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GENERATION OF MONTHLY AVERAGE FLOW RATES FROM THE HYDROLOGICAL CHARACTERISTICS IN THE HUANCANE RIVER BASIN

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ABSTRACT

Due to the dissatisfaction of not having hydrometric and hydrological stations in the middle and upper part of the basins, there is a need to have hydrological modeling tools for a sustainable management of water resources, in this work we propose the development of four mathematical models precipitation-runoff, allow them to estimate the information of monthly flows, these models are based on the hydrological characteristics of the basin taking as variables the area of the basin, precipitation, effective precipitation and evapotranspiration. The implementation and validation of the models have been applied to the Huancane river basin located in the Peruvian highlands. The models have been developed through the analysis of auto regressions, denominating them Traverso Autoregressive Hydrological Models (ART), for the validation of the models the hydrological model of Lutz Scholz has been applied, making a comparison with the volumetric flows and the flows generated by each model, using statistical validation, we found the most optimal model ART2 analyzed with the observed flow rates ($r = 0.78$, $E = 0.61$) and flow rates of the Lutz Scholz model ($r = 0.92$, $E = 0.81$). The optimal model found can be applied to other basins taking into account the hydrological characteristics, a methodology for its application has been established.

Keywords: Precipitation-runoff, Mathematical model, Auto regression, Monthly-flows.

1 INTRODUCTION

The engineering projects related to Water Resources and Environmental Management require meteorological, rainfall and flow information necessary information to make appropriate decisions that allow achieving a true sustainability of them. Within the information to be generated are the flows of the main sources and their tributaries whether maximum, minimum and average for different time intervals such as annual, monthly and daily, in this sense the development of mathematical models in Water Resources focuses on the development of formulas and / or equations, in this sense can be considered a black box in which factors or parameters enter and in which answers or results come out.

The limited capacity of the Peruvian state to install hydrometric stations hinders the adequate management of water resources in the sub-basins and micro-basins of Peru, that implies the approximate estimation of the monthly flows available for the respective projects to be carried out as irrigation, drinking water systems, reservoirs, ecological flow, among others, where the limiting factor for this type of project is the lack of hydrometric information (Reyes, 2015).

Estimates of the statistical characteristics of a hydrological record of annual values are more reliable and consistent if this is broader because being longer it is more likely to include periods of dry and wet years (Aranda 2011). From a hydrological point of view generation means the estimation of the numerical value of a meteorological variable from others through a pre-established procedure; Likewise, discharge is denominated the waters that run along the bed of a river and that can be measured and quantified in time, usually in months (Tarazona 2005).

For the present investigation four mathematical models of precipitation - runoff, capable of generating the information of monthly average flows using the analysis of auto regressions to these mathematical models are called Traverso Autoregressive Hydrological Models (ART) have been taken as variables the characteristics Basic variables that influence the physical behavior of the basin these variables are precipitation, effective precipitation, and evapotranspiration in the same way evaluate the influence or uncertainty of these variables.

2 MATERIALS AND METHODS

2.1. Study area and availability of information

The study area corresponds to Huancane river basin, located in the southern part of Peru, in the hydrographic region of Titicaca view Figure 1, which is part of the TDPS system (Titicaca-Desaguadero-Poopó-Salar de Coipasa) between the south latitude 14°31'26"-15°23'07" and west longitude 70°07'06"-69°29'12" with a maximum height of 5100masl (meters above sea level) and minimum height of 3806masl politically and administratively the basin under study is located in the department of Puno.

The Huancane river basin, basin with a total area of 3631.19km^2, with a main river length of 140.05km, average slope of the basin of 0.0067m/m and an average slope of the main river 0.007m/m, the point of gauging in the basin is in the Huancane bridge, where there is a hydrometric station operated by SENAMHI. The information necessary for the development of ART models was obtained from SENAMHI (National Service of Meteorology and Hydrology of Peru), the information was obtained from the meteorological and hydrometric stations that are in the basin and bordering it.

