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Evaluation of the SWAT Model With Respect to Different Variables Within the Tomebamba River Sub-Basin Belonging to the Paute River Basin, Ecuador

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Abstract: The objective of this study is to evaluate the efficiency of the SWAT model with respect to simulations of nitrates, organic phosphorus, dissolved oxygen, sediments and evapotranspiration, taking as reference data observed in continuous monitoring stations. The results showed that the correlation between the simulated and observed data is practically null if a linear relationship were established between them (Pearson correlation coefficient). On the other hand, the simulations overestimated the values of evapotranspiration, dissolved oxygen and sediments; and underestimated the values of nitrates and organic phosphorus, according to the PBIAS%. The RSR statistical criterion indicates that the performance of the modeling is unsatisfactory for nitrates, evapotranspiration and dissolved oxygen; and it is very good for organic phosphorus and the sediments of the Llaviuco station, which was verified with the application of the NSE statistical criterion. It is very important to pay attention to the initial calibration of the model.

Key words: SWAT, Paute, hydrological models

1. Introduction

In Ecuador, the Paute river basin is one of the most monitored due to its importance for the generation of hydroelectric power [1]. However, in recent years there have been problems related to the dry season that limit the distribution of electrical energy for industrial and domestic purposes [2]. When referring to the Paute River basin, studies have been carried out on population density, land use and coverage, housing density, density of farmers and manufacturers in the basin [3].

Thus, the main problem related to power generation projects is water quality, especially due to suspended solids that cause wear on hydromechanical equipment and the dragging of sediments that shorten the useful life of reservoirs [4], because the contamination of the water resource has gradually increased due to the discharge of urban, domestic, commercial and service waste in a large part of the Paute River basin, especially in those human settlements where there is greater urban activity. This is demonstrated by the monitoring carried out by the company ETAPA, which indicates a decrease in water quality in urban areas, since measurements were made in the upstream sections and in sections of rivers that cross the city of Cuenca (occupies 41.22% of the province) Obtaining data that showed that the quality indexes descend from an excellent-good classification for the high sections,

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to a good-medium in low sections [1].

Therefore, it is necessary to carry out studies of the environmental impacts generated by anthropogenic activities located within the basin in order to determine management strategies and protection of the water resource, starting with the micro-basins and their tributaries until reaching a higher level.

One of the hydrological models to forecast the impact of a land use is SWAT (Soil and Water Assessment Tool). SWAT is based on a water balance to determine the input, output and storage of water in the basin. For modeling, the hydrographic basin is divided into small sub-basins in order to improve the accuracy of the calculations. In Costa Rica, the model has been developed in some basins with results validated in the field [5]. This model has a physical and computationally efficient basis and requires the entry of data that is easy to obtain on official web pages, and also allows the study of a basin over long periods of time, which is a significant advantage (as well as intuitive use) for use in this study as it represents a tool to predict the effect of decisions about the management of the country's natural resources.

2. Material and Methods

The SWAT (Soil and Water Assessment Tool) model is a continuous-time, semi-distributed, process-based river basin model [6]. It works as a physically based hydrological model, it can simulate the processes that take place within the hydrological cycle. This tool allows simulating the hydrological cycle, either its surface flow in the basin or the one-dimensional flow of the main river and all its tributaries. Likewise, it allows simulating the state of water quality in the basin.

This model is continuous on a temporal scale, because it allows simulating long periods of time, whether months or years, of the processes of the hydrological cycle. It also allows identifying the information of smaller areas within the basin. First-hand, it is possible to divide the basin into sub-basins, allowing different zones within it to be differentiated.

Groups of HRUs (hydrological response units) are presented, which are subdivisions of smaller size within the sub-basin, the HRUs are grouped by similar characteristics, to better differentiate them. Thus, this model simulates the hydrological processes within each of them, organizing them by climate, groundwater, runoff routes, and drainage of the basin.

