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Article

An Investigation of SWAT Model for Environmental Health Management Using Water Quality Parameters in a Stream System in Central Anatolia (TÜRKİYE)

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Abstract: Water is one of the most critical factors affecting environmental health. For this reason, estimating and monitoring the behavior of water in nature and preventing water pollution before it occurs are advantageous to avoid problems that may occur in terms of environmental health. In order to predict the behavior of water, the hydrological cycle needs to be evaluated on a basin basis. At this point, hydrological models can be used to make mathematical representations of hydrological processes. These models play an essential role in predicting and monitoring problems such as poor water quality, pollution, particle and sediment transport, and proliferation of oil and petroleum derivatives among frequently encountered issues in environmental health. In this study, a 2D surface water model was created using soil and water assessment tool (SWAT) to simulate the lotic ecosystem and existing water quality in Tatlıçay Basin and to propose solutions for improving environmental health in Cankiri provincial center in Türkiye. The accuracy of the input data and the validity of the model were checked with the calibration and validation studies by using the monthly or 3-monthly observation data of the General Directorate of State Hydraulic Works' flow observation & water quality stations from 2016 to 2020. The aim was to provide the opportunity to produce fast, accurate, and practical solutions in the face of negative scenarios with this model. This modelling study obtained successful results in the calibration and validation process with very few observed data. With this study, a significant contribution to the literature on environmental health is made, as there aren't many examples of hydrological modeling from the Middle East.

Keywords: environmental health; eco-hydrology; hydrologic model; water quality; soil and water assessment tool (SWAT)

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1. Introduction

One of the most well-known and important sources of clean water, with unrivalled importance for the biosphere, is river ecosystems [1]. Like all other clean water sources, rivers are under threat from natural and anthropogenic pressures [2]. As a result, it is important to define these pressures and to identify the pollutant burden they cause [3]. One of the most accurate tools to make these identifications is hydrological models. Hydrological models to be applied at basin scale provide cost and time savings with results that can be obtained from available data, even in areas where parameter measurement is difficult [4]. With the use of hydrological models, precautions can be taken to protect urban and environmental health and it becomes easier to overcome problems that will be experienced [5,6].

Hydrological modelling involves tools allowing the opportunity to solve equations mathematically that are closest to reality with assumption-based simplification of surface water systems [7]. At the same time, due to being able to model water quality parameters, they are important to predict movement of pollutants in aqueous environments even in unaccessible areas without requiring large-scale, expensive chemical analyses and large labor force and to identify steps to be taken in the future to prevent water-environmental pollution [8–10]. There are several different software programs available based on pollutant features for hydrological modelling [11–13].

Hydrological model software may be chosen according to the available data, type of problem and solution to be implemented [14]. In the field of environmental health, the SWAT model, which can be used effectively to identify, monitor and solve problems causing damage in a serious sense to environmental health, like water pollution, particle/sediment transport and nutrients with the movement of water in nature, comes to the forefront [15–18].

The hydrological model inputs for SWAT comprise easily accessible data. These data may be grouped as climatic (rainfall, temperature, solar radiation and relative humidity), physical (land use, soil features, topography and slope), hydrological (flow discharge rates, water levels) and chemical (point and distributed pollutant burden) [19,20]. After calibration and sensitivity analysis performed according to observed values defined in the model, these data may provide model outputs related to daily, monthly or annual time periods for flow and water quality on a basin scale [21,22].

The main aim of this study, encompassing the years 2020-2022, is to present alternative solution recommendations about the use of hydrological models to predict and monitor problems that may occur related to water quality in the field of environmental health and to investigate the behavior in nature, distribution and sources of pollutants disrupting water quality [23,24]. In line with this aim, the target was to define the hydrological system with a SWAT model, determine the current water quality status, create a foundation for analysis of pollutant burden that may threaten environmental health in the future and provide the opportunity to be able to produce effective solutions for possible negative scenarios for the Tatlıçay river ecosystem, an important water resource in Çankırı province with moderate population density located in the Central Anatolia region of Türkiye.

2. Materials and Methods

2.1. Study Area

The study area was chosen as the Tatlıçay Basin in the Central Anatolia region of Türkiye, within Çankırı province. The dominant plant cover is Iranian-Anatolian steppe and continental climate dominates (**Figure 1**). The study area represents a sub-basin of the Kızılırmak, one of the most important rivers in Türkiye.

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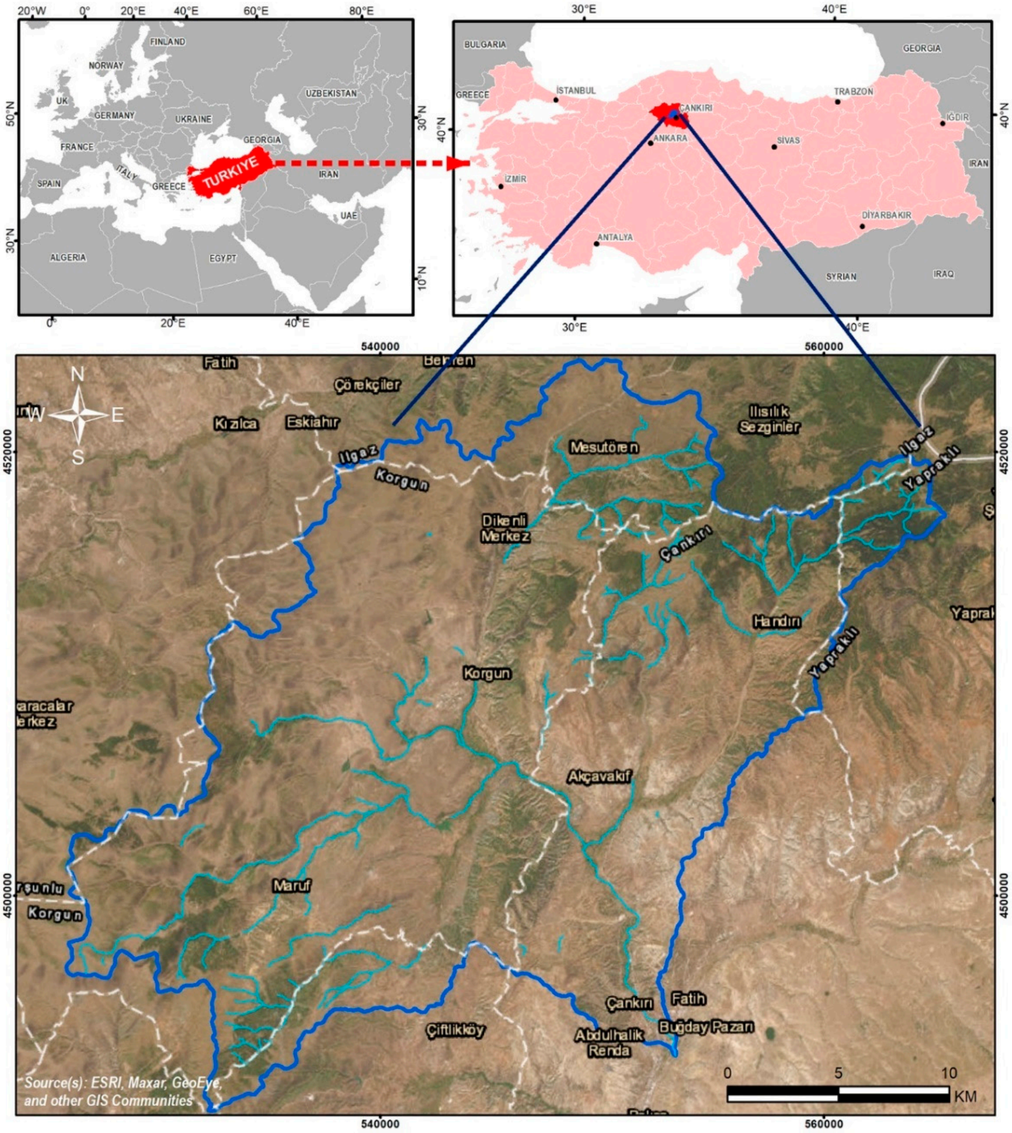