The precipitation was obtained from the PISCO database (Peruvian Interpolated Data of the Senamhi's Climatological and Hydrological Observations) this product was elaborated by SENAMHI through the direction of Hydrology – DHI this spatial database contains the information of the precipitation on a monthly scale. The database is in a netCDF format where precipitation data are stored from January 1981 to December 2016 at a monthly rate with a grid resolution of 0.05° (~ 5km^2).

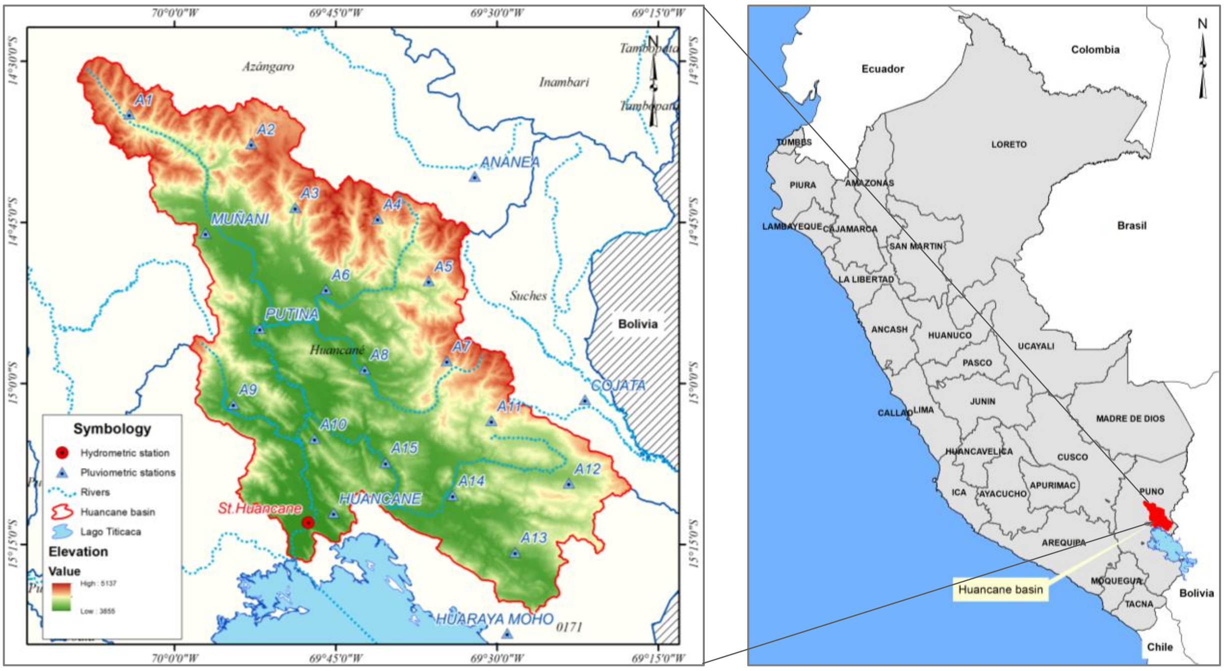

Figure 1. Huancane river basin location of rainfall and hydrometric stations.

2.2. Description of the Lutz Scholz hydrological model

In the study Generation of Monthly Flows in the Sierra Peruana (1980) of the National Program of Small and Medium Irrigations Plan Meris II sustains that this hydrological model is combined because it has a deterministic structure for the calculation of monthly flows for the average year (Water Balance - Deterministic Model) and, a stochastic structure for the generation of extended flow series (Markovian Process - Stochastic Model). It was developed by the expert Lutz Scholz for basins of the Peruvian highlands between 1979 and 1980 within the framework of the Technical Cooperation of the Republic of Germany through the Plan Meris II.