All the simulation within the model takes shape by making a balance of all the processes represented, thus constituting the basis for modeling several more physical and chemical processes, which will be influenced by the continuous interaction of all the processes of the hydrological cycle with each other. We can mention that by ground phase we will have: dragging of sediments, pesticides, nutrients and bacteria, in the conduction phase instead: discharges and transport of pesticides, bacteria, nutrients, etc. Considering that these will happen in the main channels of each sub-basin or of the main basin.

2.1 Case Study

This study has been developed on the Paute River Basin, with an area of 5645 km^2 and UTM coordinates 9745508N, 802130 E, whose origin is in the Andean region just before its mouth in the Amazon basin, found entirely in the province of Azuay, a part in the province of Cañar and minimal areas in the provinces of Chimborazo and Morona Santiago [7]. The altitude of the basin varies from 2,000 to 4,400 meters above sea level, and it is home to the third largest city in Ecuador: Cuenca.

The Paute River basin is characterized by a strong relief and a complex hydro-meteorological regime, which make it a very heterogeneous area. It is subject to the influence of two defined pluviometric regimes: one coming from the Amazon zone over two thirds of the eastern zone of the basin, with rains well distributed throughout the year; and one from the Andean regime in the western zone [8].

The study area focuses specifically on the Tomebamba River sub-basin, whose hydrographic surface is comprised of the micro-basins of the Llaviuco and Matadero Rivers (in Sayausí) together with the urban sector known as Monay, al cual confluyen los tributarios de las subcuencas de los ríos Yanuncay, Tarqui y Tomebamba [9].

The study carried out on the Tomebamba River sub-basin started from the simulations obtained in SWAT, which require the introduction of initial cartographic and hydrometeorological elements. It was considered first, an Elevation Model (MED) was introduced, extracted from the official Earth Data Search website belonging to NASA, together with a water network in the province of Azuay. Next, the types and uses of soil within the hydrographic basin were established, with which the hydrological reference units (HRU) were obtained. Finally, SWAT Editor is used to process meteorological data such as temperature, relative humidity, wind speed, precipitation and solar radiation, obtained from the Global Weather Data for SWAT website; with which the simulations of the desired parameters are run, in this case they will be: nitrates, concentration of total settleable solids, organic phosphorus, potential evapotranspiration and dissolved oxygen.

Subsequently, a comparison of the simulated data was made with those observed in studies carried out on the Tomebamba River sub-basin, establishing different monitoring stations, which are:

