment area between calculation profile  $N_{n-1}$  and  $N_n$

concerning wastewater treatment plants located in the area of the analyzed catchments were obtained from the National Water Management Authority in Poland. The data contained detailed information, including the geographic coordinates of a given wastewater treatment plant, the amount of public wastewater treated within a year in thousands m<sup>3</sup> yr<sup>-1</sup>, total suspended solids (mg L<sup>-1</sup>), total nitrogen (TN) (mg L<sup>-1</sup>) and total phosphorus (TP) (mg L<sup>-1</sup>). Meteorological input data with a daily time step, and including solar radiation, wind speed, precipitation, relative moisture, and maximum and minimum temperatures, were used. Soil maps at a scale of 1: 100,000 with classes of soil texture defined as very light, light, average, and heavy were obtained from the Institute of Soil Science and Plant Cultivation State Research Institute (IUNG 2016).

Land use maps of the Middle Warta catchment were created based on the CORINE Land Cover information system

(CORINE 2016) which divides land use into five classes. Input data used to calculate phosphorus loads from manure and mineral fertilizers were obtained from the Polish Local Database (BDL), including information regarding livestock and the surface area of arable lands, in hectares, at the provincial level. The average dose of phosphate fertilizers in the Middle Warta catchment was 47.08 kg P/ha (Directive 2000/60/EC).

### Sensitivity analysis and calibration

Sensitivity analysis demonstrates the impact that a change to an individual input parameter has on a model's response and can be performed using a number of different methods. The method in the ArcSWAT Interface combines the Latin Hypercube (LH) and One-factor-At-a-Time (OFAT) sampling. During sensitivity analysis, SWAT runs  $(p+1) \cdot m$  times, where  $p$  is the number of parameters being evaluated and  $m$  is the number of LH loops. Sensitivity analysis of the parameters in the model was carried out in further work. The main purpose of applying sensitivity analysis is to define a set of parameters with the highest sensitivity, i.e., in this case those which have the greatest impact on the parameters affecting flow and phosphorus load in the analyzed profile of the river. The parameters have been developed for ranges typical for Polish conditions. After conducting the sensitivity analysis, the next stage of study was the model calibration. This was performed through an iterative value selection process of a single parameter of the model in order to achieve the greatest possible modeling accuracy with regard to observational data. The estimation of model parameters in the assumed conditions was carried out by the OAT method (one-at-a-time), a repeated iterative loop, in order to achieve the highest convergence of the simulation and observation results. The values of parameters received during the sensitivity analysis (Tab.1) were changed successively 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 and nitrogen changes in surface waters in the area of the pilot catchment. It was recognized that such a calibration method enabled the appropriate model to be fitted to real conditions. Tab. 1 shows the parameters selected in the sensitivity analysis. These parameters were used to calibrate the model.

To evaluate the model's matching with observations in subsequent iterations of the loop, three statistical measures were used: the coefficient of determination ( $R^2$ ) (Di Bucchianico 2008), Percent Bias (PBIAS) and Nash-Sutcliffe efficiency (NSE) (Ormsbee et al. 2016). Calibration and verification were performed for flow data from the years 2003–2012, with a daily time step, obtained from IMGW-PIB, and data on TN and TP collected from State Environmental Monitoring (SEM) for the calculation profile in Poznań. Validation was performed for the years 2013–2015 for the calculation profile in Oborniki. Tab. 2 presents a summary of the results of the calibration, verification and validation step for flow, TN and TP.

The obtained NSE results show problems in the calibration, verification, and validation of TP. In all three cases negative values of this indicator were obtained. 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, the results of the statistical measures identified as "not satisfactory" 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 are negatively affected by the RAC parameter are located, among other places, in the main watercourse below the city of Poznań. This has a negative

**Table 1.** The results of the calibration, verification and validation for flow, total nitrogen and total phosphorus (green – very good, yellow – good, orange – satisfactory, red – not satisfactory)

Catchment	coeff. phases	river calculation profile	period of time	Flow			Total nitrogen			Total phosphorus		
				$R^2$	PBIAS	NSE	$R^2$	PBIAS	NSE	$R^2$	PBIAS	NSE
Middle Warta	Calibration	Poznań	2003–2012	0.93	4.94	0.91	0.37	-31.03	0.17	0.41	-0.36	-2.49
	Verification	Poznań	2003–2012	0.94	2.21	0.85	0.73	6.57	0.27	0	0.36	-1.05
	Validation	Oborniki	2013–2015	0.95	9.4	0.87	0.43	-33.28	0.3	0.65	-0.22	-5.91

