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# Applicability of the WASP Model in an Assessment of the Impact of Anthropogenic Pollution on Water Quality—Dunajec River Case Study

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**Abstract:** This article covers the analysis of the impact of agricultural and municipal pollution on surface waters in a selected pilot section of the Dunajec River in Poland. The analysis was performed using the dynamic Water Quality Analysis Simulation Program (WASP) model. The operational use of the WASP allows the assessment of current and future changes in water quality and the planning of measures to reduce adverse impacts on surface waters. Based on the acquired and processed data, the model simulated the impact of the pollutant supply on the water quality in the selected section. The simulations were carried out in three developed scenarios. The results of the simulations of the spread of pollutants in the riverbed show that the adopted scenarios, including an increased supply of pollutants and unfavorable hydrological conditions, will not adversely affect the operation and efficiency of the water intake. Thus in the considered cases, the risk will not reach an unacceptable level. However, a serious threat may be caused by the failure of the sewage treatment plant located in the vicinity of a water intake. The conducted analyses indicate that the WASP may have significant application potential in the risk assessment for surface water intakes.

**Keywords:** WASP 8.1; water quality; surface water intake; water intake security



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## 1. Introduction

Human activities have a negative impact on water quality, which is essential in the water supply to the population [1]. Climate change will increase the risk of water supply to the population [2]. The above risk also requires analyses to assess future water supply hazards to the population as a result of possible scenarios of changes in spatial development, climate, and water management development above the water intake and in its catchment [3]. Scenario methods in water management are more and more often used, not only in strategic analyses [4,5] but also locally, in the catchment scale [6].

In Poland, the Water Law Act [7] regulates the process of establishing protection zones for water intakes used to supply the population with water intended for human consumption and to supply plants requiring high-quality water. The Water Law obligated all owners of collective water intakes to carry out a risk analysis. The risk here is equated with the occurrence of a hazard and is not a classic combination of a probability of a hazard occurrence and its consequences. The risk analysis for surface water intakes will be a tool supporting the process of establishing a protection zone covering the area of direct protection and the area of indirect protection. It should be emphasized that in accordance with the provisions of the law, the risk analysis is supposed to be a repeatable process for each intake in a cycle of once every ten years. In contrast, the tools that should be used in its development have not been defined. The risk analysis takes into account the spatial development of the catchment area and water quality [3]. The tool should justify potential restrictions on economic activity and spatial planning taken when it is established. According to the authors, the risk analysis can be supported by water quality simulation models that consider the development of civilization exerting pressure on surface waters and their possible changes in the future [8], hence the research presented in this article.

The research presented in this article aims to analyze the applicability of the Water Quality Analysis Simulation Program (WASP) model [9] for risk analysis for a selected water intake. This research was based on developed scenarios, taking into account possible new sources of pressure in the catchment upstream of the intake and pressure resulting from the runoff of pollutants due to extreme precipitation [10]. This study covered a selected intake on the Dunajec River in Poland. This river is characterized by high flow variability, sensitivity to climate change, and at the same time used to supply people with water [11]. Based on the acquired and processed data, the WASP model simulated the impact of the pollutant supply on the water quality in the Dunajec River in the selected section. The Dunajec River is intensively used to supply water to the population, and the water intake in Świniarsko, together with the nearby one in Stary Sącz, and smaller local water intakes, supply water to about 100,000 inhabitants of the city of Nowy Sącz and neighboring towns [12].

The WASP model, whose detailed structure is described later in this article, is often used in water quality modeling. Currently, the eighth generation of the model is available [13]. In Poland, the model has been used, among others, for modeling and monitoring hydrodynamics and surface water quality in the Sulejów dam reservoir [14]. The results of work using the model suggested that with the assumed scenario of halving the load of nitrogen and phosphorus compounds supplied to the reservoir, the concentration of pollutants allows for achieving the first class water purity in the reservoir. The application of the model also showed its importance as a tool used in projections to assess the impact of changes on waters and the surrounding environment. In Pakistan, on the Ravi River [15], the WASP model has been used to identify the main sources of pollution along the river and their potential impact on water quality. As a result of the simulations, it was found that the solutions proposed in one of the scenarios can lead to a significant improvement in water quality, allowing it to achieve acceptable quality parameters. In Turkey, studies using the WASP model indicated that the water quality in the Porsuk River is much better in the upper course and then deteriorates after flowing through Kutahya Province [16]. In the United States [17], more complex model functionalities were used regarding the coupling of analyses performed in the HEC-RAS 2D [18]. These studies aimed to simulate the transport of sediments and pollutants caused by flooding. The hydrodynamic data from the HEC-RAS model were input into the WASP model. The research confirmed that coupled models provide a good basis for simulations of pollutant transport and analyses of selected water quality parameters in flood conditions. The WASP model can be used not only for forecasting but also for operational purposes. In studies [19] using sensors measuring selected water quality parameters in real-time, the WASP model was used to simulate the concentration of pollutants along the route of their transport from the source of pollutants to the location of the sensor. The forecasting capabilities of the WASP model related to climate change scenarios and their impact on river basins have been used, among others, in Bangladesh [20]. These studies investigated the effect of increasing temperature and solar radiation due to climate change on river water and water quality. Climate change, rising air and water temperatures, and nutrient pollution are directly related to the process of eutrophication of surface waters. Eutrophication causes problems with water treatment for consumption purposes. In the Peruvian Andes [21], the WASP model was used to analyze the process of eutrophication. The results provided the necessary arguments for the need for further quantitative and qualitative control of this source of water supply in the future, which will allow decision makers to determine the best option for water resources management and water usage.

The above-selected examples of the use of the WASP model show the potential of its use in research based on scenarios of changes affecting water management, including risk analysis, which is the basis for making decisions on establishing a protection zone for water intake.

## 2. Materials and Methods

### *2.1. Study Area*

The Dunajec River is located in southern Poland and is a right tributary of the Vistula River (the catchment area of the Baltic Sea). The length of the river to the water gauge section in Nowy Sącz is about 141 km, and its catchment area is 4334 km$^2$ [22]. The main tributary of the Dunajec in this section is the Poprad River (cross-border), whose length to the mouth is about 170 km. It is a diverse area in terms of geological structure and relief. The Tatra Chain (Central Western Carpathians)—the southern, high mountain parts of the catchment (above 2000 m above sea level) are made of crystalline rocks and resistant limestones and dolomites [23,24]. The vast Orava-Podhale Depression in the foreground of the Tatra Mountains is filled with Podhale flysch. In the north-eastern direction, the Dunajec River drains the limestone peaks of the Pieniny Mountains, and the Gorce, Beskid Sądecki, and Wyspowy, built of Carpathian flysch—the eastern parts of the Outer Western Carpathians. The Dunajec catchment is one of the most valuable natural areas in Poland. Upstream of the intake, there are 3 national parks, a landscape park, reserves, protected landscape areas, and Natura 2000 (birds and habitats) [25]. There are also two urban centers in the catchment area—Zakopane (25,500 inhabitants) and Nowy Targ (33,000 inhabitants) [26]. The population density of this area is approximately 129 people per km$^2$. Due to the complex environmental conditions (extensive mountainous areas), the settlement network and cities developed mainly in the bottoms of valleys and basins in the vicinity of rivers [27]. As a result of the inclination of the slopes and large denivelations, agriculture does not occupy large areas in the general structure of catchment use [28]. The annual variability of the flow is modified by the Czorsztyn-Sromowce reservoir complex together with the hydroelectric power plant on the Dunajec River located approx. 10 km east of Nowy Targ [29].

The section covered by modeling is a 2.5 km section of the Dunajec River—from the Brzeźnianka to the water intake in Świniarsko (approx. 2 km above the Nowy Sącz water gauge (IMGW-PIB network)). The following tributaries flow into the Dunajec on the designated section: Brzeźnianka, Poprad, and Unnamed Channel (Figure 1).