For a first step Lutz Scholz analyzed the hydro-meteorological data of nineteen basins between Cuzco and Cajamarca then proceeded to calculate the necessary parameters for the description of the phenomena of average runoff. In a second step it established a set of partial stochastic models of the parameters for the calculation of flows in these basins that lack hydrometric information. Applying the regionalized meteorological data for the respective basin and the partial models, the monthly flows can be calculated. The third step allows the generation of flows for an extended period in the collection point projected by a calculation combining (the effective precipitation with the discharges of the previous month by a Markovian process) and calibrating the integral model by gauging executed.

The model is based on the fundamental equation of the water balance in order to establish partial models whether deterministic or stochastic to regionalize the parameters that describe the monthly flow the fundamental equation of the monthly water balance is expressed in mm/month proposed by Fischer:

$$CM_i = P_i - D_i + A_i \qquad [1]$$

Where, CMi is the monthly discharge (mm / month), Pi the monthly precipitation over the basin (mm / month), Di is the runoff deficit (mm / month), Gi the retention expense of the basin (mm / month), and Ai the retention supply (mm / month). For the extension of annual flows, a stochastic model has been implemented consisting of the combination of a Markovian process of first order, the equation for the generation of monthly flows is:

$$Q_t = B1 + B2\left(Q_{t-1}\right) + B3\left(PE_t\right) + z\left(S\right)\sqrt{1-r^2} \qquad [2]$$

Where, Q_t is the flow of month t(m3/s), Q_{t-1} is the flow of the previous month (m3/s), PE_t the effective precipitation of month t(mm/month) and finally, B1 is the constant factor or basic flow rate (m3/s).

Table 1. Location of the Huancane river hydrometric station.

Name	**Code**	**Region**	**Province**	**District**	**Basin**	**Latitude (°S)**	**Longitude (°W)**	**Altitude (masl)**
Huancane	210201	Puno	Huancane	Huancane	Huancane	15°12'59.3"	69°47'33.3"	3860

2.3. Description of the autoregressive hydrological models ART

Four mathematical models that represent the hydrology of the basin are proposed, the ART models, mainly compose characteristics of the behavior of hydrology in a basin, taking as variables the area, precipitation, effective precipitation and evapotranspiration.

The evapotranspiration has been estimated by the Hargreaves by Temperature method, to obtain the monthly evapotranspiration for the period of 1981-2016, the empirical formula for the estimation of the potential evapotranspiration of the class A tank at mid-latitudes of the northern hemisphere, the The proposed equation is a function of temperature, relative humidity and the monthly coefficient of sunlight.

$$ETP = MF.TMF.CH.CE \qquad [3]$$

Where ETP is the potential evapotranspiration (mm / month), MF represents the monthly factor of latitude these factors are shown in Table 4, TMF is the average monthly temperature (° F), CH is the correction factor for relative humidity.

$$CH = 0.166\left(100 - HR\right)^{0.5} \text{ for HR>64\%} \qquad [4]$$

$$CH = 1 \text{ for HR<64\%} \qquad [5]$$

Where, HR represents the average monthly relative humidity (%) CE is the altitude correction factor of the area and finally, E represents the altitude o of the study area masl (meters above sea level).

$$CE = 1 + \frac{0.04 * E}{2000} \qquad [6]$$

These mathematical models are able to estimate the flows at monthly level; to give a validation it has taken the hydrological model developed by the expert Lutz Schulz, the equations raised are:

$$Qm = \beta_0 P^{\beta 1} PE^{\beta 2} ETo^{\beta 3} A^{\beta 4} \qquad [7]$$

$$Qm = \beta_0 P^{\beta 1} PE^{\beta 2} ETo^{\beta 3} \qquad [8]$$

$$Qm = \beta_0 P^{\beta 1} PE^{\beta 2} \qquad [9]$$

$$Qm = \beta_0 P^{\beta 1} ETo^{\beta 2} \qquad [10]$$

Where, Qm is the average monthly flow (m^3/s), P the average precipitation of the basin (mm/month), PE the effective precipitation (mm/month), ETo the evapotranspiration of the basin (mm/month), A is the area of the basin (km^2) and finally β_0, β_1, β_2, β_3 and β_4 are the calibration coefficients.