Figure 1. Location map of the Tatlıçay Basin.

The Tatlıçay river ecosystem, chosen as example study area for SWAT model implementation, contains elements of pressure affecting environmental health with anthropogenic source like agricultural practices and urban waste discharge. For agricultural irrigation, water collection for use of river water for gardening and agriculture in plains and in irrigation ponds within the basin lower the flow of the Tatlıçay and cause low water quality. Agricultural practices in the basin use intense fertilizer and pesticide, which suppress the Tatlıçay river ecosystem. Additionally, urban discharge from settlement areas with dense population in the Tatlıçay Basin discharges into the rivers without any treatment process. All these pressure elements negatively affect environmental health and cause poor water quality in the Tatlıçay river ecosystem. Direct irrigation from the river with poor water quality affects public health in the same way, through the use of the products grown with this water. Considering pollution burden in the Tatlıçay Basin in Cankiri, annual total nitrogen (TN) burden is 130 tons, while annual total phosphorus (TP) burden is 17 tons.

There are no flow monitoring stations performing current measurements on the Tatlıçay with 674.2 km^2 water collection basin (**Figure 2**).

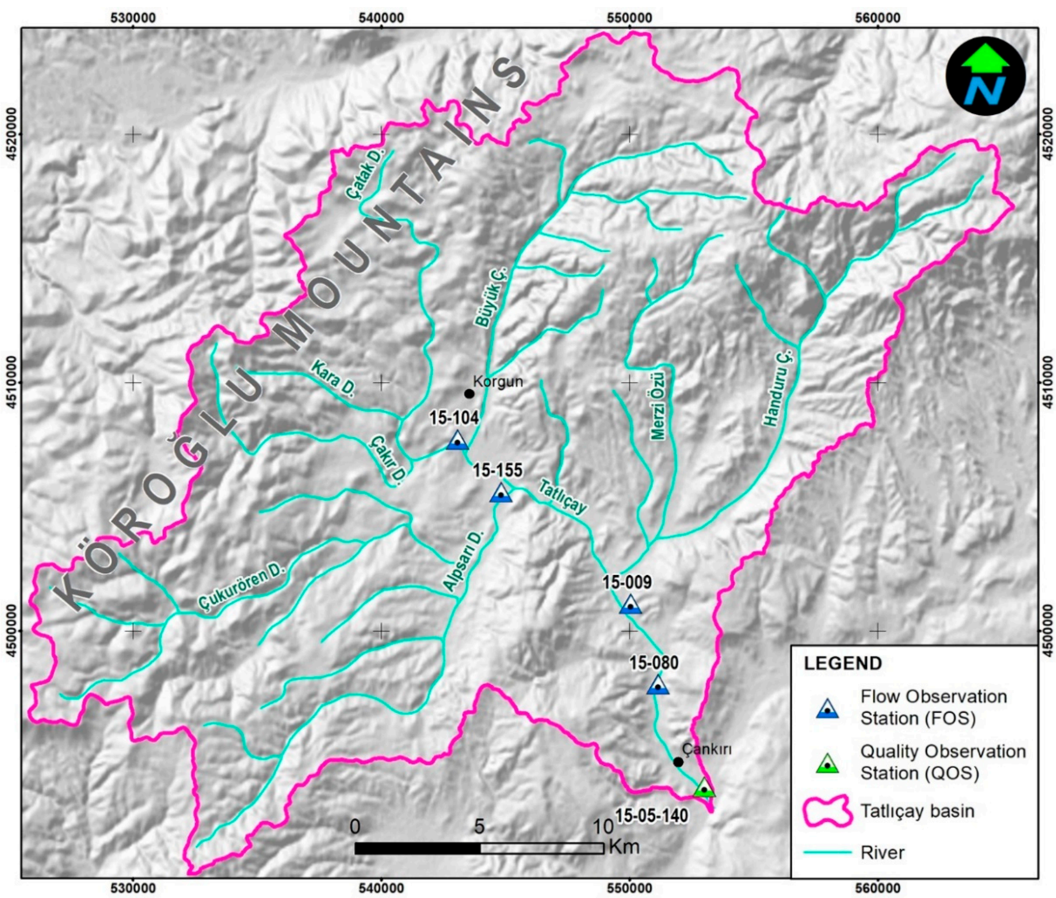

Figure 2. Location of observation stations in Tatlıçay Basin.

However, Tatlıçay water quality station no. 15-05-140 operated by the General Directorate of State Hydraulic Works (DSI) measures 400 different parameters and is located at the outlet of the Tatlıçay Basin [25]. At this station, instantaneous flow values and quality parameters were measured in monthly or 3-monthly periods from 2016 to 2020 [26].

When the total nitrogen (TN) and total phosphorus (TP) values for 2016-2019 at DSI quality monitoring station no. 15-05-140 are examined, it appears loading that may negatively affect environmental health occurred in January, February and March (**Tables 1** and **2**).

Table 1. TN loads necessary for calibration and validation (kg/month).