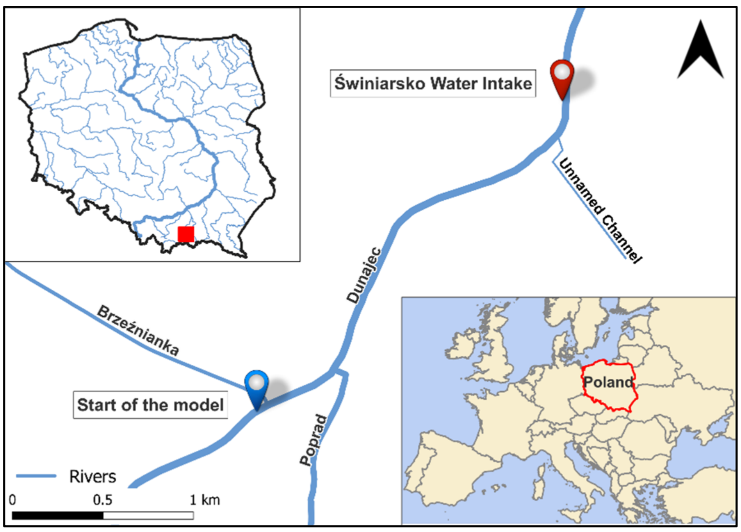


**Figure 1.** Study area.

### *2.2. Overview of Model WASP*

The Water Quality Analysis Simulation Program (WASP) model was developed by USEPA in the early 1980s [30] and has a long history of development and application in the USA and other countries in the world. WASP [31–36] is a general dynamic mass balance framework for modeling contaminant fate and transport in surface waters. WASP is capable of being applied in one, two, or three dimensions with advective and dispersive transport between discrete physical compartments, or "segments", to virtually any type of waterbody [36]. The model has the capability of handling multiple pollutant types in a single model run [37]. WASP has two kinetic modules such as advanced toxicant transformation and advanced eutrophication. Kinetic models are based on a set of transport and transformation equations. The advanced eutrophication module includes different parameters of eutrophication and is the most complicated module in the model. This module considers mass balance equations for calculations (e.g., transport, transformations, nitrification dynamics) [15]. The mass balance equation for dissolved water quality components must consider:

- All substances introduced into and removed from the system (both directly and by diffusion);
- The phenomenon of advective and dispersive transport;
- Chemical, physical, and biological transformation processes.

### *2.3. Data Collection and Segmentation of River Body*

Data to build the WASP model, including input data and data used for the segmentation process, are presented in the following subsections.

#### 2.3.1. Input Data

The input data were collected based on field research and data from the IMGW-PIB measurement and observation network. Field research included 3 measurement series carried out on 22 June, 13 September, and 4 November 2021. Measurements were made at 3 measurement points located on the Dunajec, Poprad, and Brzeźnianka (Figure 2). Based on the collected water samples, laboratory tests were carried out taking into account the following physicochemical and microbiological indicators: water temperature, ammonium nitrogen, nitrate nitrogen, total nitrogen, orthophosphates, *Enterococcus faecalis*, total coliforms, and *Escherichia coli*. In addition, during the field tests, the flow rate, water temperature, and conductivity were also measured.

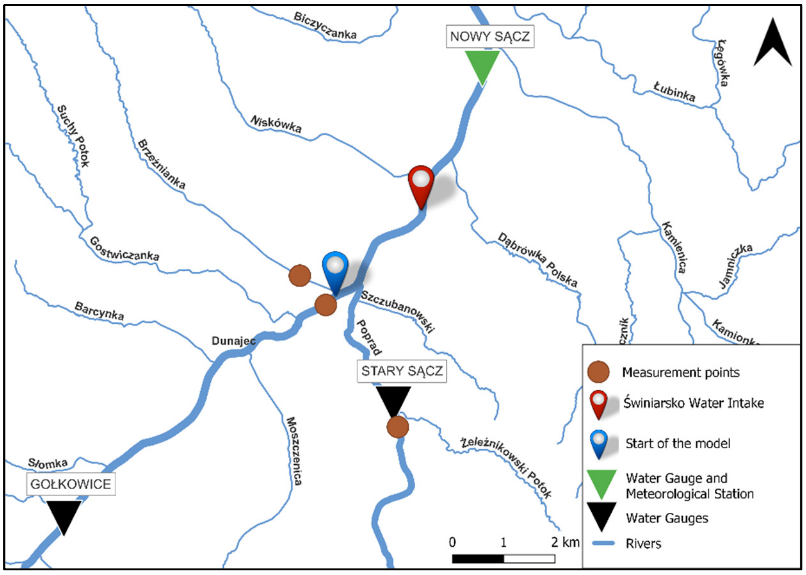


**Figure 2.** Location of the water gauges, meteorological station, and measurement points.

Input data concerning the volume of flow were entered based on IMGW-PIB water gauge data collected in the form of daily sequences from the Central Historical Database of IMGW-PIB (CBDH). The following stations were used: Gołkowice (Dunajec) and Stary Sącz (Poprad) (Figure 3). The flow rate of the Brzeźnianka River was determined based on field measurements. On the other hand, the flow rate of the Unnamed Channel was assumed to be half of the flow rate of the Brzeźnianka River, based on the assumed proportionality of the catchment area of both watercourses.

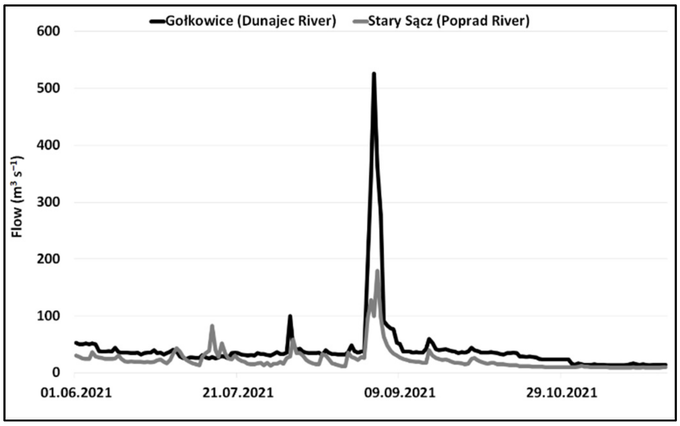


**Figure 3.** Input data concerning the volume of flow for IMGW-PIB water gauges Gołkowice (Dunajec River) and Stary Sącz (Poprad River).

The following meteorological data were also entered into the model: air temperature and wind speed for the nearest meteorological station IMGW-PIB Nowy Sącz (CBDH) and solar radiation from the Atlas of Solar Conditions of Poland [38].

2.3.2. Segmentation

The division of the modeled river section into segments was made in the ArcGIS 10.2.5 software based on the current orthophoto map [39].

The final shape of the segments network, consisting of 66 segments is shown in Figure 4.

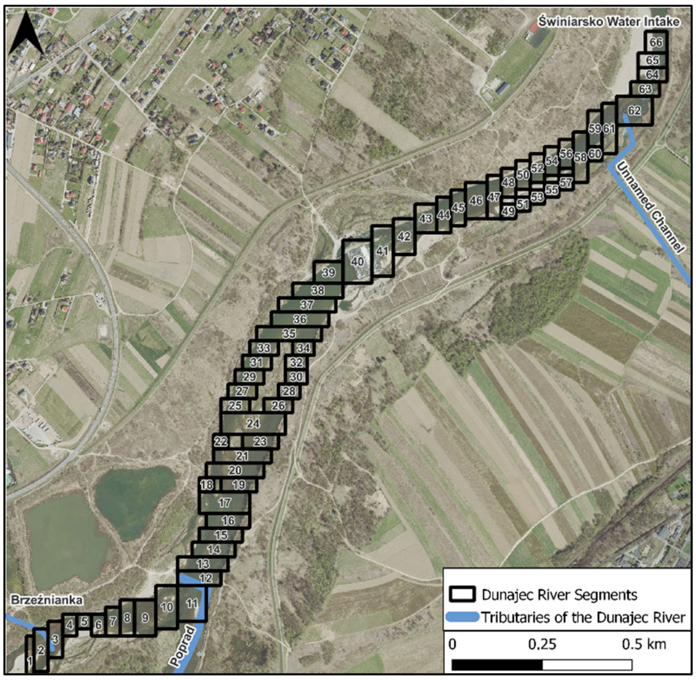


**Figure 4.** Segmentation of the Dunajec River.

All 66 segments were characterized based on cross-sections of the riverbed obtained from the Polish Waters National Water Holding, field measurements, and the literature data [36]. Information about the channel geometry, bottom slope, roughness coefficient, flow velocity, and other required coefficients was entered into the model (Table 1).