2.4. Validation of results

(Cabrera. 2017), the calibration of models usually focuses on an "accuracy criterion", which is based on the quantification of the goodness of fit of the model. For this purpose, different "measures of goodness of fit" are used.

2.4.1. Calibration coefficient (r)

Express the linear dependence between two variables that in our case are the observed flows and the simulated flows, is defined by the expression:

$$r = \frac{S_{obs,sim}}{\sqrt{S_{obs}.S_{sim}}} \qquad [11]$$

Where, $S_{obs,\,sim}$ is the covariance without bias between observed and simulated flows

$$S_{obs,sim} = \frac{1}{n-1}\sum_{i=1}^{n}\left(Q_i - \overline{Q}\right)\left(Q_{sim,i} - \overline{Q}_{sim}\right) \qquad [12]$$

S_{obs} and S_{sim} are the non-biased variances of the observed and simulated flows respectively

$$S_{obs} = \frac{1}{n-1}\sum_{i=1}^{n}\left(Q_i - \overline{Q}\right)^2 \qquad [13]$$

$$S_{sim} = \frac{1}{n-1}\sum_{i=1}^{n}\left(Q_{sim,i} - \overline{Q}_{sim}\right)^2 \qquad [14]$$

Where the values with bars represent average values and n is the number of simulated data. The correlation coefficient can take values between 0 <r <1 a higher value of r, better fit.

2.4.2. Schultz criteria (D)

The Schultz criterion represents the deviation of the simulated flows from the observed ones, it is calculated as the expression:

$$D = 200\frac{\sum_{i=1}^{n}\left|Q_{sim,i} - Q_i\right|Q_i}{n\left(Q_{\max}\right)^2} \qquad [15]$$

Where, Q_{max} is the maximum discharge observed in the period under study the use of this criterion is recommended for the analysis of high resolution temporal events.

Table 2. Referential values of the Schultz criterion (Molnar, 2011).

D	Adjusted
0 – 3	Very god
3 – 10	Good
10 – 18	Enough
> 18	Insufficient

2.4.3. Nash-Sutcliffe efficiency (E)

The Nash-Sutcliffe criterion is one of the most used in Hydrology, it is defined as:

$$E = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim,i} - Q_i\right)^2}{\sum_{i=1}^{n}\left(Q_i - \overline{Q}\right)^2} \qquad [16]$$

And it measures how much of the variability of the observations is explained by the simulation. If the simulation is perfect, E = 1; if we tried to adjust the observations with the average value, then E = 0. Some suggested values for decision making are summarized in Table 10.

Table 3. Referential values of the Nash-Sutcliffe Criterion (Molnar, 2011).

E	Adjusted
< 0.2	Very good
0.2 – 0.4	Satisfactory
0.4 – 0.6	Good
0.6 – 0.8	Very Good
> 0.8	Excellent

2.4.4. Mass balance error (m)

Express quantitatively the relationship between the volume of the observed and the simulated hydrograph, expressed as:

$$m = 100\frac{\sum_{i=1}^{n}\left(Q_{sim} - Q_i\right)}{\sum_{i=1}^{n} Qi} \qquad [17]$$

Where m is a percentage, if the adjustment is perfect m = 0. In the calibration process you should look for the lowest value of m this average of goodness of fit is adequate for monthly and annual analyzes and for cases where it is required to reproduce the water balance.

3 RESULTS

3.1. Generation of monthly average flows bay the model Lutz Scholz

Flows have been generated for the average year following the methodology proposed by the expert Lutz Scholz where these previous results have been necessary for the calibration of the hydrological model, as shown in Table 7, where a retention of 31 mm/year and a runoff coefficient of 0.275 mm / year for the Huancane basin the supply period has been calibrated during the months that rainfall occurs from October to March. In Figure 2, it shows the model calibrated for flow rates average year.