TN	Year	1	2	3	4	5	6	7	8	9	10	11	12
kg/month	2016	52472.0	13913.1	18519.5	4743.8	14692.7	3631.6	4535.1	3714.9	1179.2	5156.9	6834.9	4705.9
kg/month	2017	44479.1	11604.6	12848.0	4466.5	9031.1	7401.7	7191.4	4562.0	3504.0	3135.5	1556.0	3887.8
kg/month	2018	17790.6	3115.9	3449.8	4017.6	3448.7	6158.6	9450.4	5422.3	864.1	5009.0	9319.4	5558.9
kg/month	2019	31058.7	10818.0	11977.1	4466.5	9031.1	12347.0	7191.4	4562.0	6414.7			

Table 2. TP loads necessary for calibration and validation (kg/month).

TP	Year	1	2	3	4	5	6	7	8	9	10	11	12
kg/month	2016	14337.2	1026.8	1165.2	241.2	316.3	64.6	96.0	1129.7	10.4	28.1	9.6	226.6
kg/month	2017	6598.6	359.5	398.0	150.4	130.1	144.3	86.4	699.9	91.9	14.9	8.6	350.3
kg/month	2018	121.6	73.0	80.8	79.3	24.8	82.1	14.3	27.9	3.3	0.8	22.1	45.5
kg/month	2019	4376.3	499.2	552.7	150.4	130.1	18.8	86.4	699.9	320.2			

2.2. SWAT Model Application

SWAT is commonly used to assess land use, to estimate the effects of land management applications and climate change on the environment, and to assess erosion prevention and control, diffuse source pollution control and regional and watershed management. The software is frequently chosen due to rapid creation of the model, user-friendly interface, easily accessible data requirements and offering GIS solution support [16]. Models created using SWAT software pay attention to basic hydrological principles like the water cycle when assessing climatic and physical conditions together.

In the model to be created with SWAT, firstly information about the digital elevation map for the topic of the study, land use and soil properties maps, meteorological data (rainfall, temperature, relative humidity, solar radiation and mean wind speed), management implementations in the basin and ponds/reservoirs located within the study area are needed [27]. After presenting this data as input for the model, the SWAT basin is firstly divided into sub-basins and then each sub-basin is divided into units comprising homogenous land use/management, topographic features and soil properties called a hydrologic response unit (HRU) [28]. Later, the hydrological cycle is simulated on a daily basis using the equation given below.

$$SW_t = SW_0 + \Sigma R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \quad (1)$$

After accurately expressing the operation of the hydrological system in the modelled basin, negative mechanisms on the system are defined and the current status of pollution in the area may be modelled [29].

During the natural water cycle, there are natural and anthropogenic-derived pressures affecting water quality. In addition to natural events like climate change, floods, storms and earthquakes, anthropogenic-derived pressures significantly affect water quality [1]. These threats may be listed as water structures like dams, ponds, etc. that change the natural flow of water and the climatic features of the environment, bad implementations in agriculture, carbon release, unplanned urbanization and industrialization, changes to plant patterns, leaching from waste storage sites and urban discharge. The nutrient cycle is linked to chemical conversions involving nitrogen and phosphorus compounds in the soil. It is possible to model the whole nutrient cycle for nitrogen and phosphorus using the SWAT model. The nitrogen cycle is a dynamic system involving water, air and soil environments. Plants require more nitrogen than other basic elements, apart from carbon, oxygen and hydrogen. Nitrogen and phosphorus may be modelled in the soil profile and shallow aquifers by SWAT [16].

The Tatlıçay SWAT model was completed using the ArcSWAT Version 2012 developed by Texas A&M University (TAMU) operating on ArcGIS 10.5 (**Figure 3**).

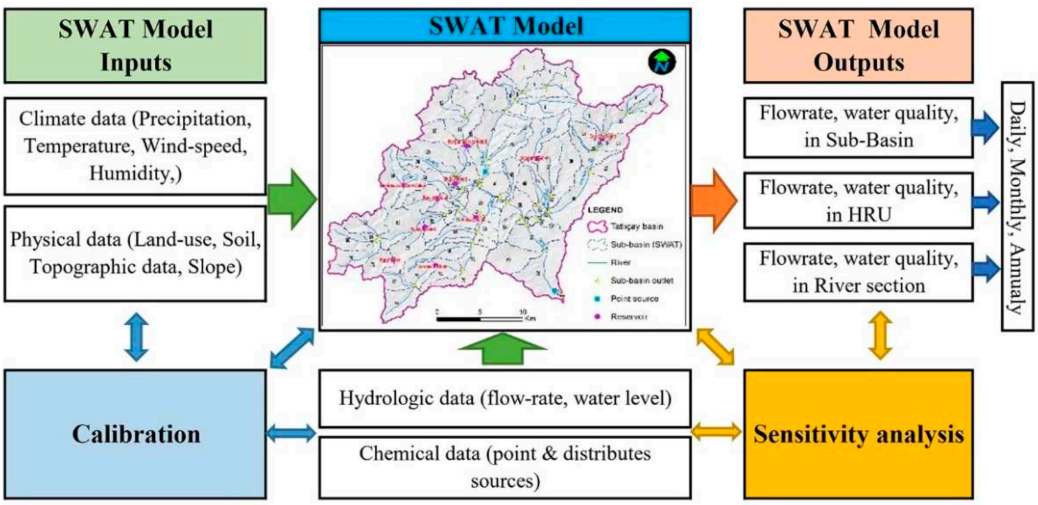

Figure 3. SWAT Model setup.

2.3. Model Setup

2.3.1. Data definition

Data and sources uploaded to the SWAT model of the Tatlıçay river ecosystem are given in **Table 3**.

Table 3. Data required for the model.

Data name	Type	Source
Digital elevation model	Raster	STRM 30
Land cover	Vector	CORINE 2018
Soil data	Vector	FAO soil data [30,31]
Climate data	Table	General Directorate of Meteorology (MGM)
Hydrological data	Table	General Directorate of State Hydraulic Works (DSI)
Point pollutant sources	Table	Turkish Statistical Institute [32,33]
Flow (m³/s)	Table	DSI
Total nitrogen load (TN)	Table	DSI
Total phosphorus load (TP)	Table	DSI

2.3.2. Watershed delineations

For the study area, 30-m resolution SRTM data from [34] was used as digital elevation model. The elevations in the Tatlıçay Basin vary from 706 m to 1848 m. Çankırı city is located at the lowest elevation in the basin (**Figure 4**).