**Table 1.** Segments characteristics.

| Parameter | Value |
|---|---|
| Segment slope (m $m^{-1}$) | 0.0042 |
| Segment roughness | 0.04 |
| Initial depth (m) | 1.00 |
| Velocity (m $s^{-1}$) | 0.97 |

The characteristic points of the modeled section of the river in the form of tributaries to the Dunajec River and the opening and closing points of the model were assigned segments presented in Table 2.

**Table 2.** Segment descriptions.

| Segment | River | Description | Distance from the Water Intake (km) |
|---|---|---|---|
| Segment-1 | Dunajec | Start of the Model | 2.5 |
| Segment-2 | | Tributary of the Brzeźnianka River | 2.5 |
| Segment-11 | | Tributary of the Poprad River | 2.4 |
| Segment-62 | | Tributary of the Unnamed Channel | 0.2 |
| Segment-66 | | End of the Model—Świniarsko Water Intake | - |

*2.4. Scenario Development*

The analyses were carried out for 3 scenarios (Table 3).

**Table 3.** Scenarios.

| Scenario | Description |
|---|---|
| S-1—constant pollution of water | The constant load of the riverbed with anthropogenic pollutants in the period of low flows |
| S-2—failure of the sewage treatment plant | Temporary increased supply of municipal pollutants from a point source |
| S-3—supply of nitrogen compounds from agricultural land | Rapid delivery of pollutants of agricultural origin during rapid rainfall and high water |

The model simulated the spread of 5 physicochemical indicators and 3 microbiological indicators (Table 4).

**Table 4.** Modeled physicochemical and microbiological indicators in scenarios.

| Indicator | | Unit | S-1 | S-2 | S-3 |
|---|---|---|---|---|---|
| Physicochemical | Water temperature | °C | ✓ | | |
| | Ammonia nitrogen | mg $L^{-1}$ | ✓ | ✓ | |
| | Nitrate nitrogen | | ✓ | ✓ | |
| | Total nitrogen | | | | ✓ |
| | Orthophosphorus | | ✓ | ✓ | |
| Microbiological | *Enterococcus faecalis* | CFU per 100 mL | ✓ | ✓ | |
| | Total coliforms | | ✓ | ✓ | |
| | *Escherichia coli* | | ✓ | ✓ | |

In each scenario, input data were entered as described in Section 2.3.1, and segmentation was performed as described in Section 2.3.2. A detailed description of the developed scenarios and the adopted assumptions is presented in the subsections below.

#### 2.4.1. Scenario 1—Constant Pollution of Water

This is a reference scenario presenting the actual pollutant load on the water in the analyzed period. Data from the IMGW-PIB water gauge station in Nowy Sącz (CBDH) were used to identify periods of low flows on the Dunajec River. The pollutant load assumed in the scenario for the simulated indicators was determined based on field measurements.

#### 2.4.2. Scenario 2—Failure of the Sewage Treatment Plant

Two variants of a three-day discharge of untreated sewage as a result of a failure of a municipal sewage treatment plant with a capacity of 8500 P.E. were analyzed. In the first variant (12–14 November 2021), the receiver of the waste discharge is the Brzeźnianka River, while in the second variant (24–26 November 2021), the receiver is the Unnamed Channel. It was assumed that the flow of both watercourses at the moment of their mouth to the Dunajec is 0.05 $m^3 s^{-1}$. The quality of water in watercourses (receivers of sewage discharge) was determined based on the literature [40] (Table 5).

**Table 5.** Water quality data, based on Boroń et al. [40].

| Indicator | | Unit | Value |
|---|---|---|---|
| Physicochemical | Ammonia nitrogen | mg $L^{-1}$ | 56.92 |
| | Nitrate nitrogen | | 20.55 |
| | Orthophosphorus | | 134.85 |
| Microbiological | *Enterococcus faecalis* | CFU per 100 mL | 5,876,000 |
| | Total coliforms | | 24,860,000 |
| | *Escherichia coli* | | 6,300,000 |

#### 2.4.3. Scenario 3—Supply of Nitrogen Compounds from Agricultural Land

Two variants of nitrogen supply from agricultural land were analyzed during the flood on the Dunajec River on 30 June 2021. ArcGIS tools were used to determine the directions of runoff accumulation and the catchment area's size. Due to the levees, pollution from agricultural land enters the river through an Unnamed Channel (Segment 62). The area of the designated catchment area was 683 ha. The land cover was determined based on Corine Land COVER data (CLC, 2018) [41]. The area of agricultural land is 331 ha, which is 48% of the designated catchment area. A load of total nitrogen flowing away from agricultural land in Poland was determined based on the literature [42,43]. In the first variant, the load of total nitrogen was 108 kg $d^{-1}$ (for precipitation $\geq$ 30 mm $d^{-1}$). In the second variant, the nitrogen load was 4037 kg $d^{-1}$ (for precipitation $\geq$ 100 mm $d^{-1}$).

### *2.5. Model Application and Calibration*

The simulation of pollutant dispersion in the riverbed and the calibration of the model were carried out from 1 June to 30 November 2021. The advanced eutrophication module and the Euler calculation formula were used, and all segments were of the Surface type. To achieve a more realistic simulation of flow dynamics in a one-dimensional network the kinematic wave flow option was used. To determine the values of the calculation constants, standard settings for this type of simulation described in the literature were used [30,44–46] (Table 6).

**Table 6.** Constant parameters used in model WASP.

| Constant Parameters | Value |
|---|---|
| Advection factor for solution (0 = backward difference; 0.5 = central difference) | 0 |
| Fresh water = 0; Marine water = 1 | 0 |
| Salinity Simulation Option (1 = Salinity; 2 = TDS) | 2 |
| Heat exchange option (0 = full heat balance; 1 = equilibrium temperature) | 0 |
| Coefficient of bottom heat exchange—Watts $m^2$ $°C^{-1}$ | 0.3 |
| Sediment (ground) temperature (°C) | 10 |
| Ice switch (0 = no ice solution; 1 = ice solution; 2 = detailed ice solution) | 0 |
| Nitrification Rate Constant at 20 °C ($day^{-1}$) | 0.09 |
| Nitrification Temperature Coefficient | 1.07 |
| Half Saturation Constant for Nitrification Oxygen Limit (mg $O_2$ $L^{-1}$) | 2 |
| Minimum Temperature for Nitrification Reaction (°C) | 7 |
| Denitrification Rate Constant at 20 °C ($day^{-1}$) | 0.09 |
| Denitrification Temperature Coefficient | 1.04 |
| Half Saturation Constant for Denitrification Oxygen Limit (mg $O_2$ $L^{-1}$) | 0.1 |
| Dissolved Organic Nitrogen Mineralization Rate Constant at 20 °C ($day^{-1}$) | 0.075 |
| Dissolved Organic Nitrogen Mineralization Temperature Coefficient | 1.08 |
| CBOD Decay Rate Constant at 20 °C ($day^{-1}$) | 0.21 |
| CBOD Decay Rate Temperature Correction Coefficient | 1.047 |
| CBOD Half Saturation Oxygen Limit (mg $O_2$ $L^{-1}$) | 0.5 |
| Fraction of solar radiation reflected at the water surface | 0.06 |
| Light Option (0 = light from lat–long; 1 = input diel light; 2 = input daily light-calculated diel light) | 1 |
| Background Light Extinction Coefficient ($m^{-1}$) | 0.1 |
| Bacteria Death Rate ($day^{-1}$) | 3.4 |
| Theta: Bacteria Death Rate Temperature Correction | 1 |
| Light efficiency factor for pathogens | 1 |

The calibration of the WASP model took place in Segment 46 located 0.7 km from the water intake (Figure 4). Data from laboratory tests of water quality obtained based on field measurements carried out in 3 measurement series carried out on 22 June, 13 September, and 4 November 2021, were used for the calibration.