Table 4. Generation of flows for the average year of the Lutz Scholz hydrological model.

Monthly Precipitation			**Contribution of retention**							**Flows**		
			Effective precipitation			Spending		Supplying		Simulated		Observed
Month	Days	PP (mm/month)	PE II (mm/month)	PE III (mm/month)	PE	bi	Gi mm/month	ai	Ai mm/month	mm/month	m3/s	m3/s
Jan	31	130.24	45.90	70.99	55.94			0.71	22.01	33.93	46.00	51.64
Feb	28	90.01	18.95	31.64	24.03			-0.37	-11.47	35.50	53.29	55.25
Mar	31	102.13	25.57	41.99	32.14			-0.05	-1.55	33.69	45.67	49.14
Apr	30	45.12	5.04	9.39	6.78	0.65	11.73			18.51	25.93	28.75
May	31	12.47	1.40	2.88	1.99	0.42	7.63			9.62	13.04	10.87
Jun	30	5.94	0.71	1.48	1.02	0.28	4.96			5.98	8.38	5.13
Jul	31	3.50	0.43	0.89	0.61	0.18	3.23			3.84	5.20	3.52
Ago	31	11.06	1.26	2.59	1.79	0.12	2.10			3.89	5.27	2.72
Sep	30	29.56	3.04	6.03	4.23	0.08	1.36			5.60	7.84	2.78
Oct	31	46.68	5.30	9.80	7.10			0.01	0.31	6.79	9.20	4.06
Nov	30	54.84	6.85	12.29	9.02			0.16	4.96	4.06	5.69	5.50
Dec	31	96.18	22.16	36.69	27.97			0.54	16.74	11.23	15.22	15.03
Total		627.73	136.60	226.65	172.63			1.00	31.00	172.63	240.73	234.39
Coefficients		0.275	0.60	0.40	1.00							

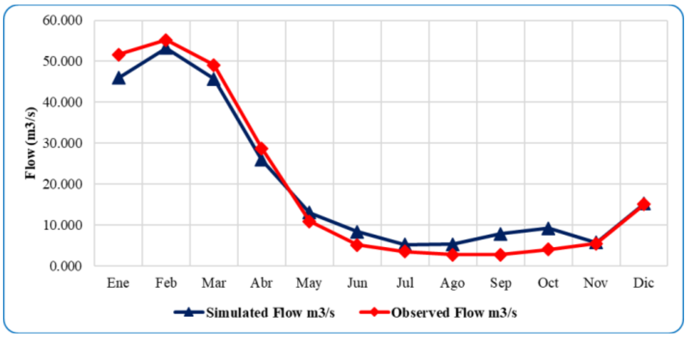

Figure 2. Calibration of the Lutz Scholz model for the average year.

From the previous result for the flows of the average year the extension of them has been carried out following the Markovian process where variables B1, B2, B3, R2 and S have been determined based on the calibrated model for this purpose takes (QT) as dependent variable (QT-1) and (PE) as independent variables

Table 5. Dependent and independent variables for multiple linear regression.

Month	QT	QT-1	PE
Jan	33.93	11.23	55.94
Feb	35.50	33.93	24.03
Mar	33.69	35.50	32.14
Apr	18.51	33.69	6.78
May	9.62	18.51	1.99
Jun	5.98	9.62	1.02
Jul	3.84	5.98	0.61
Ago	3.89	3.84	1.79
Sep	5.60	3.89	4.23
Oct	6.79	5.60	7.10
Nov	4.06	6.79	9.02
Dec	11.23	4.06	27.97

Multiple linear regression was applied, obtaining the following results:

- B1 = -0.8979
- B2 = 0.5761
- B3 = 0.4864
- S = 2.9541
- R2 = 0.9777

According to the results of the applied regression, the coefficient B1 is negative which does not make sense because the negative basic flow does not exist therefore a basic flow rate of 1.36mm/month is established these results were replaced in the equation [2] for its extension at monthly average flows.