**Table 2.** The value of recommended environmental flow in relation to SQ acc. Tennant (Pyrce 2004)

Narrative description of general condition of flow	Recommended flow regimens (% of MAF) October to March	Recommended flow regimens (% of MAF) April to September
Flushing or maximum	200%	200%
Optimum range	60–100%	60–100%
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	<10%	<10%

impact on the waters of the Warta. The remaining water bodies that had negative RAC values for total phosphorus are small watercourses in the southern part of the analyzed basin, characterized by low flow rates as well as sewage treatment sites and other points of wastewater discharge (Ostojski et al. 2015, Wilk et al. 2017). The calibrated, verified, and validated Macromodel DNS/SWAT allowed data (with a daily time step) to be received about flows, TN and TP for all seventy calculation profiles on the analyzed catchment. Based on this data, RAC parameter for all JCWPs could be calculated. Given data on flows and concentrations of TN and TP obtained from the model, the contamination loads were recalculated using the inviolable flows described in this article. On the basis of these TN and TP values calculated using these inviolable flows, subsequent values of the RAC parameter were determined – a total of four RAC values for each calculation profile in the catchment area.

**River absorption capacity – RAC**

For the purposes of the study, the RAC was calculated for each of the 70 JCWPs. On each JCWP calculation profiles were designated, marked as  $N_{n-1}$  and  $N_n$ , and for these profiles loads and concentrations of the selected pollutants were calculated (Fig. 4).

As already mentioned, RAC is the maximum permissible load of pollution that will not extend the boundary load in the

calculation profile  $N_n$  (LL), which is determined on the basis of the limit values of concentration LC for good water status (RM 2011) and for inviolable flow CF in a computational profile. If the river section chosen for analysis is excessively polluted, the calculated RAC will have a negative value, which will indicate the amount of pollutant load to be removed. Thus, we can write:

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

$$RAC = LL - AL \tag{1}$$

where:

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

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

Actual load at control profile is described with the equation:

$$CL = AC \cdot CF \tag{2}$$

where:

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

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

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

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

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

From these simple patterns, it can be seen how important it is to select the appropriate inviolable flow and how greatly it affects the final RAC result.

**Inviolable flows CF**

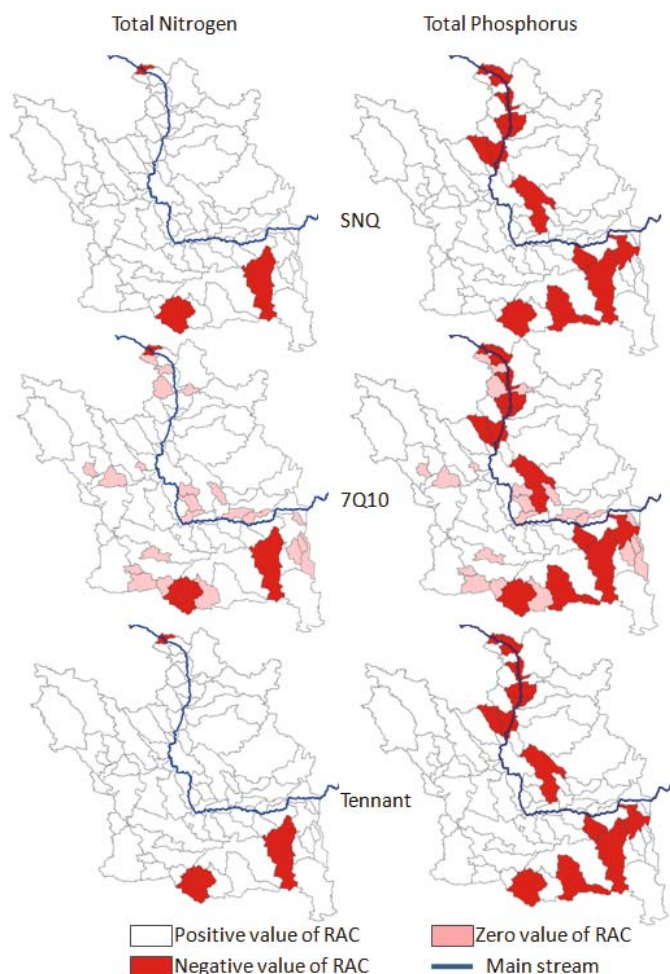
In accordance with the principle of sustainable development, water management must be conducted in such a way as to meet the needs of mankind and the economy, while at the same time protecting the quantity and quality of water resources. This flow is defined as a limit value which should not be reduced by human activity. The need to maintain this flow does not fall within economic criteria (Ozga-Zielińska et al. 1997). Currently, many methods are used in Poland to determine the inviolable flow, e.g., the Kostrzewa method (most commonly used in Poland), the Małopolska method, and the method based on fishing criteria. Attention should be paid to the variety of available formulas, so there is currently no standardized methodology for calculating  $Q_{ch}$ , and taking into account the conditions for sustainable development (Mlynski and Wałęga 2015).