## 3. Results

The results of model calibration and pollutant dispersion in the Dunajec River according to 3 scenarios are presented below. Calibration results were developed for Segment 46, while the results for three scenarios were developed for Segment 66, i.e., the surface water intake in Świniarsko.

### 3.1. Model Calibration

Hydrological, meteorological, and water quality data used to build the model for Scenario 1 were used to calibrate the model by comparing simulated and measured data. In the conducted research, the trial and error method was used to calibrate the model parameters. The figures below show the calibrated indicators of *Escherichia coli*, nitrate nitrogen, and flow in Segment 46 of the model (Figure 5).

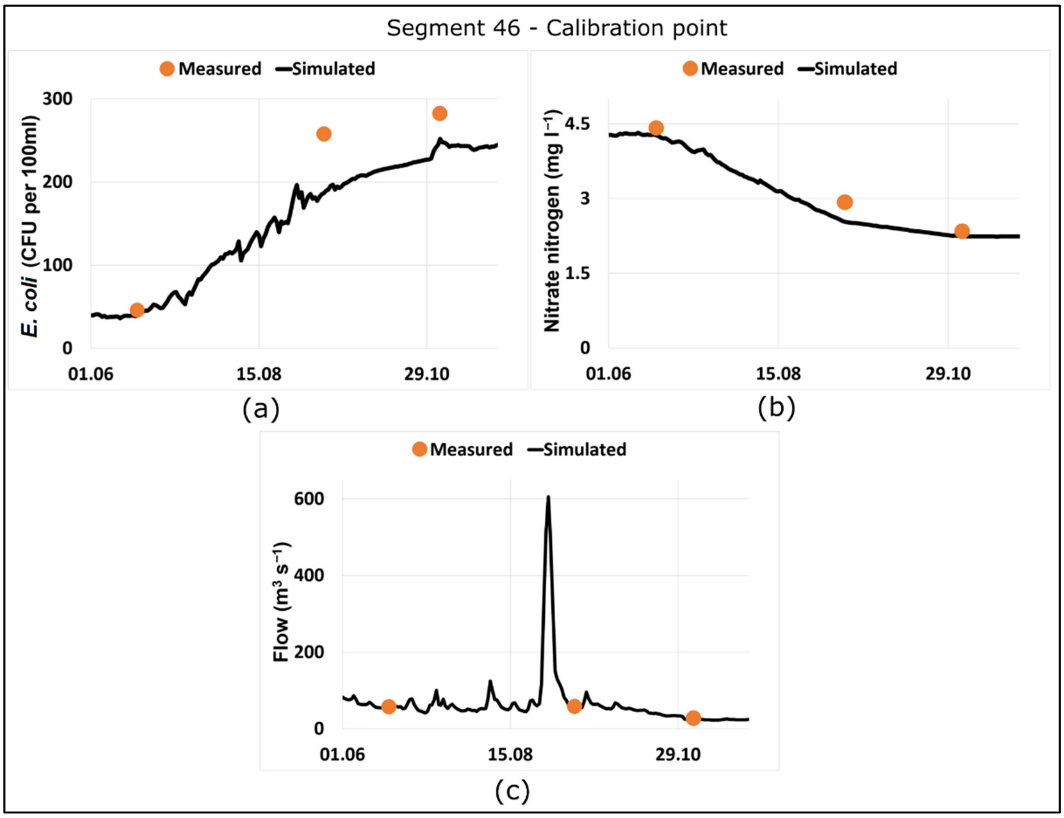


**Figure 5.** Model calibrated parameters: (**a**) *E. coli*, (**b**) nitrate nitrogen, and (**c**) flow.

### *3.2. Scenario 1*

In the analyzed 6-month period, the flow of the Dunajec River was very diversified. The highest water level occurred at the turn of August and September. During this period the highest average daily flow exceeding 600 $m^3$ $s^{-1}$ was recorded. On the other hand, the lowest average daily flow was recorded in November. It was the only month in which the flow values fell below 30 $m^3$ $s^{-1}$. The average monthly flow of the Dunajec River in the analyzed period is presented in Table 7.

**Table 7.** Average monthly water flow of the Dunajec River.

| Month | Average Monthly Flow ($m^3$ $s^{-1}$) |
|---|---|
| VI | 64.5 |
| VII | 61.3 |
| VIII | 91.7 |
| IX | 126.3 |
| X | 49.7 |
| XI | 27.1 |

The flow at Segment 66 which represents the model output is shown in Figure 6.

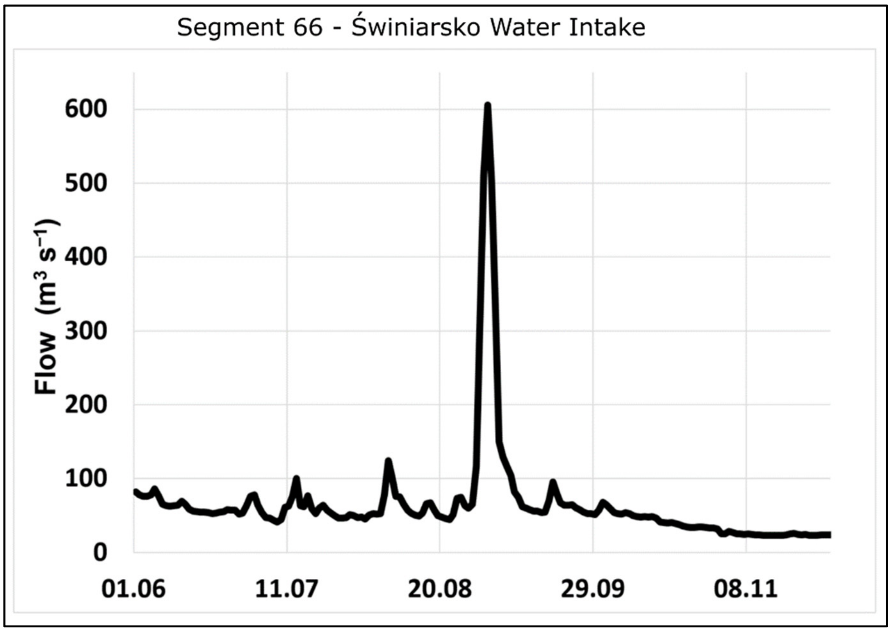


**Figure 6.** Scenario 1, flow at Segment 66—Świniarsko water intake.

The water temperature in the analyzed period ranged from 7.6 to 23.0 °C, reaching the lowest values in November and the highest in June.

Chemical indicators reach the highest values in the first months of the analysis period. Then, until September, they gradually decrease. During the period of the smallest flows, the concentrations of both nitrate nitrogen, ammonia nitrogen, and orthophosphorus are at a constant level and no significant changes are observed at that time. In the analyzed period, the concentration of ammonia nitrogen ranges from 0.12 to 0.99 mg $L^{-1}$, nitrate nitrogen from 2.34 to 4.32 mg $L^{-1}$, and orthophosphorus from 0.02 to 0.76 mg $L^{-1}$.

On the other hand, microbiological indicators in the first months of the analysis period are characterized by the smallest number of bacteria. Enterococcus faecalis bacteria reach the highest number in the middle period, while total coliforms bacteria, including *Escherichia coli*, in the final period. In the period of deepening low water, total coliforms bacteria, including *Escherichia coli*, show a slight upward trend in numbers, while Enterococcus faecalis bacteria in the low water period do not show significant changes in numbers. In the analyzed period, the number of Enterococcus faecalis bacteria ranges from 8.01 to 101.60 CFU per 100 mL, total coliforms bacteria from 89.63 to 262.83 CFU per 100 mL, *Escherichia coli* from 35.43 to 243.99 CFU per 100 mL.