3.2. Generation of monthly average flows of ART models

From the autoregressive models, the first proposed model has been discarded, the basin area has already been considered variable, this variable being erroneous since it is constant over time, making impossible the application of auto regressions for this ART1 model.

3.2.1. Hydrological model ART2

The ART2 model has considered the variables of average precipitation of the basin P(mm/month), the effective precipitation PE(mm/month) and the evapotranspiration ETo obtained by the Hargreaves method by temperature (mm/month) the expression obtained is:

$$Qm = 15629.03\frac{P^{0.563267}.PE^{0.522792}}{ETo^{2.138567}} \qquad [18]$$

3.2.2. Hydrological model ART3

The ART3 model has considered two variables, the average precipitation of the basin P(mm/month) and the effective precipitation PE(mm/month) the expression obtained is:

$$Qm = 5.953650\frac{PE^{0.828729}}{P^{0.224805}} \qquad [19]$$

3.3.3. Hydrological model ART4

The ART4 model has considered two variables, the average precipitation of the basin P(mm/month) and the evapotranspiration ETo(mm/month) the expression obtained is:

$$Qm = 1466.37\frac{P^{1.528913}}{ETo^{2.194696}} \qquad [20]$$

3.3. Measures of goodness of fit and determination of the proposed model

Goodness-of-fit methods have been applied for the three ART hydrological models using the Calibration Coefficient (r), Schulz criterion (D), Nash-Sutcliffe (E) and Mass balance error statistics. The goodness of fit methods has been applied to the Lutz Scholz model and the three ART Hydrological Models comparing these with the volumetric flow rates in the Huancane basin applying the statistical methods analyzed the results obtained see Table 10 to determine the model with more reliability for the generation of monthly flows.

Table 6. Measures of goodness of fit of the models developed with respect to the observed flows

Adjustment Method	Lutz Scholz	ART2 Model	ART3 Model	ART4 Model
Calibration Coefficient (r)	0.88	0.78	0.74	0.78
Schultz criteria (D)	2.98	2.98	4.00	3.64
Efficiency Nash-Sutcliffe (E)	0.74	0.61	0.54	0.61
Mass Balance Error (m)	10.71%	1.21%	-1.65%	2.66%

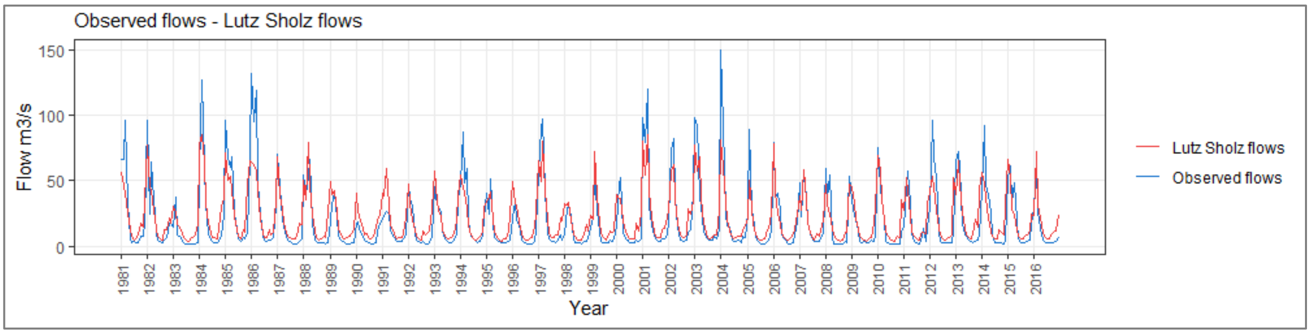

Figure 3. Monthly hydrograph of observed and simulated flows by Lutz Scholz model.