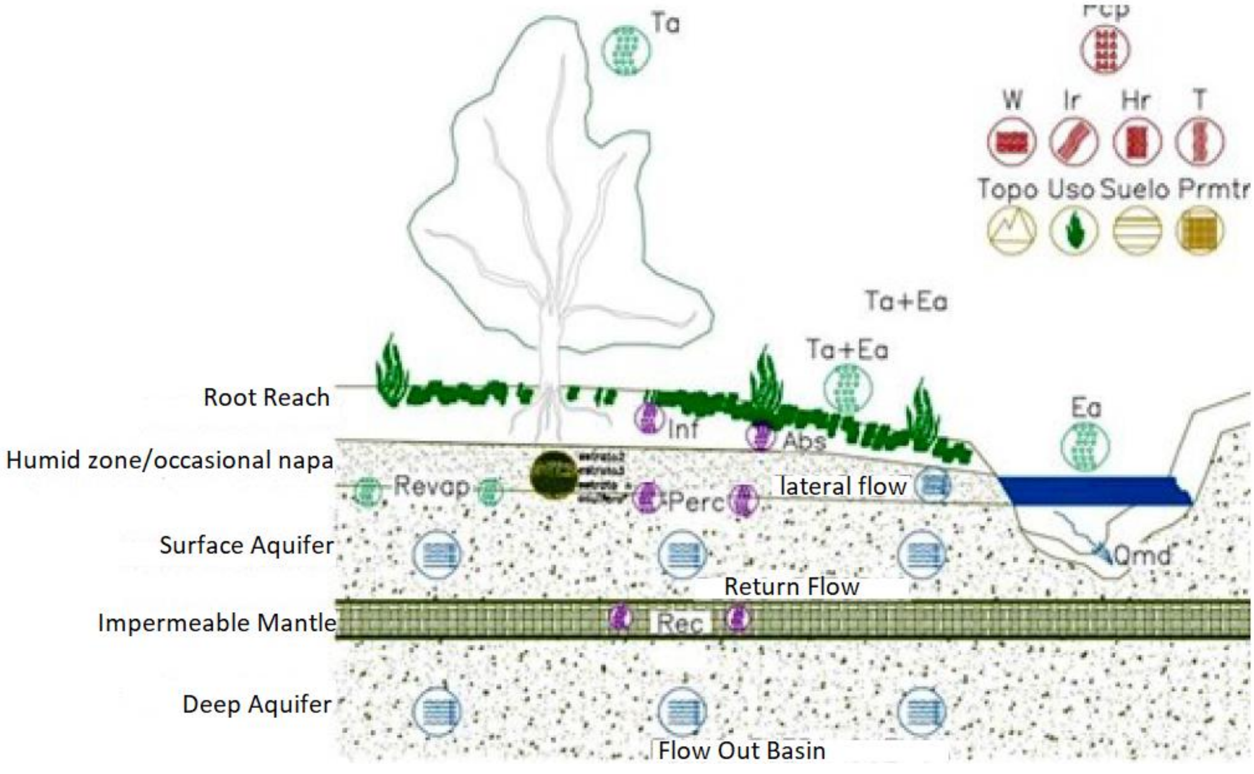

Fig. 1 Hydrological cycle processes in SWAT (adapted from Neitsch et al., 2011)

3. Results and Discussion

3.1 Nitrate Concentration

When performing a contrast between the simulated and observed data for each parameter evaluated in relation to a given period of time, the following results (Table 2) are obtained.

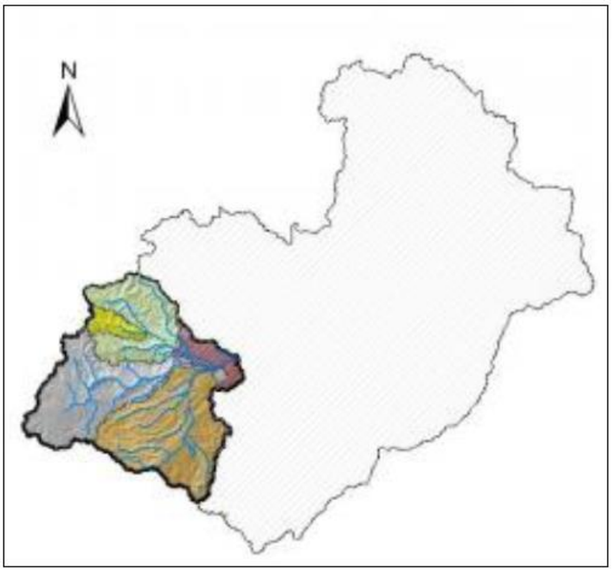

Fig. 2 Location of the Tomebamba river sub-basin within the Paute river basin.

Table 1 Location of monitoring stations within the Tomebamba River sub-basin [10].

Code	Station	Coordinates UTM Zone 17S	
		Este	Norte
LL	Llaviuco	706707	9686019
MS	Matadero en Sayausi	712673	9683055
TM	Tomebamba en Monay	726402	9680352