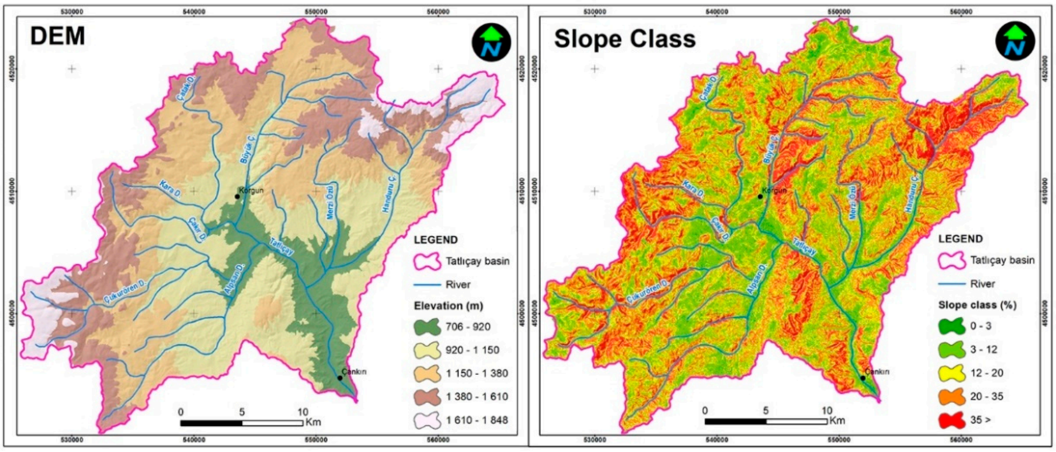

Figure 4. Topographic properties in the Tatlıçay Basin.

CORINE data prepared by the European Environment Agency (EAA) in 2018 were used to classify land cover and use in the Tatlıçay Basin [35].

For the Tatlıçay SWAT model, the basin division tool was used with DEM data in the ArcSWAT interface in the stage of dividing the basin. The basin was divided into 79 sub-basins, each with 500 ha area. Two points pollutant discharge points of Korgun and Çankırı settlements and 10 current and planned ponds were defined in the model of the basin (**Figure 5**).

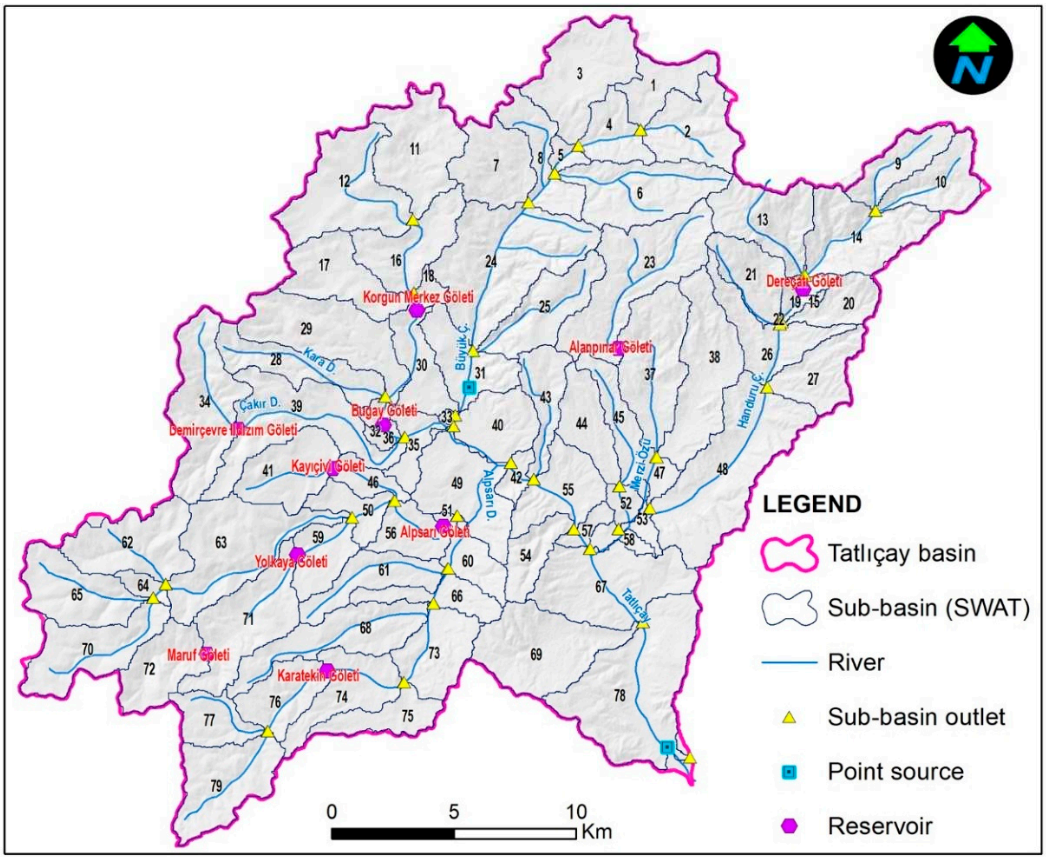

Figure 5. Reservoirs and point sources defined with sub-basins in the SWAT model.

2.3.3. HRU definition

For the Tatlıçay SWAT model, a total of 269 HRU were defined paying attention to land use, slope, soil structure data and spatial distribution [28]. The criteria used to define HRU and the flow scheme are summarized in **Figure 6**.