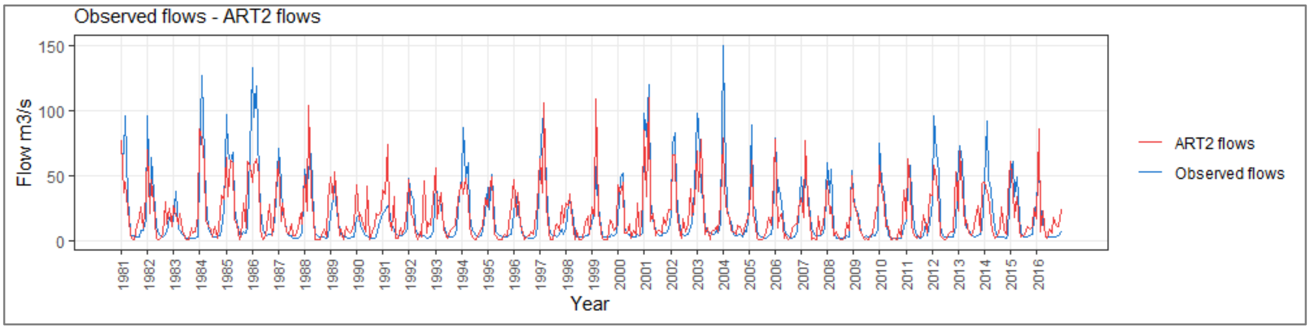

Figure 4. Monthly hydrograph of observed and simulated flows by ART2 model.

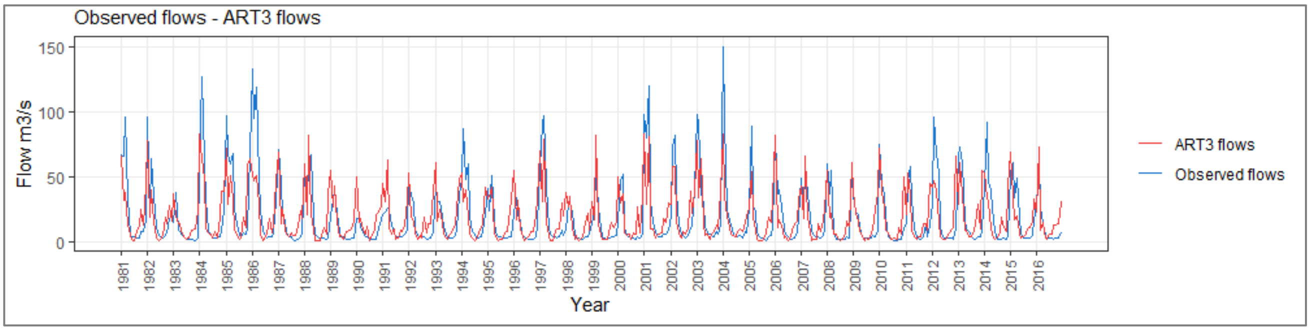

Figure 5. Monthly hydrograph of observed and simulated flows by ART3 model.

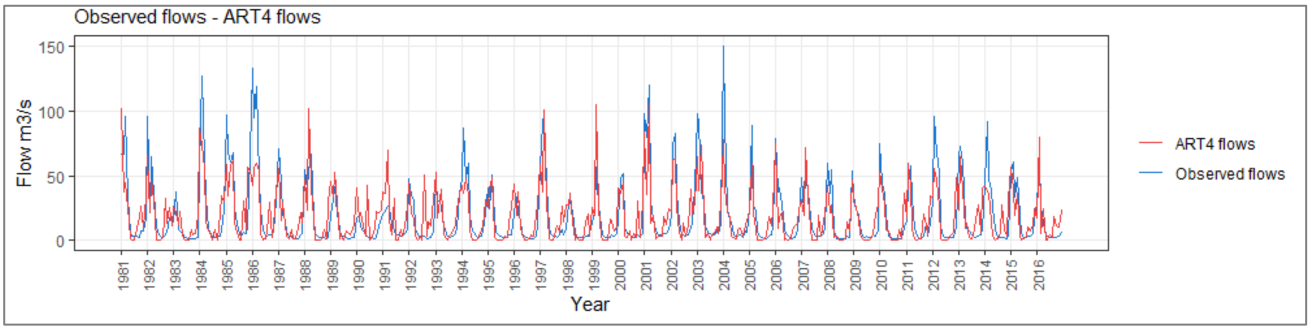

Figure 6. Monthly hydrograph of observed and simulated flows by ART4 model.