**The Kostrzewa inviolable flow calculation method**

The MLF flow is the arithmetic average of the lowest flows that occur in a multi-year period. From the set of daily flows, the lowest annual values are selected and calculated as an average value of flow (Byczkowski 1999). For lowland rivers the MLF flow is the same as inviolable flow. This is due to the fact that the  $k$  factor occurring in formula (4) (Kostrzewa 1977) should be approximately 1 for lowland rivers.

$$CF = k \cdot MLF \tag{4}$$

The uncomplicated mathematical formula and a small amount of necessary data means that the Kostrzewa method is commonly used in the calculation of inviolable flow.



**Fig. 4.** Flow values for selected characteristic flows and Tennant environmental flow for JCWPs located on the main river channel

However, calculations carried out using MLF flow are subject to increasing criticism. It has been shown that, in small lowland rivers, the values of inviolable flows which are determined by the relationship between discharge and flow velocity are considerably higher (from 1.8 up to as much as 28.2 times) than an average low flow MLF (the inviolable flow in lowland rivers in the Kostrzewa method). The inviolable flow thus calculated is burdened with errors, which in some cases exceed 70%. These errors are due to the high variability in time of the conditions of hydraulic flow in the channels of lowland rivers. The inviolable flows calculated on the basis of their relationship with flow velocity and with a relationship to average low flow rate (MLF) have random values which are not justified from the point of view of the minimum necessary for the life of aquatic organisms (Szymczak 2002). The flow profiles in accounting profiles are based on the impact of the use of surface water resources (intake and discharge) and the underground (intake) on decay and characteristic flows being taken into account. This process serves to “unnaturalise” the flows so as to reflect the conditions of no or minimal anthropogenic impact on the state of water resources. Naturalized decade flows are used to calculate flows with a certain guarantee of occurrence and are the basis for calculating the availability of surface water resources. In this article it was important to show the differences in the results of environmental calculations using various inviolable flows. Unnaturalized flow was used.

**The 7Q10 flow**

Characteristic flow of 7Q10 is the second most commonly used flow index in English-speaking countries. The 7Q10 is the lowest 7-day average flow that occurs (on average) once every 10 years. This flow is used to habitat protection under drought conditions and assessment of aquatic organisms’ quality of life criteria. The 7Q10 is suitable for acute and chronic aquatic life criteria as well as conventional parameters such as dissolved oxygen. Critical low flows can be calculated using standard statistical methods for hydrology. Distributions of low flow well-fed either a Log-Pearson Type III or a Weibull distribution (Haan 2002). This method is applicable only for data of flow with a daily time step, so in Polish conditions it is necessary to use mathematical modeling.

**The environmental flow – Tennant method**

The Tennant (or Montana) flow parameter is the most commonly used characteristic for calculating environmental

flow, used worldwide. This is mainly due to its simplicity and ease of calculation. It uses the percentage of average annual flow (SQ) for two periods of the year (October-March and April-September) to determine the flow conditions associated with fisheries, nature, recreation and environmental resources (Özdemir et al. 2007). In Tennant method the value of environmental flow depends to the average annual flow SQ, the period for which the flow is determined, and the specific conditions of the aquatic habitats of ecosystem (Tab. 3).

In the described analyses the value of the environmental flow was determined at the level corresponding to good water-habitat conditions.

**Results**

The Macromodel DNS/SWAT after the calibration, verification and validation gives the discharge rates and TN and TP loads and concentrations for 70 JCWP closing profiles with a daily time step for the 2000–2015 multi-annual period. The modeling results enabled the determination of inviolable flows using three different methods described in point 3. Tab. 4 shows the values of calculated inviolable flows for eight JCWP closing profiles (no. 56–63) on main channel of the Middle Warta catchment.