The concentrations of the analyzed chemical and microbiological indicators are shown in the graphs below (Figure 7).

### *3.3. Scenario 2*

In the case of chemical indicators for both sewage discharges, the concentration of ammonia nitrogen more than doubled (from 0.11 to 0.23 mg $L^{-1}$), the concentration of orthophosphorus increased by more than tenfold (from 0.03 to 0.32 mg $L^{-1}$), while the increase in the concentration of nitrate nitrogen was small (from 2.24 to 2.28 mg $L^{-1}$).

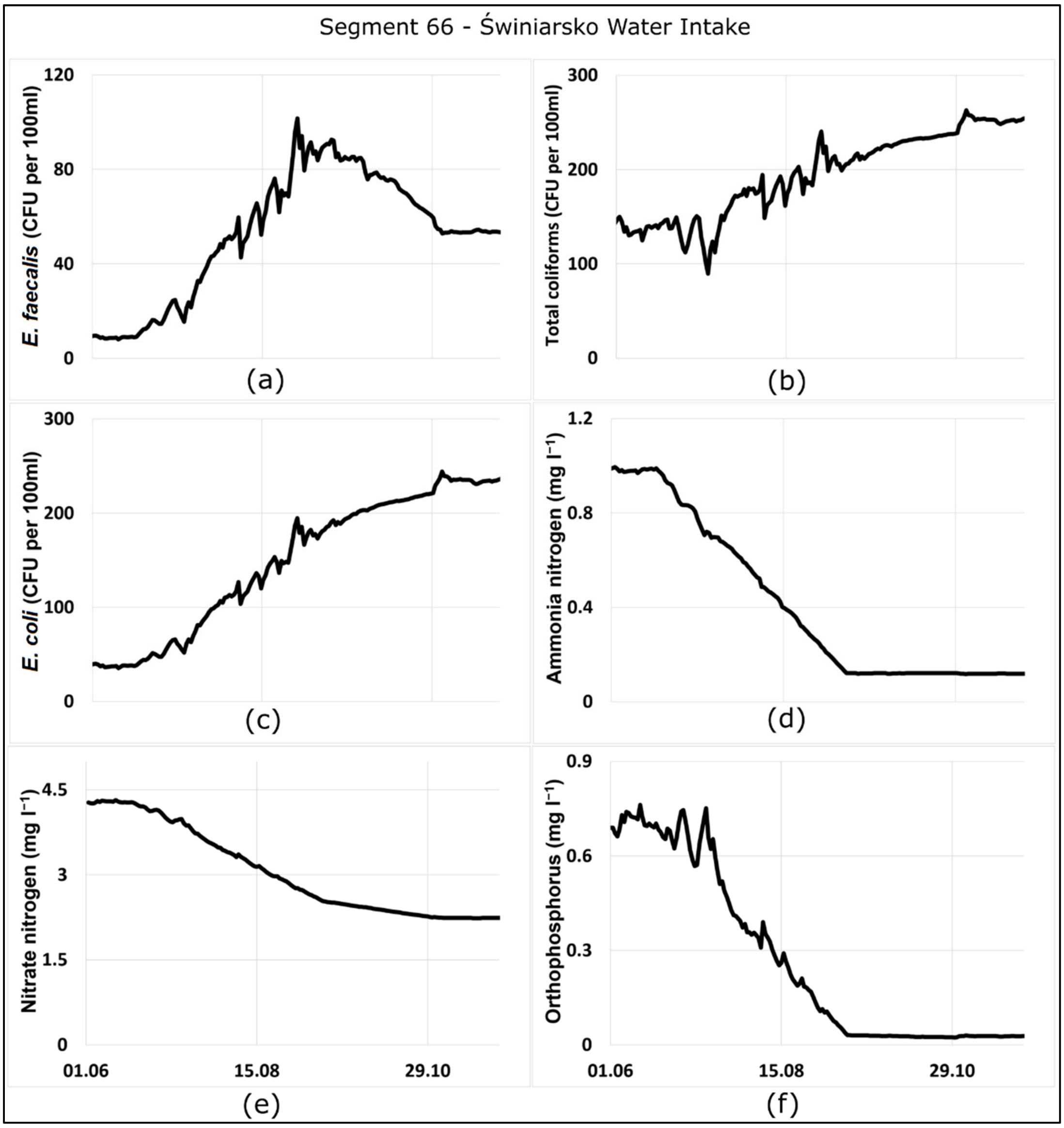


**Figure 7.** Scenario 1, pollution loads at Segment 66—Świniarsko water intake: (**a**) *E. faecalis*, (**b**) total coliforms, (**c**) *E. coli*, (**d**) ammonia nitrogen, (**e**) nitrate nitrogen, and (**f**) orthophosphorus.

Much greater increases in concentrations took place in the case of microbiological indicators. The number of Enterococcus faecalis bacteria as a result of discharge 1 increased more than 200-fold, and as a result of discharge 2 more than 230-fold. In the case of discharge 1, it increased from 53.75 CFU per 100 mL to 11,165.51 CFU per 100 mL and to 12,653.57 CFU per 100 mL for discharge 2. A similar increase can be seen for total coliforms bacteria. Their number increased more than 180 times as a result of sewage discharge 1, and more than 210 times as a result of discharge 2. In the case of discharge 1, it increased from the level of 53.75 CFU per 100 mL to 11,165.51 CFU per 100 mL and to 12,653.57 CFU per 100 mL in the case of discharge 2. However, a significantly lower increase in the number of bacteria was noted in the case of *Escherichia coli*. Their numbers increased more than 50 times as a result of both discharges. In the case of discharge 1, it increased from 23.77 CFU per 100 mL to 12,148.43 CFU per 100 mL and to 13,744.40 CFU per 100 mL for discharge 2.

The concentrations and numbers of the analyzed chemical and microbiological indicators are shown in the graphs below (Figure 8).