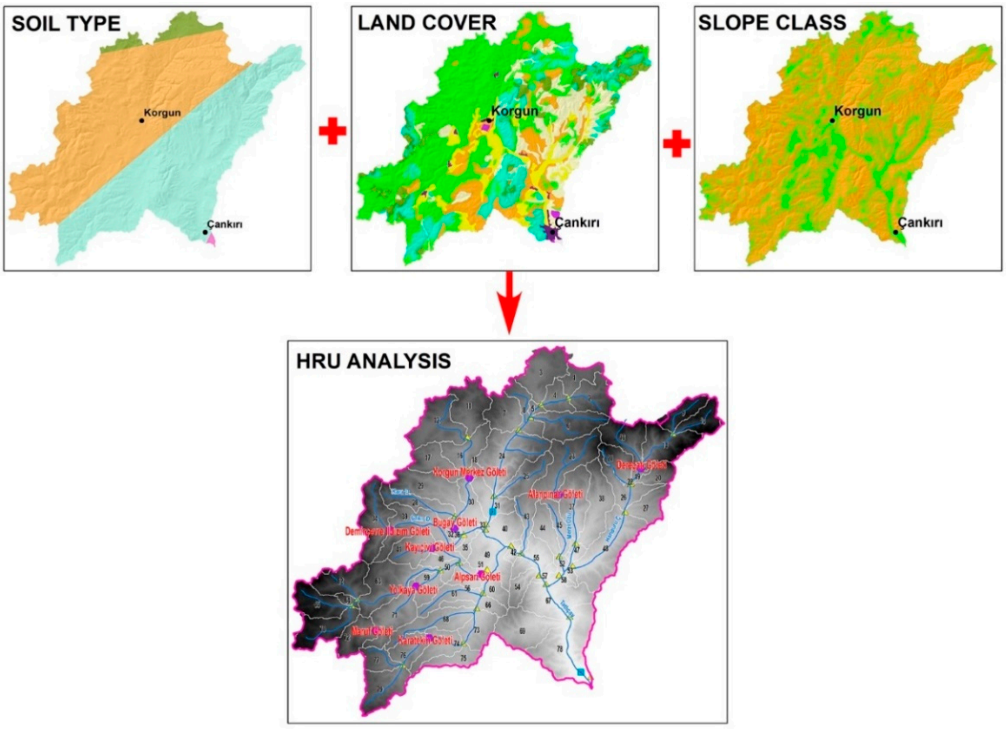

Figure 6. HRU definition scheme.

2.4. Climatic Parameters

In this study, the climatic parameter inputs for the SWAT model were obtained from meteorology station no. 17080 in Çankırı provincial center representing the basin. Hydrometeorological features used included daily rainfall (mm), temperature (max/min °C), relative humidity (%), wind speed (m/s), solar radiation (MJ/m²) and evapotranspiration (mm) for the years 2013 to 2020 (**Figure 7**).

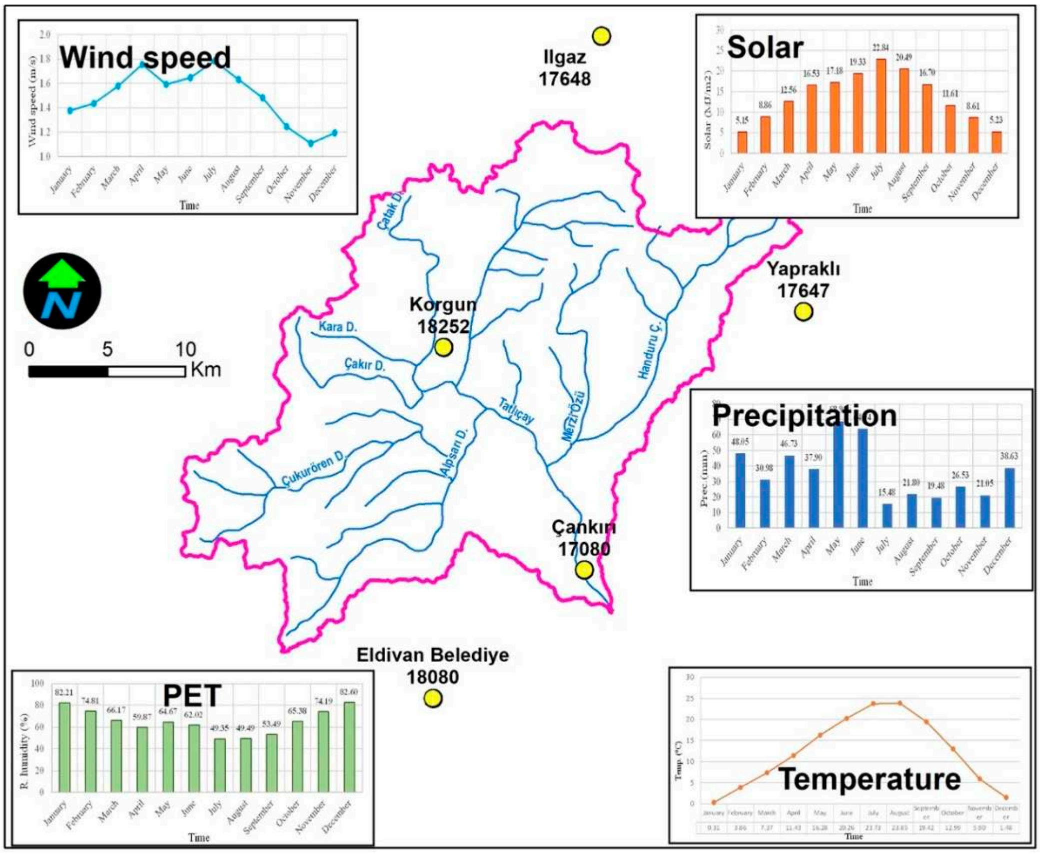

Figure 7. Use of climatic parameters.

3. Results

3.1. Sensitivity Analysis, Calibration and Validation

SWAT-CUP software was used for sensitivity analysis, calibration and validation. The SWAT-CUP software ensures analysis of basin parameters in model results with the sequential uncertainty fitting (SUFI-2) algorithm. The uncertainty concept in the SUFI-2 algorithm defines the parameter uncertainty for variables like conceptual model parameters and measured data [36]. This parameter uncertainty is defined by measures named 95PPU, d factor and p-factor [37]. The SUFI-2 algorithm in SWAT-CUP operates as shown in **Figure 8**.

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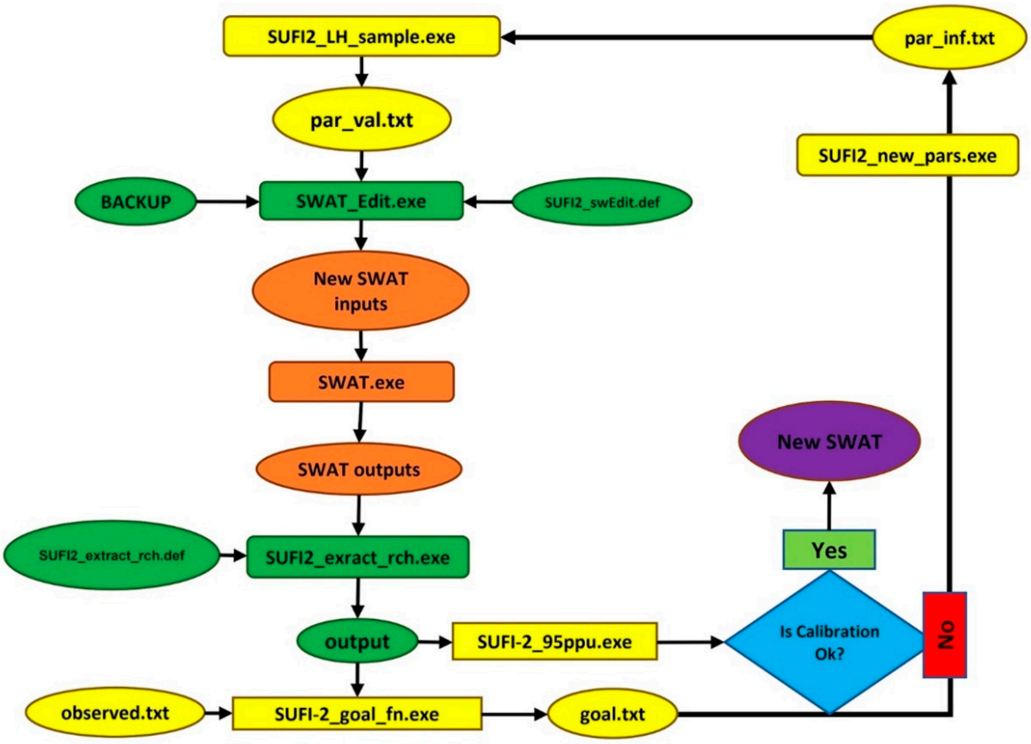