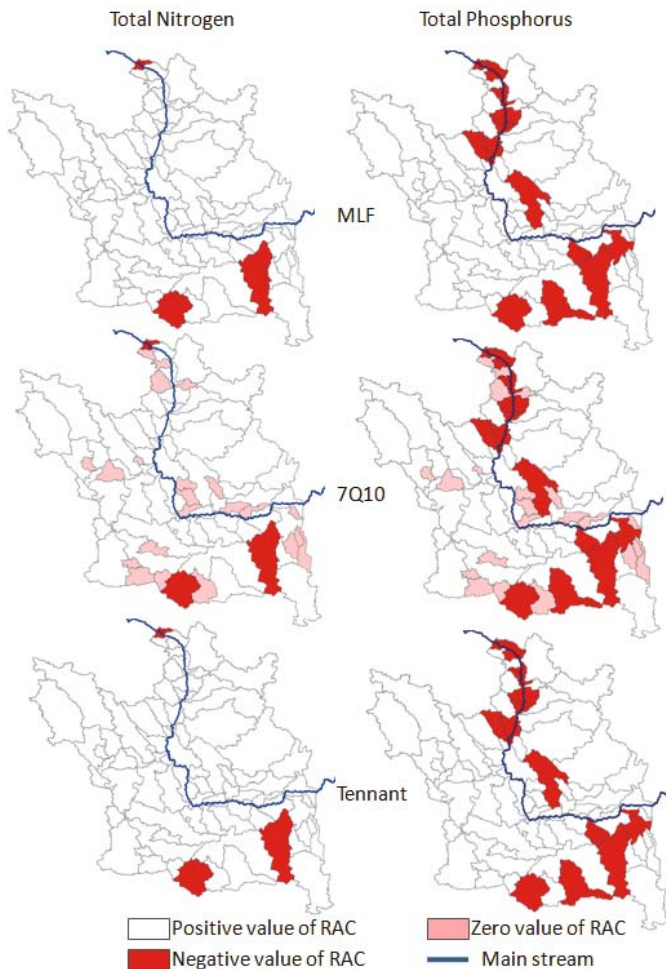
The next step was to use the data obtained from the model to calculate the RAC for 70 JCWP using formulas 1 to 3. The RAC was calculated for (TN) and (TP) using characteristic values of MLF, 7Q10 and Tennant environmental flow. Fig. 5 shows these JCWPs at the Middle Warta catchment that have negative or zero RAC values (red) and those which have positive RAC values (white).

**River absorption capacity (RAC) for TN**

No matter which inviolable flow was chosen, only three JCWPs (10, 63 and 64) had negative RAC values. The exception were the results of the RAC obtained for the 7Q10 flow where, except for these abovementioned three, there were three negative sub-catchments with negative RAC values, and in the next 22 JCWPs the RAC were zero (1, 3, 8, 11, 12, 13, 15, 16, 20, 22, 25, 26, 28 34, 35, 36, 39, 40, 46, 47, 48, 65). The RAC parameter was set to zero only for small flow-rate JCWPs. At the same time, the RAC values for sub-catchments decreased by an average of approximately 90% relative to the RAC values calculated used the MLF flow. The use of the Tennant method yielded an average of 40% reduction of RAC

**Table 3.** Flow values for selected characteristic flow and Tennant environmental flow for JCWPs located on the main river channel

Catchment	Q [m³/s]	SNQ [m³/s]	7Q10 [m³/s]	Tennant [m³/s]	
				April–Sept.	Oct.–March
56	87.5	41.3	29.8	35.0	17.5
57	86.8	39.7	28.0	34.7	17.4
58	86.6	38.0	26.2	34.6	17.3
59	91.7	36.8	24.6	36.7	18.3
60	92.5	35.3	22.9	40.4	20.2
61	94.2	35.2	22.7	37.7	18.8
62	93.5	33.4	20.8	37.4	18.7
63	91.9	36.9	18.4	36.8	18.4



**Fig. 5.** River absorption capacity (RAC) for TN and TP using low flow MLF, 7Q10 and Tennant for the Middle Warta catchment

relative to using the MLF for the summer semester and about 70% for the winter semester.

#### *River absorption capacity (RAC) for TP*

For TP the negative RAC values were obtained for 11 JCWPs (no. 10, 27, 38, 43, 51, 59, 60, 61, 62, 63, 64). All of the JCWPs that had a negative RAC for TN, had at the same time negative RAC values for TP. No matter which inviolable flow was used, the number of JCWPs with negative RAC was the same. It is also characteristic that catchments with negative RAC values for TP are located in the lower part of the Warta main channel, directly behind the Poznań agglomeration. This region is characterized by very rapid urbanization which often does not correspond to the expansion of the sewage network (Michałkiewicz et al. 2011). The number of JCWPs characterized by positive RAC for inviolable flow calculated by the Kostrzewa and Tennant methods are the same. In the case of inviolable flow 7Q10, as with TN, 22 JCWPs were characterized by a zero RAC value. In tables 5 and 6 the RAC values for all of the 70 JCWPs are shown. As we can see, no matter which inviolable flow was chosen, the number of JCWPs with negative RAC values is the same, but the calculated values are significantly different. Clearly contrasting here are the RAC values for JCWPs located on the main channel (56–63). This is due to high discharge rate