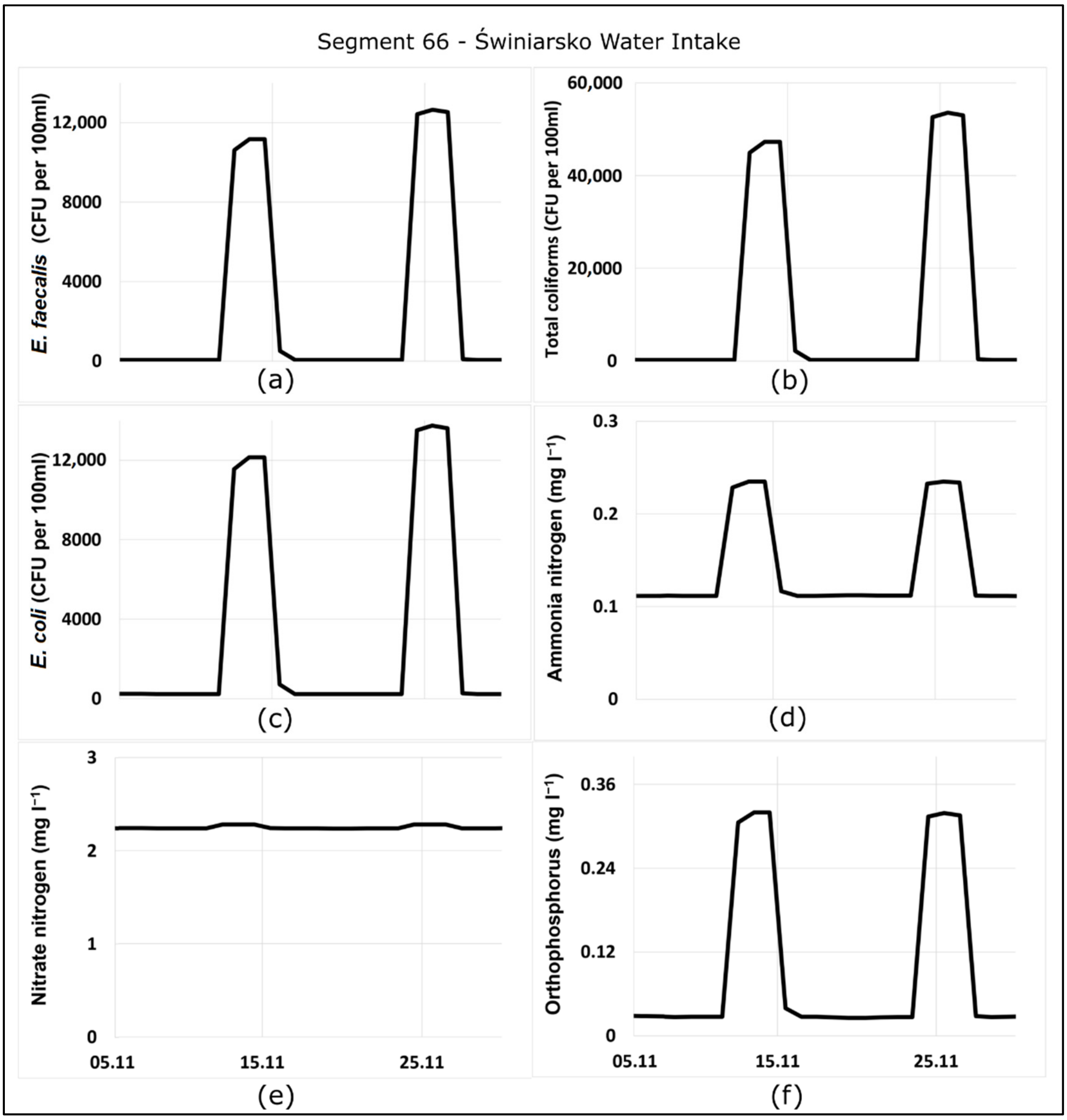


**Figure 8.** Scenario 2, pollution loads at Segment 66—Świniarsko water intake: (**a**) *E. faecalis*, (**b**) total coliforms, (**c**) *E. coli*, (**d**) ammonia nitrogen, (**e**) nitrate nitrogen, and (**f**) orthophosphorus.

In the case of discharge 1 located above the tributary of the Poprad River and approx. 2.4 km away from the intake, the highest bacterial counts are at the point of discharge of sewage, i.e., in Segment 2, 21,533.78 CFU per 100 mL (*Enterococcus faecalis* bacteria), 91,024.69 CFU per 100 mL (total coliforms), and 23,216.45 CFU per 100 mL (*Escherichia coli* bacteria). Then, in Segment 11, to which the Poprad River flows, the number of bacteria in the Dunajec River is reduced by 42.0% (*Enterococcus faecalis* bacteria), 41.9% (total coliforms), and 41.5% (*Escherichia* bacteria), respectively coli. Then, up to Segment 66, the number of bacteria systematically decreases, reaching the final reduction values in Segment 66, respectively, 48.2% (*Enterococcus faecalis* bacteria), 48.1% (total coliforms), and 47.7% (*Escherichia* bacteria) coli (Figure 9).

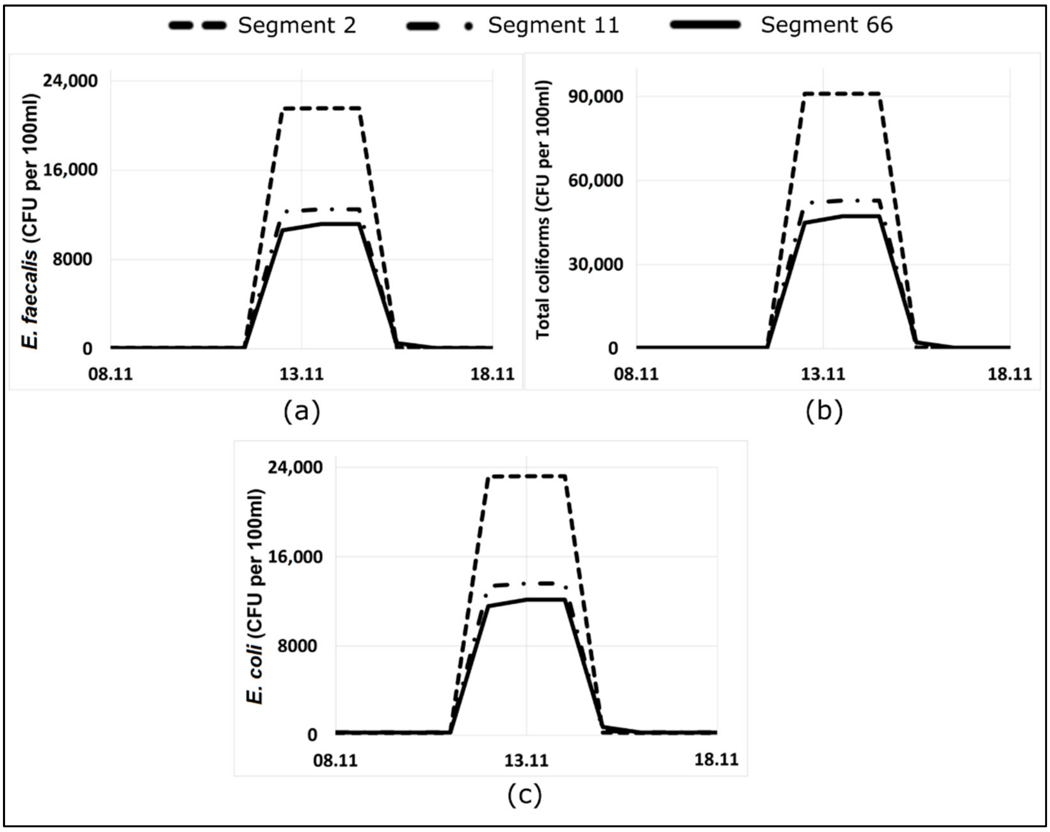


**Figure 9.** Scenario 2, variability of pollutant loads via the Dunajec River: (**a**) *E. faecalis*, (**b**) total coliforms, and (**c**) *E. coli*.

### 3.4. Scenario 3

As a result of the introduction of a load of total nitrogen into the Dunajec River in Segment 62 on 30 June 2021, no significant changes in the concentration of total nitrogen in the river are observed in the first analyzed variant. The concentration increase is only 0.2% (from 11.50 to 11.52 mg $L^{-1}$). On the other hand, in the second analyzed variant, the increase in total nitrogen concentration in the river was 6.4% (up to 12.24 mg $L^{-1}$).

The concentrations of the analyzed indicator are shown in the graphs below (Figure 10).

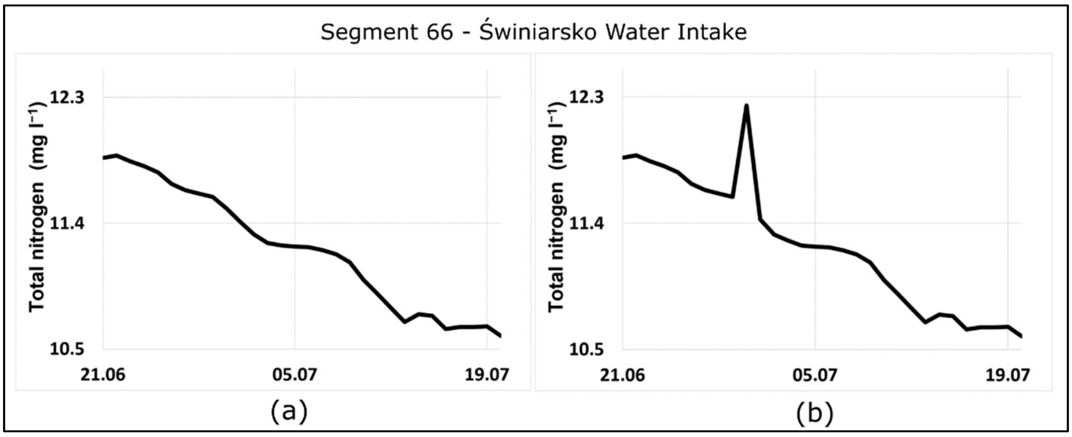


**Figure 10.** Scenario 3, total nitrogen loads at Segment 66—Świniarsko Water Intake: (**a**) variant 1 and (**b**) variant 2.