Figure 8. SUFI-2 algorithm in SWAT-CUP [38] .

The identified sensitive parameters are manually changed by (±)10% to (±)20% considering the effect on the natural system in the ArcSWAT software and transferred to the SWAT-CUP software to identify the most appropriate values for the parameters.

With sensitivity analysis, the parameters ALPHA_BF, ESCO, GWQMN, ESCO, SLSUBSN, and HRU_SLP were identified to be sensitive (**Table 4**). It appears that these parameters directly affected the surface flow and nutrient matter (TN and TP) burden.

Table 4. Sensitive parameters in the model.

No	Parameter	Data	Explanation
1	ALPHA_BF	.gw	Base flow alpha value (1/day)
2	GWQMN	.gw	Necessary threshold water depth for return flow to shallow aquifer due to irrigation (mm H_2O)
3	GW_DELAY	.gw	Groundwater delay (days)
4	SLSUBSN	.hru	Soil depth from surface to lower level (mm)
5	HRU_SLP	.hru	HRU mean slope steepness (m/m)
6	ESCO	.hru	Soil evaporation equilibration factor

According to the value intervals given in **Table 5**, 1000 runs were performed using the SUFI-2 algorithm with SWAT-CUP software and fit values were found.

Table 5. SWAT-CUP parameter values.

No	Parameter name	Min_value	Max_value	Fit value
1	r__ALPHA_BF.gw	-0.2	0.2	-0.1642
2	v__GW_DELAY.gw	200	300	264.55
3	r__GWQMN.gw	-0.2	0.2	0.161
5	r__SLSUBBSN.hru	-0.2	0.2	0.0782
6	r__HRU_SLP.hru	-0.2	0.2	0.1498
7	r__ESCO.hru	-0.2	0.2	0.011

When the success statistics for the model according to SUFI-2 algorithm in SWAT-CUP software for the time periods for calibration and validation of 2016-2017 and 2018-2019, respectively, are investigated, though the observation data are for a short period, the model appears to provide successful results.

The calibration and validation stages in modelling applications assess the model performance statistics based on connection values between the observed and model outcomes. In hydrological models, it is recommended to use the Nash-Sutcliff efficacy statistic-NSE [39], coefficient of prominence (R^2) and percentage error statistic (PBIAS), along with both direct and derived statistical methods to more comprehensively assess model performance and ensure reliability of model outputs [40]. **Table 6** gives the interval values for model success statistics for flow and nutrient matter SWAT models.

Table 6. SWAT model success statistics [40,41].

Parameter	Model Success			
	Very good	Good	Satisfactory	Failed
		Flow model		
R^2	R2 > 0.85	0.75 < R2 ≤ 0.85	0.60 < R2 ≤ 0.75	R2 ≤ 0.60
NSE	NSE > 0.80	0.70 < NSE ≤ 0.80	0.50 < NSE ≤ 0.70	NSE ≤ 0.50
PBIAS	PBIAS < ± 10	± 10 < PBIAS ≤ ± 15	± 15< PBIAS ≤ ± 25	PBIAS ≥ ± 25
		Nutrient model (N, P)		
R^2	R2 > 0.70	0.60 < R2 ≤ 0.70	0.30 < R2 ≤ 0.60	R2 ≤ 0.30
NSE	NSE > 0.65	0.50 < NSE ≤ 0.65	0.35 < NSE ≤ 0.50	NSE ≤ 0.35
PBIAS	PBIAS < ± 25	± 25 < PBIAS ≤ ± 40	± 40 < PBIAS ≤ ± 70	PBIAS ≥ ±70

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (2)$$

O_t: Observed value
P_i: Calculated value
$\bar{O}$: Variance of observed value

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})^2}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \quad (3)$$

O_t: Observed value
P_i: Calculated value
$\bar{O}$: Variance of observed value
$\bar{P}$: Variance of calculated value

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$$PBIAS = \frac{\sum_{i=1}^{n} O_i - P_i}{\sum_{i=1}^{n} O_i} x100 \quad (4)$$

O_i: Observed value

P_i: Calculated value

Using the SUFI-2 algorithm with the SWAT-CUP software, 1000 runs were performed. It was identified that the values obtained as a result of the 792nd run provided the best performance. The performance statistics (R^2, NSE and PBIAS) for the SWAT-CUP models for flow, TN and TP are presented in **Table 7**.

Table 7. SWAT-CUP model performance.

	Flow		TN		TP	
Calibration	R2	0.64	R2	0.56	R2	0.63
	NSE	0.60	NSE	0.55	NSE	0.60
	PBIAS	15.4	PBIAS	7.2	PBIAS	29.8
Validation	R2	0.81	R2	0.39	R2	0.34
	NSE	0.66	NSE	0.04	NSE	0.17
	PBIAS	-2.1	PBIAS	-10.0	PBIAS	-43.9

4. Discussion

In this study, the sample study area of Tatlıçay river ecosystem located within Çankırı province in the Central Anatolia region of Türkiye was modelled with the hydrological modelling SWAT software. There is no flow monitoring station recording daily in the Tatlıçay Basin. There is one quality monitoring station measuring at monthly periods located at the outlet of the Çankırı basin. The lack of one or more stations providing current daily data over many years lowers model quality. For modelling of the Tatlıçay river ecosystem, the model was set up with flow and nutrient matter (TN and TP) data from the quality monitoring station in Çankırı city center.