in the main stream compared to that of tributaries of the Warta. In addition to the main channel, the high RAC values for TN and TP occurred in the Mosinski channel JCWPs (4–7). The results clearly show how much impact on the RAC calculations the choice of the inviolable flow has.

## Discussion

The paper presents the results of a study in the Middle Warta catchment. As part of the studies, the RAC values for the seventy JCWPs were calculated, using the data obtained from the Macromodel DNS/SWAT, the MLF and 7Q10 flow characteristics, and the Tennant's environmental flows. Using the model allows for the reconstruction of the discharge rate, TN and TP loads with a daily data time step for all JCWP calculation profiles. Using the two different flow characteristics as well as the environmental flow characteristic had a direct effect on the RAC results. Choosing too restrictive an inviolable flow resulted in low RAC values for individual JCWPs. The results of general phosphorus calibration using 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, validate and verify the model. In spite of this, the results of the statistical measures identified as "not satisfactory" have been obtained mainly for the NSEs, so the authors decided to use the obtained model data for general phosphorus. In the studies described in this paper, the most restrictive flow is 7Q10. Selecting this flow for environmental analysis for the JCWPs located on the main stream of the Middle Warta catchment assumes that only 27% of the estimated natural flow for which the RAC is calculated, flows into the river. From the point of view of environmental protection, the choice of a very restrictive flow is advantageous because it guarantees better protection from pollution for the aquatic environment, even in periods of very low water levels in rivers. On the other hand, from the economic point of view and the development of areas located near rivers, the choice of too restrictive an inviolable flow can have negative effects – for example, by imposing very strict conditions on water users; these restrictions may also generate disproportionate usage costs. In extreme cases, this may lead to the reduction of some investment as a result of a limit being placed on the number of permits issued. Thus, the correct selection of indicators and the parameters for their calculation on the basis of which the decisions of the administrative authorities are taken are crucial. The problem may also arise when using the 7Q10 flow characteristic for RAC calculations on the small rivers with low discharge rates. In such cases, the 7Q10 flow rate is often close or equal to zero and therefore the RAC value is also zero. For TN, this was the case in 24 JCWPs, and for TP it was only slightly lower – in 22 JCWPs; for other flows characteristics there were no such cases. The MLF flow, as opposed to 7Q10, is commonly used in Poland for environmental calculations. This is because it is easy to calculate, and for lowland rivers such as the Warta it can be assumed that it is also an inviolable flow. The choice of MLF flow to calculate the main stream RAC (Warta RAC), assumes that the river has about 40% of the natural flow. Thus, the RAC values obtained using this flow in calculations is about 50% higher than that of the 7Q10 flow application.

Table 4. Summary of the results of river absorption capacity for individual JCWP for TN (red color = negative RAC)