## 4. Discussion

The choice of the intake was also dictated by the fact that the Dunajec is characterized by high variability of flows, which is typical for mountain rivers. It is worth noting that during the highest water level at the turn of August and September, the flow of the Dunajec River was over 20 times higher than during the low flow in November. The conducted modeling of water quality in such variable hydrological conditions proves the great application possibilities of the WASP model, which can be applied to other Polish rivers. It should be noted, for example, that the maximum tested flow of the Dunajec River in 2021 was higher than the average daily flow of the Odra River (the second largest river in Poland) at the mouth of the Szczecin Lagoon (448 $m^3$ $s^{-1}$) [47].

The presented analysis of the applicability of the WASP model is also directly related to the amendment of the Water Law Act [7]. The change in regulations in Poland regarding water intakes opened a discussion on how to properly assess and evaluate the risk for water intake, in particular for consumers and plants requiring high-quality water. Numerous interpretation doubts regarding the correct assessment of the protection of water intakes caused the need to urgently develop a uniform methodology for preparing risk analysis for surface water intakes on a national scale. In Poland in 2021, there were 360 surface intakes used for collective water supply [48]—from the perspective of the security of water supply and current legal requirements, there is a significant need to look for solutions that allow risk assessment. The WASP model thanks to the possibility of modeling the migration of pollutants in the riverbed in various scenarios, may be a response to this need. The modeling results indicate the need for restrictions on the development of settlement structures, i.e., the location of residential buildings and the discharge of sewage into the water which indicates the need to establish protection zones and introduce the above restrictions under the Water Law. At the same time, it should be emphasized that the built and configured model also allows it to be used to update the risk analysis after ten years as required by law.

The main problem in establishing a protection zone is choosing an appropriate method. Basically, it should be desirable to protect the catchment area above the water intake. However, in the case of intakes such as those presented in this paper, the zone would cover an area of more than 2000 $km^2$. Considering other intakes located on transit rivers in Poland, this would lead to a situation where a significant part of the country would be covered by protection zones for surface water intakes. The Water Law indicates the possibility of prohibiting in such areas the construction of new roads, railways, airports, the location of industrial plants, livestock breeding, and the use of fertilizers in agriculture [7]. In practice, this would therefore mean a drastic reduction in the economic functioning of the country. The catchment approach becomes contrary to the general interest of society. As the definition of the boundaries of a conservation zone will imply a number of socio-economic impacts, answering this question is very difficult and requires a series of case studies. In this paper, we have used the WASP model, which, with its ability to model the migration of pollutants in the riverbed under different scenarios, can support those making the decision to define the boundaries of an intermediate protection zone. However, due to the pilot nature of the study, it cannot provide a comprehensive solution to the problem. It should be noted that modeling the hydrological and chemical processes occurring in the channel using the WASP model allows the precise determination of the buffer capacity of a lake or river in a given section, which can significantly determine the need for and size of the protection zone.

The application of the WASP model in studies that can support the management of water resources in Poland was presented in the example of the Sulejowski Reservoir (Pilica River), where a drinking water intake for the city of Łódź (800,000 inhabitants) is located [14]. The results indicated a high buffer capacity of the reservoir for nitrogen compounds. The analyses carried out in Scenario 3 for the presented section of the Dunajec River also showed a significant capacity to dilute this type of pollution—despite the fact that it is a much smaller catchment area (about four times smaller) and the intake is a riverbed type. The WASP model also makes it possible to determine which hazard may be generated by facilities already present in the catchment. Research presented in the article by Iqbal et al. [15] showed that existing sources of pollution generate a significant threat of water quality downgrading, which poses a hazard to both aquatic ecosystems and humans. Scenario 2 showed that the existence of facilities such as sewage treatment plants in the immediate vicinity, in case of failure or overloading, e.g., during the tourist season, could lead to a real hazard of water scarcity in Nowy Sącz.

The application of the WASP model in operational mode in the form of a monitoring network based on the Internet of Things and Blockchain technology solutions is also currently being developed. A study by Lin et al. [19] proposed a solution integrating a sensor network and a real-mode WASP model for monitoring existing pollution sources in support of the management process in field irrigation. Such a solution can undoubtedly provide significant support to intake operators. These unique capabilities of the model make it possible to simulate the concentration of pollutants along the entire route of their transport from the source of pollution to the location of the sensor, which could be located at the water intake. The presented paper identifies the key sources of pollution and their potential impact on the intake. The reconnaissance carried out in the presented pilot section can become the basis for the construction of a micro-scale monitoring network, but this requires the cooperation of stakeholders involved in the process of supplying water to consumers and the outlay of adequate human and financial resources. Significantly, the solutions used so far to control the quality status of Poland's rivers are based on monitoring carried out by the Chief Inspectorate of Environmental Protection and do not have adequate time resolution [49]. Consequently, the availability of up-to-date measurement data on water quality is limited, and each time a model is built, a separate field study is required, as in the case of the presented pilot section. On the other hand, however, the hydrological and meteorological measurement network of the Institute of Meteorology and Water Management is well developed on a national scale, so that in the case of large water intakes on transit rivers such as the Dunajec and the aforementioned Sulejowski Reservoir it is possible to obtain daily, and in selected water gauges hourly, data on flow and meteorological conditions [50]. In addition, the environmental catastrophe on the Oder River in 2022 [51] has led to an increased interest of the state administration in the development of a network for continuous monitoring of water quality parameters throughout the country, which in the future may provide high-resolution temporal data for the construction of the WASP model and the analysis of the threat of declining water quality in other intakes in Poland [52].

The process of building a model for any river in WASP is related to the performance of many activities, the sequence of which is basically unchanged, although local environmental conditions and goals allow the introduction of proprietary modifications. The key issue is to collect hydrological, meteorological and water quality data. The availability of measurement data and its time–frequency has a very strong influence on the results obtained. In the presented paper, flow simulation using tools integrated into the WASP model was used. Daily data from the nearest water gauge stations, located a few kilometers from the modeled river section, were input. As the rivers Dunajec and Poprad are by far the largest rivers in the analyzed region, the model captures realistic flow variability for the analyzed time period. WASP also offers the implementation of simulation results from hydrodynamic or other water quality models. This functionality of model coupling was shown in the work of Shabani et al. [17] using hydrodynamic data from the HEC-RAS model as input. In addition, Cope et al. [30] indicated the possibility of using such hydrodynamic models as DYNHY5, RIVMOD, DYRESM, EFDC, and SWMM. The next necessary step is the division of the riverbed into computational segments and their characteristics using, for example, transverse profiles of the riverbed. However, it should be borne in mind that building simulations using multiple models will certainly increase the accuracy of simulations performed by the WASP, but when the aim is to build a universal tool that is relatively simple to implement in other areas, it is necessary to optimize the solutions used. The results of the simulations carried out on the pilot section showed high agreement (mean $R^2$ = 0.98) between the simulated values and the actual measurements, but the preliminary nature of the study, which did not take into account measurements during flood events (safety considerations prevented manual sampling at this time), allows only limited conclusions in this field. The final stage of work on the model includes the correct determination of the calculation constants and calibration. Model calibration is one of the most significant challenges. The chosen calibration technique should adapt the parameters of the kinetic model to the water body in question by obtaining the smallest possible discrepancies between simulation results and measured data [14]. Four main methods are known for calibrating parameters: theoretical, experimental, empirical, or trial and error. One commonly used and effective method for calibrating water quality models is trial and error. In their work, Obin et al. [53] and Huang and Tian [54], using this method, achieved satisfactory and reasonable results for calibrating model parameters. In the presented study, similarly to Iqbal et al. [15], the input data used in the construction of the first reference scenario were used to calibrate the model by trial and error. Then, by comparing simulated and measured data, individual environmental, stoichiometric, and kinetic parameters were manually adjusted to obtain reasonable results. The model was calibrated based on field data conducted at the Segment 46 site located approximately 700 m from the water intake.