The results show that the ART2 hydrological model generates the monthly average flows with more certainty with respect to the others this model has been compared with the flows obtained by Lutz Scholz see Table 9 analyzing the necessary statistics to validate it.

Table 7. Measures of goodness of fit model Lutz Scholz and model proposed ART2

Adjustment Method	Values
Calibration Coefficient (r)	0.92
Schultz criteria (D)	4.71
Efficiency Nash-Sutcliffe (E)	0.81
Mass Balance Error (m)	8.59%

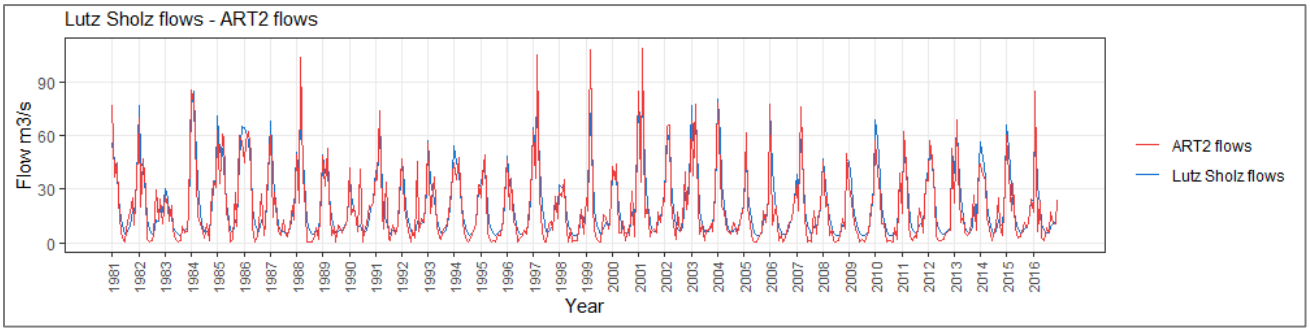

Figure 7. Monthly hydrograph of Lutz Scholz model and simulated flows by ART2 model.

4 DISCUSSION

The Lutz Scholz model applied to the Huancane river basin, is a model that adjusts the conditions of the Peruvian high plateau, although this precipitation-runoff model is a robust model and that needs several parameters to be considered for the estimation of monthly flows. that in part makes its application complex.

From the goodness-of-fit measures, it was determined that the second model proposed Auto-Regressive Hydrological Model (AR2T) presents an acceptable adjustment in relation to the flow rates observed, obtaining the following results from the measures of goodness of fit such as Calibration coefficient r = 0.78, Schulz criterion D = 2.98, Nash-Sutcliffe efficiency E = 0.61, and mass balance error 1.21%, this model takes as varies the precipitation, effective precipitation and evapotranspiration at monthly levels.

There is some uncertainty in the observed information of the flows in the Huancane River since in some parts of the hydrograph it presents atypical values, this information is not of good quality

5 CONCLUSION

The use of rainfall information provided by the PISCO product, is information that is free of charge provided by SENAMHI, it is recommended that this information be used for future research pertaining to the Peruvian highlands and nationwide.

Understand the parameters and / or variables that are included in the Lutz Scholz models and the proposed self-regressive hydrological models, since acceptable results can be obtained quickly, but the understanding of these variables is of utmost importance for the elaboration of mathematical models as it is posed in the present investigation.

Evaluate the possibility of incorporating the parameters and / or variables that can be added to the model proposed in this case the second proposed model (ART2), as an important variable could be the contribution of groundwater, both in times of low water and flood, it could be evaluated how it affects the precipitation-runoff model, waiting for a better fit and validity.

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