water bodies number	TN – tons/year				water bodies number	TN – tons/year				water bodies number	TN – tons/year			
	SNQ	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)		SNQ	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)		SNQ	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)
1	2.4	0.0	1.3	0.7	25	4.7	0.0	3.1	1.5	49	7.2	1.5	45.8	22.9
2	85.3	1.3	51.3	25.6	26	6.0	0.0	3.3	1.7	50	3.0	0.3	25.1	12.6
3	4.1	0.0	2.3	1.1	27	2.7	0.0	1.4	0.7	51	3.2	1.4	14.3	7.2
4	344.2	11.2	190.2	95.1	28	7.0	0.0	4.0	2.0	52	32.3	8.0	259.8	129.9
5	909.1	14.5	482.5	241.2	29	42.7	0.4	25.0	12.5	53	20.6	4.3	265.1	132.5
6	1064.9	9.4	572.7	286.4	30	59.7	0.3	37.0	18.5	54	21.4	6.8	121.2	33.0
7	142.4	1.3	80.3	40.1	31	22.7	0.2	13.3	6.6	55	32.1	5.8	194.5	97.3
8	1.2	0.0	0.8	0.4	32	16.0	0.0	9.1	4.5	56	2980.9	2149.8	2523.8	1261.9
9	44.3	0.6	27.1	13.5	33	28.5	0.5	15.7	7.9	57	2203.3	1556.1	1928.8	964.4
10	-54.6	-13.4	-31.6	-15.8	34	2.8	0.0	1.7	0.8	58	2009.4	1385.2	1829.3	914.7
11	2.0	0.0	1.5	0.8	35	6.6	0.0	3.7	1.8	59	2345.3	1567.2	2336.7	1168.3
12	1.2	0.0	0.9	0.5	36	13.4	0.0	7.5	3.8	60	3041.4	1969.2	3478.9	1739.4
13	3.6	0.0	2.7	1.3	37	71.9	0.5	40.2	20.1	61	879.7	566.2	941.4	470.7
14	135.5	0.7	76.9	38.5	38	18.3	0.6	12.6	6.3	62	588.2	365.8	657.6	328.8
15	9.7	0.0	5.2	2.6	39	0.1	0.0	2.0	1.0	63	-883.2	-549.2	-971.0	-485.5
16	4.8	0.0	3.4	1.7	40	0.3	0.0	4.0	2.0	64	-1.8	-1.5	-2.8	-1.4
17	274.2	4.5	140.7	70.4	41	6.0	1.6	32.0	16.0	65	0.8	0.0	6.5	3.2
18	95.6	1.5	56.1	28.1	42	3.8	1.9	16.0	8.0	66	2.3	0.2	12.2	6.1
19	67.8	0.8	36.0	18.0	43	10.9	1.1	22.0	11.0	67	2.3	0.2	24.8	12.4
20	14.2	0.0	7.4	3.7	44	14.1	0.9	28.5	14.2	68	13.9	6.3	51.3	25.7
21	62.0	0.2	34.9	17.5	45	19.5	3.3	94.5	47.3	69	7.0	2.8	28.1	14.1
22	17.2	0.0	11.2	5.6	46	0.1	0.0	3.9	1.9	70	7.3	0.8	44.1	22.1
23	137.4	1.7	74.2	37.1	47	0.1	0.0	2.5	1.2					
24	285.0	4.8	148.9	74.5	48	0.2	0.0	2.8	1.4					



Table 5. Summary of the results of river absorption capacity for individual JCWP for TP (red color = negative RAC)

water bodies number	TP – tons/year				water bodies number	TP – tons/year				water bodies number	TP – tons/year			
	SNQ	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)		SNQ	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)		SNQ	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)
1	0.10	0.00	52.96	26.48	25	0.19	0.00	122.79	61.39	49	0.29	59.90	1834.09	917.04
2	0.98	14.86	590.60	295.30	26	0.24	0.00	133.91	66.96	50	-0.02	-1.45	-133.24	-66.62
3	0.16	0.00	90.70	45.35	27	-0.21	-3.53	-118.04	-59.02	51	-3.22	-1378	-14120	-7059.9
4	5.30	172.47	2929.51	1464.75	28	0.28	0.00	159.48	79.74	52	1.14	279.99	9137.75	4568.87
5	16.13	256.77	8558.87	4279.44	29	0.84	7.84	493.24	246.62	53	0.67	140.07	8594.59	4297.29
6	8.01	70.99	4310.04	2155.02	30	1.32	6.42	813.95	406.97	54	0.44	141.58	2508.31	683.45
7	3.48	30.75	1959.53	979.77	31	0.91	8.08	532.74	266.37	55	0.66	120.15	4004.58	2002.29
8	0.05	0.00	32.13	16.07	32	0.64	0.40	363.87	181.93	56	129.26	93217	109436	54718
9	0.48	6.38	295.37	147.68	33	1.15	22.01	630.14	315.07	57	123.97	87546	108517	54259
10	-15.52	-3792	-8974	-4487.2	34	0.11	0.00	67.38	33.69	58	104.05	71729	94727	47363
11	0.08	0.00	61.59	30.80	35	0.27	0.00	147.19	73.60	59	79.82	53335	79525	39762
12	0.05	0.00	36.43	18.21	36	0.54	0.00	301.79	150.89	60	-151.81	-98288	-173642	-86821
13	0.15	0.00	107.36	53.68	37	2.88	21.29	1611.92	805.96	61	-592.32	-381207	-633779	-316889
14	5.01	27.07	2842.27	1421.14	38	-1.23	-38.95	-844.76	-422.38	62	-1069.14	-664756	-1195195	-597598
15	0.39	0.00	209.03	104.51	39	0.00	0.00	79.64	39.82	63	-1485.20	-923449	-1632612	-816306
16	0.19	0.00	134.76	67.38	40	0.01	0.00	160.64	80.32	64	-1.01	-823.02	-1524	-761.83
17	10.24	168.49	5252.69	2626.35	41	0.09	25.61	499.64	249.82	65	0.04	0.00	258.98	129.49
18	3.69	56.56	2167.03	1083.52	42	0.12	59.54	512.47	256.24	66	0.10	7.62	489.84	244.92
19	1.28	15.42	681.40	340.70	43	-0.48	-47.59	-971.20	-485.60	67	0.10	7.62	992.53	496.27
20	0.57	0.00	295.81	147.91	44	0.57	36.12	1140.78	570.39	68	0.52	235.25	1912.99	956.50
21	0.74	2.55	414.05	207.02	45	0.78	132.16	3785.04	1892.52	69	-0.04	-13.93	-139.56	-69.78
22	0.69	0.00	450.29	225.15	46	0.00	0.00	155.91	77.96	70	0.15	16.42	899.41	449.70
23	3.10	39.14	1670.90	835.45	47	0.01	0.00	98.49	49.25					
24	8.82	148.42	4609.77	2304.88	48	0.01	0.00	114.02	57.01					