As a result of the simulations carried out for the three developed scenarios, diversified results of concentrations and numbers of the analyzed chemical and microbiological indicators were noted. In the period of low flows (Scenario 1), no significant changes in water quality parameters were found. Furthermore, the extreme surface runoff discharged directly into the river in the vicinity of the water intake (Scenario 3), a large load of total nitrogen, does not adversely affect the water quality. Both in the case of Scenario 1 and Scenario 3, it is stated that the adopted assumptions have no impact on the operation and efficiency of the water intake. On the other hand, a simulation assuming a failure of a municipal wastewater treatment plant (Scenario 2) allows for observing a significant deterioration of water quality parameters, both for chemical and microbiological indicators. In the case of microbiological indicators in both variants of sewage discharge located both upstream and downstream of the Poprad River tributary to the Dunajec River, in Segment 66 the limit values of water quality indicators that should correspond to surface waters used to supply the population with water intended for human consumption were exceeded [55]. In Poland, based on the currently transposed regulations of the European Union [56], the maximum permissible values of water quality indicators are set by Category A3. If the set standards are exceeded, even the use of high-efficiency physical, chemical, and biological treatment may turn out to be insufficient. Table 8 presents the maximum values of the indicators obtained in Scenario 2 and compares them with the acceptable standards. The results of the simulation show that the failure of the sewage treatment plant located in the vicinity of the intake poses a serious threat to its uninterrupted and proper functioning. Thus, the existing intake should be additionally technically secured, or, in the case of building a new intake, the WASP model simulation results should be used to determine the appropriate, safe location of the intake.

**Table 8.** Simulation results in the context of normative standards [55].

| Month | Unit | Value | |
|---|---|---|---|
| | | Category A3 | Scenario 2 |
| *Enterococcus faecalis* | CFU per 100 mL | 50,000 | 53,561 |
| Total coliforms | | 20,000 | 13,744 |
| *Escherichia coli* | | 10,000 | 12,653 |

The results of the conducted research also enable the observation of the processes of pollutant dilution and self-purification of the river. In the case of the analyzed microbiological indicators, a reduction in the number of bacteria by over 40% was observed from the place of discharge to the water intake. This may prove the good condition of the Dunajec River above the sewage discharge and the high buffer capacity of the river.

The analyses carried out by Mamani Larico and Zuniga Medina [21] are arguments indicating the need for further research and quantification of current and potential sources of pollution, which may lead to the development of better regional practices in the field of sustainable development for the aquatic environment. Therefore, the results of pollutant dispersion obtained based on the simulation may be an important stage in planning protection zones for water intakes.

From a practical point of view, the obtained results indicate that total coliforms bacteria may pose a significant threat to the functioning of the intake. The fact that the intake itself poses a bacterial threat shows that the entire sanitary installation and water storage tanks are also at risk [57]. This means that the entire water supply system must be thoroughly disinfected as some types of bacteria have the ability to multiply again and contaminate the water supply system. It should be emphasized that human contact with coli bacteria is also dangerous in an indirect form, for example in the case of agricultural irrigation (bacteria entering food). For this purpose, among others, the risk of coliform bacteria was modeled in waters used for this purpose [58]. Most often, the presence of coliform bacteria indicates that the intake is susceptible to microbial contamination. A frequent cause of the presence of coli bacteria in water intended for consumption is contamination with fecal matter or animal waste. They can get into surface and underground waters through leaky installations or heavy rainfall flowing from fertilized fields [59].

In Poland, river valleys are very often heavily transformed and subject to strong investment pressure. This particularly applies to the southern part of Poland [60], where surface water intakes predominate. Possible restrictions in the zone should be analyzed in two ways. From the point of view of water users, the restrictions should ensure safe water quality. However, from the point of view of those conducting business and investment activities above, restrictions should be rationally justified, taking into account their impact on the economic condition and the possibility of development [61]. Then the boundary of the protection zone of the intake will be optimally determined. The model in this respect provides significant support for the decision maker.

The results of the presented application of the WASP model for the tested section of the Dunajec River in practical terms can also be used for the purposes of crisis management. Hazards to the water intake can be analyzed assuming their different scenarios [62]. These may be hazards caused by natural factors, such as the scenario of pollutant runoff due to extreme rainfall, analyzed in the research. The second group may include hazards classified as NATECH (Natural Disasters Triggering Technological Disasters) [63]. An example of such an event may be an oil leak resulting from a tanker crash caused by unfavorable weather conditions on its route above the intake [64]. In order to reduce potential losses as a result of a hazard, it is possible to increase the readiness of crisis services and those responsible for maintaining the intake in the event of a hazard by planning appropriate mitigation measures in the crisis management plan for the intake [65]. The implementation of the model and its successive updating allow for its use in analyses related to crisis management. The analysis of variant hazard scenarios also allows for the development of a crisis management plan for the intake and enables better preparation of relevant services in the event of a threat. In this regard, the implemented model allows for an increase in the preparedness of these services. Preparedness is related to appropriate, optimal response allowing the reduction of losses related to contamination of the intake's internal installations as a result of emergency pollution and launching alternative water supplies in the event of closure of the intake. The basis for such activities is having reliable information about the simulation results from the model. In view of the above, the model can also be considered an element of the early warning system [66].

## 5. Conclusions

The security of water supplies for people is one of the key tasks of water management. In Poland, especially in its southern parts, surface water intakes dominate. Water intakes, especially those supplying larger cities, are located on transit mountain rivers, where catchments have undergone significant transformations. The concentration of the settlement network, investment pressure, and unregulated water and sewage management make waters in mountain rivers particularly vulnerable to anthropogenic pressures. These pressures may have a negative impact on the security of water supplies of good quality and quantity. The answer to these problems is the new legal framework introduced in the Polish legislation imposing the obligation to carry out a risk analysis and to designate protection zones for surface water intakes. However, the legislation does not define the methods to be used. The presented paper recognizes the applicability of water quality modeling using the WASP model to analyze the risk of water quality decline at a surface water intake. The conducted research indicates that the WASP model, thanks to the modeling of processes occurring in the longitudinal profile of the riverbed, can provide significant support for decision makers. The results of the simulations of the spread of pollutants in the riverbed in the light of the requirements of the Water Law Act may constitute a substantive basis for designating the zone of indirect protection of the intake or ascertaining the lack of such a need. The possibility of using the WASP model to simulate emergency scenarios can support crisis management, the development of action plans, and the preparation of services in the event of a hazard. Identification of hazards and simulation of pollutant dispersion in the channel can also be the basis for the development of early warning about the risk of water quality decline at the intake. This functionality of the model would provide significant support for water intake safety procedures. However, it should be noted that the research carried out was of a preliminary nature, so the implementation of the above applications will require a great deal of effort and resources, as well as the cooperation of stakeholders involved in the water supply process, which may pose a challenge to the current solutions used in water management in Poland.

It should be noted that the legal requirements regarding the risk analysis for water intakes apply to already existing water intakes and areas where pressure sources are located that may adversely affect the quality of the water intakes. From this point of view, the risk analysis is an ex-post analysis because, apart from the possible location of new sources of pressure, it must also take into account existing sources. Conclusions from the case of the Dunajec River analyzed in the study indicate that the risk of microbial contamination will increase if further sources emitting such contamination are located in the analyzed domain of the model. At the same time, the risk of failure will increase due to the increase in the number of pollution sources. The exemplary water intake risk analysis presented in the study shows the possibilities of the WASP model for such a task, but it does not determine the range of the intermediate zone due to the short section of the river covered by modeling selected as an example for the analysis. Simulations of the spread of pollutants in the Dunajec riverbed indicate that the adopted scenarios involving increased pollutant delivery and unfavorable hydrological conditions, in stable and correct operation conditions, do not harm the functioning of the water intake. On the other hand, failures that rapidly deteriorate the quality of water in the river may be dangerous for the quality of water obtained for consumers at the intake. The WASP model implemented for the analyzed section of the river excludes the location in the study area of objects that do not have appropriate treatment facilities.

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