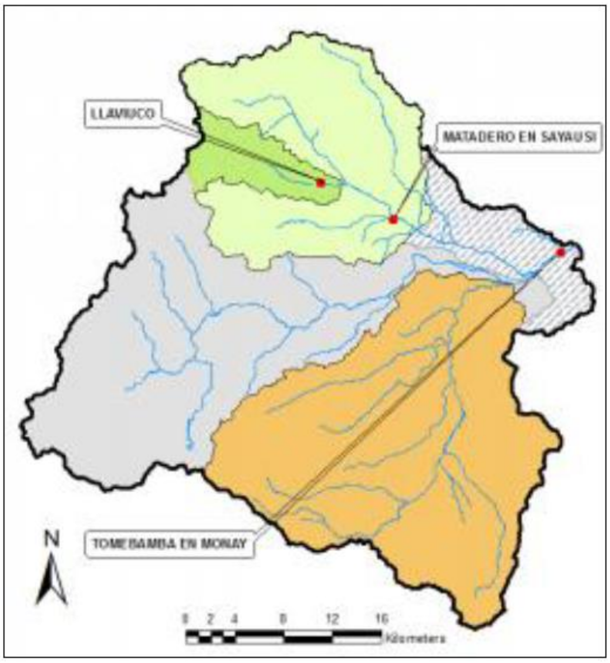

Fig. 3 Location of the monitoring stations within the Tomebamba River sub-basin.

Table 2 Nitrate concentration (mg/l) in the Tomebamba River sub-basin in the period September 2010 to July 2011.

	Simulated data			Observed data		
	LL	MS	TM	LL	MS	TM
15 Sep. 2010	0.0217	0.0269	0.016	0.13	0.12	0.77
27 Sep. 2010	0.0301	0.0333	0.0234	0.16	0.11	0.74
6 Oct. 2010	0.126	0.146	0.0917	0	0.05	0.51
15 Oct. 2010	0.0293	0.0351	0.0218	0.16	0.18	1.1
27 Oct. 2010	0.0491	0.0543	0.0328	0.01	0	0.57
10 Nov. 2010	0.0386	0.0452	0.0297	0.3	0.07	1.05
22 Nov. 2010	0.0305	0.0345	0.022	0.04	0.11	0.4
1 Dec. 2010	0.0182	0.0204	0.0133	0.03	0.17	0.57
5 Jan. 2011	0.0258	0.0299	0.0229	0	0	0.16
12 Jan. 2011	0.0237	0.027	0.0211	0.07	0.08	0.2
31 Jan. 2011	0.0334	0.0383	0.416	0.04	0.06	0.37
9 Feb. 2011	0.0112	0.0284	0.045	0.04	0.03	0.17
14 Feb. 2011	0.0109	0.0156	0.022	0.06	0.09	0.2
28 Feb. 2011	0.00637	0.0069	0.008	0.07	0.02	0.36
10 Mar. 2011	0.00546	0.00602	0.00635	0.29	0.12	0.44
24 Mar. 2011	0.00259	0.00271	0.00363	0.23	0.26	0.39
6 Apr. 2011	0.00187	0.00188	0.00226	0	0	0.24
13 Apr. 2011	0.00312	0.00332	0.00326	0.05	0.2	0.27
20 Apr. 2011	0.00244	0.0026	0.00272	0.04	0.01	0.44
4 May 2011	0.00214	0.00239	0.00301	0	0.13	0.23
18 May 2011	0.000742	0.000794	0.00119	0	0.13	0.12
1 June 2011	0.000517	0.00056	0.000723	0	0	0.05
14 June 2011	0.000341	0.000361	0.000532	0.17	0.04	0.28
29 June 2011	0.0118	0.0174	0.00643	0.07	0	0.06
13 July 2011	0.0195	0.386	0.243	0.03	0.16	0.26

It is observed that the concentrations simulated by the program are lower than those recorded by the monitoring stations, we see a high concentration of nitrates in the months of September to December of the year considered.

3.2 Sedimentable Solids Concentration

As we observe in the results, the simulated total sedimentable solids, show to be close to those observed during a period of 11 months, there are few observed values that exceed 400 mg/l sediment, while in the simulated concentrations with values higher than 400 are more frequent.

Table 3 Concentration of total sedimentable solids (mg/l) in the Tomebamba River sub-basin in the period from September 2010 to July 2011.

	Simulated data			Observed data		
	LL	MS	TM	LL	MS	TM
Sep. 2010	245	271	236	235	287	256
Oct. 2010	332	370	316	335	372	357
Nov. 2010	431	448	418	397	415	447
Dec. 2010	481	494	469	372	385	434
Jan. 2011	403	435	384	384	370	390
Feb. 2011	345	376	330	338	356	364
Mar. 2011	266	293	260	292	308	344
Apr. 2011	377	422	357	322	406	409
May 2011	244	270	241	240	306	308
June 2011	162	172	171	208	283	310
July 2011	115	126	115	130	146	149

3.3 Organic Phosphorus Concentration

For the analysis of organic phosphorus present in the water of the riverbeds, data is available for only 2 months of the year 2011 and one of 2014, observing that both the simulation and the data recorded in the stations obtained a value of zero for the concentration of this element in June 2014.