Table 6. Summary of the results of river absorption capacity for individual JCWP for TP (red = negative RAC)

water body number	TP – tons/year				water body number	TP – tons/year				water body number	TP – tons/year			
	MLF	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)		MLF	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)		MLF	7Q10	Tennant (April–Sept.)	Tennant (Oct.–March)
1	0.10	0.00	52.96	26.48	25	0.19	0.00	122.79	61.39	49	0.29	59.90	1834.09	917.04
2	0.98	14.86	590.60	295.30	26	0.24	0.00	133.91	66.96	50	-0.02	-1.45	-133.24	-66.62
3	0.16	0.00	90.70	45.35	27	-0.21	-3.53	-118.04	-59.02	51	-3.22	-1378	-14120	-7059.9
4	5.30	172.47	2929.51	1464.75	28	0.28	0.00	159.48	79.74	52	1.14	279.99	9137.75	4568.87
5	16.13	256.77	8558.87	4279.44	29	0.84	7.84	493.24	246.62	53	0.67	140.07	8594.59	4297.29
6	8.01	70.99	4310.04	2155.02	30	1.32	6.42	813.95	406.97	54	0.44	141.58	2508.31	683.45
7	3.48	30.75	1959.53	979.77	31	0.91	8.08	532.74	266.37	55	0.66	120.15	4004.58	2002.29
8	0.05	0.00	32.13	16.07	32	0.64	0.40	363.87	181.93	56	129.26	93217	109436	54718
9	0.48	6.38	295.37	147.68	33	1.15	22.01	630.14	315.07	57	123.97	87546	108517	54259
10	-15.52	-3792	-8974	-4487.2	34	0.11	0.00	67.38	33.69	58	104.05	71729	94727	47363
11	0.08	0.00	61.59	30.80	35	0.27	0.00	147.19	73.60	59	79.82	53335	79525	39762
12	0.05	0.00	36.43	18.21	36	0.54	0.00	301.79	150.89	60	-151.81	-98288	-173642	-86821
13	0.15	0.00	107.36	53.68	37	2.88	21.29	1611.92	805.96	61	-592.32	-381207	-633779	-316889
14	5.01	27.07	2842.27	1421.14	38	-1.23	-38.95	-844.76	-422.38	62	-1069.14	-664756	-1195195	-597598
15	0.39	0.00	209.03	104.51	39	0.00	0.00	79.64	39.82	63	-1485.20	-923449	-1632612	-816306
16	0.19	0.00	134.76	67.38	40	0.01	0.00	160.64	80.32	64	-1.01	-823.02	-1524	-761.83
17	10.24	168.49	5252.69	2626.35	41	0.09	25.61	499.64	249.82	65	0.04	0.00	258.98	129.49
18	3.69	56.56	2167.03	1083.52	42	0.12	59.54	512.47	256.24	66	0.10	7.62	489.84	244.92
19	1.28	15.42	681.40	340.70	43	-0.48	-47.59	-971.20	-485.60	67	0.10	7.62	992.53	496.27
20	0.57	0.00	295.81	147.91	44	0.57	36.12	1140.78	570.39	68	0.52	235.25	1912.99	956.50
21	0.74	2.55	414.05	207.02	45	0.78	132.16	3785.04	1892.52	69	-0.04	-13.93	-139.56	-69.78
22	0.69	0.00	450.29	225.15	46	0.00	0.00	155.91	77.96	70	0.15	16.42	899.41	449.70
23	3.10	39.14	1670.90	835.45	47	0.01	0.00	98.49	49.25					
24	8.82	148.42	4609.77	2304.88	48	0.01	0.00	114.02	57.01					