4.1. Flow Model

The calibration and validation results for the flow model from 2016-2020 and comparative graph with rainfall are given in **Figure 9**. The mean flow distribution for the whole river ecosystem from 2016-2020 is presented in **Figure 10**.

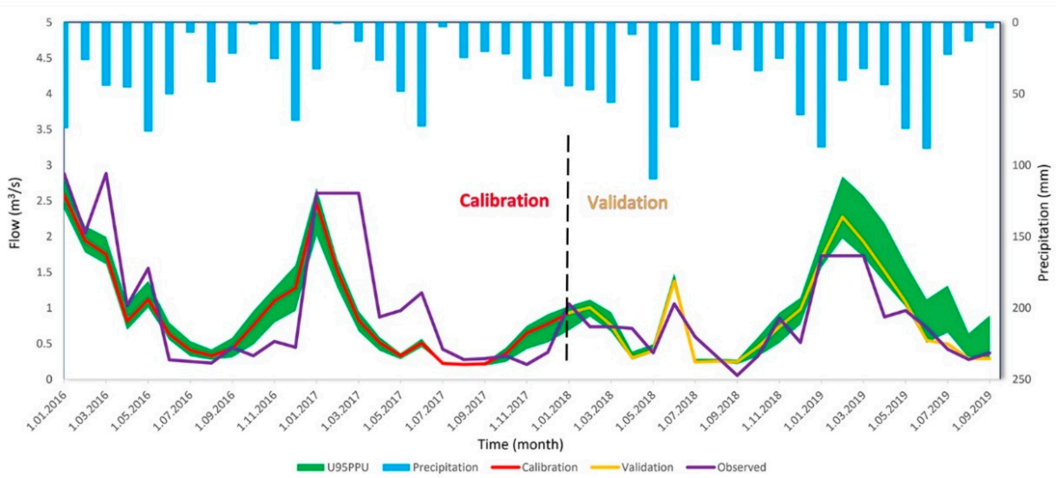

Figure 9. Calibration and validation results for flow model.

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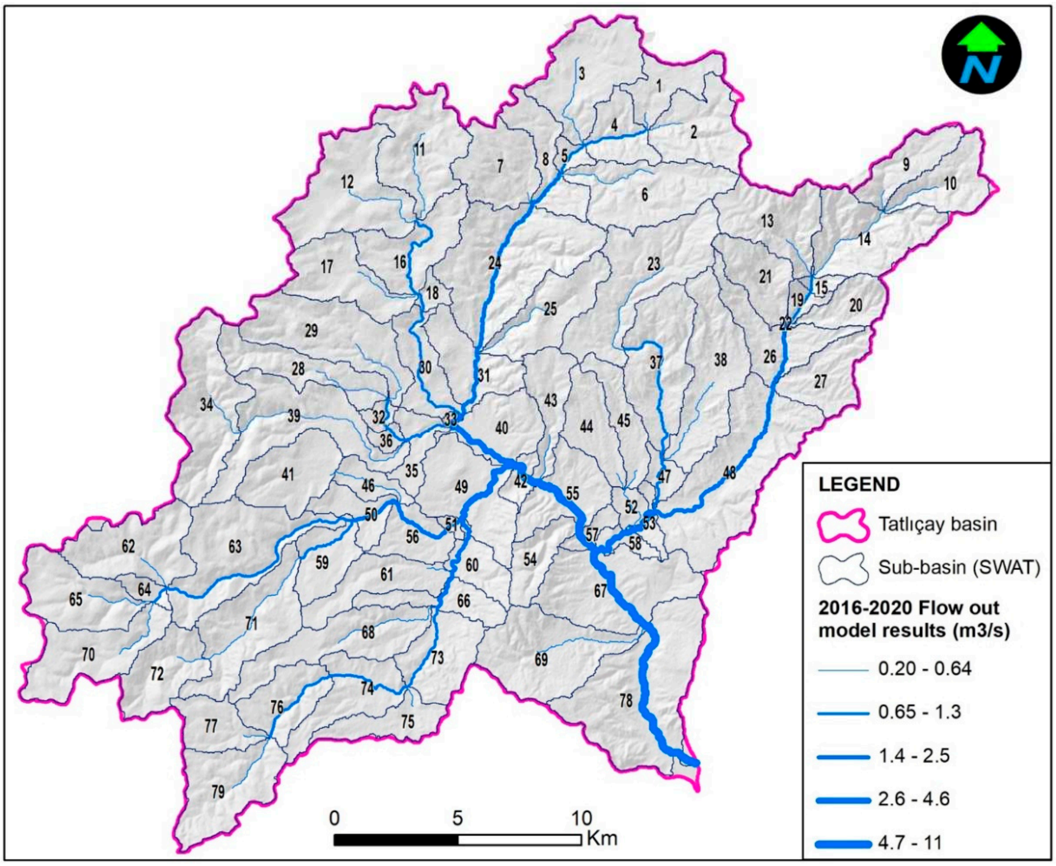

Figure 10. Flow model for Tatlıçay river ecosystem.

The model success statistics for calibration and validation results of the flow model were compared. The R^2 values in the validation stage appeared to increase compared to the calibration stage. This increase in R^2 means that the model's capacity to estimate the future increased during validation [42]. In the validation stage, the NSE value appeared to increase compared to the calibration stage. This increase in the NSE value means the accuracy rate for model predictions were higher than during the validation process. The PBIAS value during calibration showed the model data overestimated compared to the observed data. However, though this value reduced in a negative way during the validation stage, it was close to 0 at the end of calibration, so it may be said to make successful predictions [43].

When flow model results are compared to monthly mean rainfall data from Çankırı Meteorological Monitoring station (MMS), it appears the flow in the river ecosystem was compatible with rainfall data (see **Figure 9**). Considering the whole river ecosystem given in **Figure 10**, the continuation of regular accumulation of flow in all river tributaries supports this situation.

4.2. Nutrient (TN and TP) Pollution Model Findings

The calibration and validation results for the TN model from 2016-2020 and comparison with rainfall graphs are given in **Figure 11**, with the same comparison for the TP model given in **Figure 12**.