Table 4 Organic phosphorus concentration (mg/l) in the Tomebamba River sub-basin in the period from June 2011 to June 2014.

	Simulated data			Observed data		
	LL	MS	TM	LL	MS	TM
15 June 2011	0.0504	0.0674	0.923	0.05	0.07	0.97
29 June 2011	0.237	0.166	1.21	0.26	0.18	1.12
23 June 2014	0	0	0	0	0	0

3.4 Potential Evapotranspiration

The analysis of evapotranspiration in the basin was carried out only based on the Tomebamba station in Monay due to the absence of data from other stations, where it can be seen that most of them are around 2mm. Furthermore, the simulation data shows to be much more variable over time compared to the data recorded by the monitoring stations.

Table 5 Potential evapotranspiration (mm) in the Tomebamba River sub-basin in the period September 2010 to July 2011.

	Simulated data	Observed data
	TM	TM
15 Sep. 2010	2.95	2.34
27 Sep. 2010	2.68	2.34
6 Oct. 2010	2.28	2.46
15 Oct. 2010	2.23	2.46
27 Oct. 2010	2.33	2.46
10 Nov. 2010	1.94	2.53
22 Nov. 2010	1.82	2.53
1 Dec. 2010	1.34	2.5
5 Jan. 2011	2.16	2.39
12 Jan. 2011	2.88	2.39
31 Jan. 2011	2.54	2.39
9 Feb. 2011	2.23	2.34
14 Feb. 2011	2.6	2.34
28 Feb. 2011	2.45	2.34
10 Mar. 2011	2.1	2.31
24 Mar. 2011	1.88	2.31
6 Apr. 2011	2.34	2.2
13 Apr. 2011	2.33	2.2
20 Apr. 2011	2.84	2.2
4 May 2011	2.9	2.08
18 May 2011	2.58	2.08
1 June 2011	2.68	1.95
14 June 2011	2.95	1.95
29 June 2011	1.98	1.95
13 July 2011	1.92	1.96

3.5 Dissolved Oxygen

Dissolved oxygen has a very different behavior between both series of data, since the simulation yields data in most cases, very close together for stations on the same day, possibly this will happen, because it is the same stretch of river, but at different sampling points; however, the observed data turns out to be individual for each station and in many cases they do not coincide.

Table 6 Dissolved oxygen (mg/l) in the Tomebamba River sub-basin from September 2010 to July 2011.

	Simulated data			Observed data		
	LL	MS	TM	LL	MS	TM
15 Sep. 2010	9.91	9.91	9.9	8.6	8.1	6.25
27 Sep. 2010	9.06	8.79	8.99	9.31	8.27	7.8
6 Oct. 2010	9.83	9.83	9.83	6.6	7.74	6.89
15 Oct. 2010	8.93	8.93	8.93	7.35	7.48	7.82
27 Oct. 2010	10.3	10.3	10.3	7.31	7.55	8.03
10 Nov. 2010	10.1	10.1	9.8	8.27	7.7	8.61
22 Nov. 2010	8.93	8.93	8.93	7.91	7.52	7.04
1 Dec. 2010	10.6	10.6	10.6	9.5	8.37	7.21
5 Jan. 2011	8.77	8.77	8.76	7.6	8.13	7.74
12 Jan. 2011	8.9	8.9	8.86	7.1	7.68	8.18
31 Jan. 2011	9.14	9.12	9.12	7.25	7.63	7.64
9 Feb. 2011	8.79	8.79	8.79	7.37	8.23	7.62
14 Feb. 2011	8.73	8.73	8.73	6.86	7.98	7.9
28 Feb. 2011	8.58	8.58	7.81	7.02	7.8	7.3
7.310 Mar. 2011	8.86	8.86	8.86	7.34	7.98	7.74
24 Mar. 2011	6.7	4.78	1.41	8.04	8.15	6.97
6 Apr. 2011	8.76	8.76	8.72	6.76	8.54	0
13 Apr. 2011	4.89	1.62	6.02	7.31	7.92	7.55
20 Apr. 2011	6.79	9.39	9.24	6.8	8.27	8.04
4 May 2011	8.6	8.6	8.6	7.03	7.94	7.83
18 May 2011	8.91	8.91	8.91	6.76	7.3	7.28
1 June 2011	8.88	8.88	8.88	12.4	16.8	8.23
14 June 2011	8.62	8.62	8.62	6.92	8.05	7.95
29 June 2011	8.77	8.76	8.76	9.22	7.92	7.63
13 July 2011	9.12	9.12	5.87	8.28	8.62	8.42