Unlike inviolable flow estimation methods, where emphasis is placed on preserving low flows (Kostrzewa – MLF, 7Q10), the methods of determining environmental flows also take into account the role of medium and high flows in maintaining the good status of rivers and river ecosystems. The Tennant method selected in this paper is one of the simplest and most frequently used. The selection of this flow for the RAC calculations of the main stream means that we have available 40% (for the summer period) and 20% (for the winter period) of the estimated natural flow. The division of the year into two separate periods and the consideration of other parameters which characterize the catchment area gives environmental flows an advantage over 7Q10 and MLF inviolable flows. These characteristics are related only to the flow volume in the riverbed, excluding the needs of water dependent ecosystems such as wetlands. Thus, the environmental flows fit with the principle of sustainable development, meeting the needs of people and the economy, while at the same time protecting the quantity and quality of the aquatic environment and water dependent areas.

## Conclusions

- Choosing the right data for environmental calculations is crucial when the results of the calculations are intended to help improve the environment;
- The highest flows and highest RAC values were obtained using the MLF arithmetic average for total nitrogen. For total phosphorus, the highest RAC values were obtained using the Tennant environmental flow;
- The lowest values of flows and lowest RAC values for TN were obtained using the Tennant method for the winter period (October–March), while the most restrictive flow for the whole period is the 7Q10 flow;
- The use of inviolable flows, where emphasis is placed solely on maintaining low flows, may adversely affect the sustainable development of the catchment area;
- The use of purely statistical methods for the protection of biological life in the river is unsuitable;
- Selecting too restrictive an inviolable flow (i.e., very low) for environmental calculations results in lower RACs;
- Generally, the use of environmental flows in environmental calculations is the best solution. These flows show much better hydrological characteristics of the river, and this has a direct effect on the results obtained.
- There are currently hundreds of ways to calculate environmental flows. There are both very simple and very complex methods that take into account, inter alia, social and economic factors. Choosing the right method depends on the goal one wants to achieve when calculating. The article uses a simple environmental flow (Tennant), which at this level of detail proved to be effective.

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## Wpływ wybranych charakterystyk przepływu na wyniki analizy środowiskowej na przykładzie chłonności rzeki

**Streszczenie:** Celem pracy było określenie wpływu wybranych przepływów nienaruszalnych na otrzymany wynik chłonności rzeki poszczególnych JCWP na zlewni Warty środkowej. Do osiągnięcia tego celu wykorzystano wyniki uzyskane z Makromodelu DNS/SWAT i trzech różnych metod obliczania przepływu nienaruszalnego: metoda Kostrzewy, przepływ 7Q10 i przepływ środowiskowy Tennanta. Wykorzystanie modelu SWAT jako modułu Makromodelu DNS znacznie rozszerzyło jego możliwości i pozwoliło obliczyć parametr RAC. Użycie SWAT pozwoliło na podzielenie analizowanej zlewni na poszczególne JCWP, a następnie wprowadzenie do modelu bardzo szczegółowych danych dotyczących zlewni. Makromodel DNS/SWAT pozwolił uzyskać dane o stężeniach i ładunkach zanieczyszczeń dla wszystkich siedemdziesięciu profili zamykających JCWP. Zlewnią wybraną do badań była Warta środkowa pomiędzy profilami Nowa Wieś Podgórna i Oborniki na której zlokalizowanych jest 70 JCWP. W pierwszej kolejności obliczono ładunki zanieczyszczeń wykorzystując metodę Kostrzewy, a następnie kolejne dwie metody. Otrzymane wartości ładunków zanieczyszczeń posłużyły do obliczeń chłonności rzeki (RAC). W przypadku azotu ogólnego dla każdego z wybranych przepływów nienaruszalnych tylko trzy JCWP uzyskały ujemne wartości chłonności. W przypadku fosforu ogólnego aż 11 JCWP uzyskało ujemną wartość chłonności. Ujemną wartość chłonności dla fosforu ogólnego uzyskały m.in. JCWP zlokalizowane poniżej miasta Poznania. Wybór odpowiedniej metody obliczania przepływu nienaruszalnego ma kluczowe znaczenie dla obliczeń środowiskowych takich jak wyznaczanie chłonności rzeki. Wybór zbyt restrykcyjnego przepływu nienaruszalnego może mieć negatywne skutki dla całej zlewni.