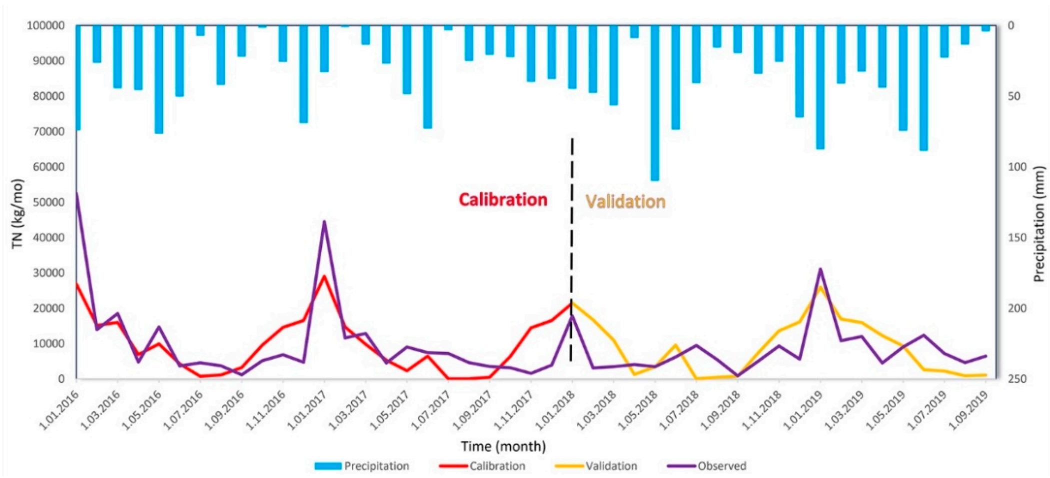

Figure 11. Calibration and validation results for TN model.

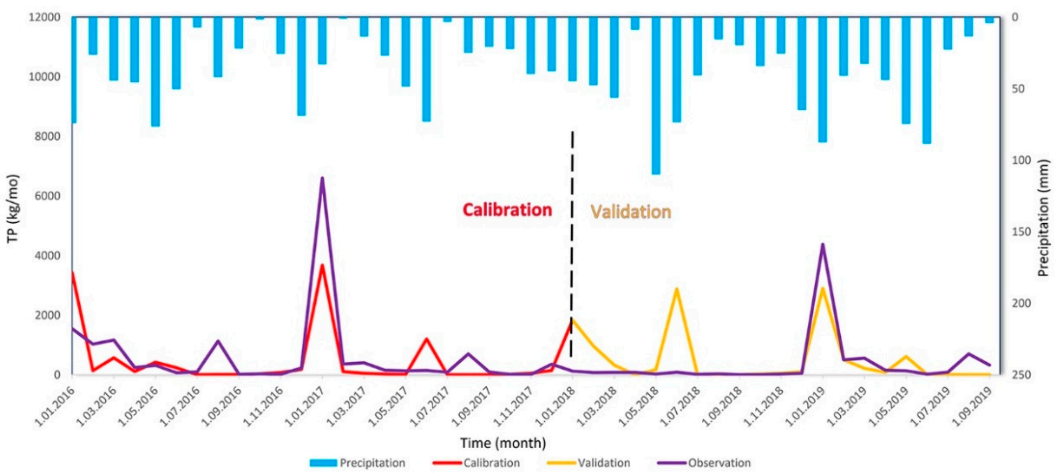

Figure 12. Calibration and validation results for TP model.

When the model statistics for calibration and validation results for the TP and TN models are compared, the R^2 value in the validation stage appears to reduce compared to the calibration stage. This means the model had reduced estimation capacity for the future [44]. The NSE value in the validation stage was calculated to be lower compared to the calibration stage. This situation was accepted as valid considering other statistical performances due to the shortness of the model period, though it means there were deviations in the predictions. In the calibration stage, the PBIAS value showed predictions were at higher values than the observed data, while in the validation stage, values were predicted to be much lower than the observed values.

When the TN and TP model results are compared with the monthly mean rainfall data from Çankırı MMS, it appears the TN and TP in the river ecosystem were not compatible with the rainfall data (see **Figures 11** and **12**). Considering the whole river system, the TN and TP burden in all stream tributaries increased in town centers and in the main branch of the Tatlıçay with low slope.

This modelling study obtained successful results in the calibration and validation process with very few observed data. When the model results are assessed, it appears the sources of the TN and TP burden in the Tatlıçay are anthropogenic effects like agricultural activities and urban discharge [43,45,46].

5. Conclusions

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

Water is one of the most important headings in the environmental health area. This study was performed with the aim of presenting alternative solution recommendations and investigating the behavior of water in nature, distribution and sources of pollutants disrupting water quality by using a hydrological model for prediction and monitoring of problems that may occur related to water quality. In line with this a SWAT model was calibrated and validated with acceptable error statistics for the Tatlıçay river ecosystem. Model calibration studies obtained high accuracy rate even for the Tatlıçay basin, with few measurement stations providing flow and water quality data. A model emerged that may produce effective solutions in future scenarios and in negative situations that threaten environmental health.

The topic of hydrological modelling with high accuracy, even in areas where water quality cannot be measured or is difficult to measure, is included in the literature mainly in engineering fields like hydrology, hydrogeology, construction and environmental engineering. Additionally, hydrological modelling with water quality studies are included in the global environmental health literature. However, in Türkiye, there are academic studies about determining point water quality in certain regions and national and local projects like the Environmental Health Information System. With this research, a great contribution is offered to the environmental health literature, with very few examples in Türkiye about the topic of hydrological modelling. Additionally, hydrological models included in ecosystem-based water quality management will benefit the development of information systems for national and local administrations.

Due to surface water models being dynamic, accuracy rates of predictions should be improved by long-term daily or monthly flow and water quality measurements. Additionally, uncertainties should be resolved and effect assessments should be performed for pollutant sources disrupting environmental health.

The model results show the causes of poor water quality in the Tatlıçay river system are urban discharge and agricultural use. To prevent these causes of poor water quality in the Tatlıçay basin, it is recommended to construct packet water treatment facilities in settlement areas with dense population and water treatment facilities according to future population projections for Çankırı provincial center. Additionally, it is recommended to perform good agricultural practices for fertilization and irrigation implementations during agricultural activities.

Supplementary Materials: “Not applicable”

Author Contributions: This study is an original research article that has been prepared for publication by compiling the outstanding results of the master's thesis titled as “*Application of SWAT Model In Water Quality Assessment In The Lotic Ecosystem: A Case Study In Tatlıçay Basin (Çankırı, Türkiye)*” conducted by the first author Eren Germeç, under the supervision of Okan Ürker. All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Eren Germeç and Okan Ürker. The first draft of the manuscript was written by Eren Germeç and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. Research and publication ethics were complied with during the study. We declare that the figure or figures obtained from external sources within the study are materials that do not require copyright permission, by citing the relevant source.

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Institutional Review Board Statement: “Not applicable”

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Data Availability Statement: The data used to support the findings of this study are included within the manuscript. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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