3.6 Pearson Correlation Coefficient

Subsequently, a formal comparison was made between the simulated data and the observed data by using several statistical criteria, among which is the Pearson correlation coefficient.

The most common method of determining if there is a linear association between two continuous quantitative variables is the Pearson Correlation Analysis. With this method, the Pearson Correlation Coefficient is obtained, usually represented by the letter R. Since a sample is usually used, what you actually get is an estimate of the population correlation coefficient, r [11].

For the case study, the Pearson correlation coefficients are established in the Table 7.

Table 7 Pearson's correlation coefficient between the variables defined as simulated data and observed data of the parameters evaluated in 3 monitoring stations of the Tomebamba River sub-basin.

Parameter	Station		
	LL	MS	TM
Nitrates	-0.10	0.14	-0.01
Sediment	0.955	0.915	0.915
Organic phosphorus	0.9998	0.9998	0.9945
Evapotranspiration			-0.337
Dissolved oxygen	0.1945	0.0153	0.0065

Pearson's correlation coefficient varies markedly from one parameter to another, but in general it can be noted that for nitrates, dissolved oxygen and evapotranspiration the relationship between the observed and simulated data is quite low or almost null; while for sediments and organic phosphorus, the correlation is almost perfect. Despite this, the value of this statistic for organic phosphorus may be questionable, since only three data are analyzed, which are insufficient to show an acceptable correlation.

At the same time, statistics associated with the performance criteria of the SWAT model developed by Moriasi were calculated, finding that the PBIAS or percentage bias, measures the trend of simulated data, if they are higher or lower in relation to the measured or observed data, being its optimal value 0% for a very precise modeling, positive values reveal an underestimation of the model and negative values an overestimation of the model. The RSR or standard deviation of the observations, the lower it is, better will be the model performance; whose value of zero corresponds to a perfect simulation with zero residual variation. Another of the statistics used is called NSE or Nash-Sutcliffe efficiency, which indicates how well the graph of the observed versus simulated data fits a 1:1 ratio linevalues between 0 and 1 are considered acceptable for a model, while values less than 0 show an unacceptable performance of the model [12].

The Moriasi valuation scheme to evaluate the performance of a hydrological model, is given by the following reference.

Valoración del desempeño	Estadisticos recomendados				
	RSR	NSE	PBIAS%		
			Escorrentía	Sedimento	N,P
Muy Buena	[0,0-0,5]	(0,75-1,00]	< ±10	< ±15	< ±25
Buena	(0,5-0,6]	(0,65-075]	[±10 - ±15)	[±15 - ±30)	[±25 - ±40)
Satisfactoria	(0,6-0,7]	(0,50-0,65]	(±15 - ±25)	(±30 - ±55)	(±40 - ±70)
Insatisfactoria	> 0,7	< 0,50	> ±25	> ±55	> ±70

Table 8 Performance evaluation criteria of the SWAT model according to Moriasi for the simulations carried out in the Tomebamba River sub-basin with reference to each parameter evaluated and each station monitored.

Statistical parameter	Parameter	Station		
		LL	MS	TM
PBIAS %	Nitrates	74.60	54.87	89.36
	Sediment	-4.55	-1.18	12.5
	Organic Phosphorus	7.29	6.64	-2.06
	Evapotranspiration			-3.39
	Dissolved oxygen	-12.60	-4.29	-16.09
RSR	Nitrates	1.26	1.51	1.68
	Sediment	0.53	0.74	0.74
	Organic Phosphorus	0.12	0.11	0.12
	Evapotranspiration			2.72
	Dissolved oxygen	1.46	1.42	1.68
NSE	Nitrates	-0.59	-1.29	-1.82
	Sediment	0.72	0.45	0.46
	Organic Phosphorus	0.986	0.988	0.986
	Evapotranspiration			-6.40
	Dissolved oxygen	-1.12	-1.01	-1.81

For nitrates, the PBIAS% has quite high values in the three stations, although for the Llaviuco and Tomebamba stations in Monay the simulation is unsatisfactory and for the Matadero station in Sayausí it is placed in the Satisfactory category; their RSRs are outside the optimal range and the NSE is negative in all cases, resulting in an unsatisfactory modeling for this parameter.

In sediments, with respect to PBIAS, the simulation is very good, existing an overestimation of the data in the stations LL and MS, and an underestimate for the TM station. The RSR shows a good simulation for the LL station and unsatisfactory for TM and MS, which is confirmed by the NSE values.

A particular case is organic phosphorus, which has very few data, for which, despite the fact that all its statistics indicate a very good modeling, this assertion cannot be accepted with certainty.

The evapotranspiration simulation for the TM station is overestimated and it is unsatisfactory according to the RSR and NSE statistics.

Finally, the dissolved oxygen simulation presents overestimated data for the three stations and it is unsatisfactory in terms of the evaluation of the RSR and NSE statistics.

It should be noted that the benefits of biological wastewater treatment involve the removal of suspended matter (which directly affects the efficiency of power generation plants, one of the main focuses of the Paute River basin), the treatment of biodegradable organic compounds, elimination of pathogenic microorganisms and polluting substances such as phosphorus, nitrogen and toxic or recalcitrant compounds, and even the separation of heavy metals. Additionally, an application that is currently being used is the recovery of nutrients such as nitrogen and phosphorus for reuse in fertilizers.

4. Conclusion

A database of various analysis parameters was developed for the Tomebamba River sub-basin belonging to the Paute River basin, highlighting nitrates, organic phosphorus, total sedimentable solids, dissolved oxygen and evapotranspiration, from a literature review to collect the observed data and a simulation generated in SWAT for the variable called simulated data. The mentioned parameters were taken because they constitute the most important for the analysis of the water quality of the study area, because they directly influence the levels of contamination that it can present and in the planning of strategies that allow its remediation. Likewise, they constitute a way of evaluating the state of the hydrological cycle, that will vary depending on how much contamination exists in the environment, when evaluating an important variable such as evapotranspiration.

The data obtained from the SWAT simulations were compared with the data observed in studies previously carried out through a statistical, Pearson's correlation coefficient; through which it was possible to specify that the linear relationship between the observed and simulated data was deficient for all the parameters, except for organic phosphorus which had an almost perfect relationship, although this fact could not be valid because the amount of data available for comparison was scarce and not representative.

The efficiency of the SWAT hydrological model was analyzed for the evaluation of various parameters within the Tomebamba River sub-basin, by using the performance evaluation criterion of a Moriasi model, identifying that according to the PBIAS the simulations underestimate the real values of nitrates in the monitored stations, as well as organic phosphorus and sediments (only at the Tomebamba station in Monay); and underestimate evapotranspiration values, dissolved oxygen and sediment (at two other stations). The performance of the SWAT model is evaluated with the RSR statistic, which shows that the modelling is unsatisfactory for nitrates, evapotranspiration and dissolved oxygen; and it is very good for organic phosphorus and the sediments of the Llaviuco station. On the other hand, with the NSE statistic it is evident that the efficiency of the simulations performed is unsatisfactory for dissolved oxygen, evapotranspiration and nitrates, but very good for sediment and organic phosphorus.

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