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Assessment of the Sensitivity of Soil Parameters in Sediment Production in the Ichu River Experimental Basin

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Abstract: This research aims to determine how much is the sensitivity of soil parameters in the production of sediments through the model distributed at the level of cells in the Ichu River Basin, which is located in the Andes of Peru, with an approximate surface area of 1,380.17 km^2, corresponding to the control section and tributary to the Mantaro River. Also, for the evaluation of sensitivity determine the amount of sediments of the textures: silt, clay and sand. To achieve the objectives that have been raised in this research has been used the conceptual distributed hydrological model TETIS v9.1, which has been calibrated and validated using the climatic variables that are recorded at the hourly level in six weather stations and a hydrometric station, synthetic precipitation was also used withsatellite stations (CHIRPS) of the Climate Hazards Group that has registered with a grid of 0.05 degrees of resolution, from 1981 to the present. To determine the solid component, the TETIS v9.1 model uses the equations developed in the CASCade 2 Dimensional SEDimentation model (CASC2D-SED) that presents conceptual approaches with physical basis. The sediment processes on slopes this CASC2D-SED model simulates in two dimensions,as well as helps to determine the quantification of sediments at any point in the basin considering all physical processes. On the other hand, the OpenLandMap data portal has been used for land cover data of the K factor corresponding to the susceptibility of the soil that can suffer losses due to erosion. Also, the Moderate Resolution Imaging Spectroradiometer (MODIS) observation system to determine the Normalized Difference Vegetation Indices (NDVI) for the culture factor C. The parameter P corresponding to the conservation technique applied, has been developed using remote sensing techniques using the Google Earth Engine (GEE) platform. Finally, the results obtained from the evaluation of the sensitivity of the parameters are significant, in this way the hypothesis that is raised is approved.

Key words: Sediments, distributed model, CASC2D-SED model.

1. Introduction

The study of sediment transport and deposition is very important for the construction of waterworks along the experimental basin of the Ichu River and this will also depend on the different soil parameters. For this we will start from the climatic variables in the production of sediments, the most essential are the rainfall in the headwaters and along the basin to the gauging point that is located in the district of Mariscal Cáceres, where the Ichu River flows into the Mantaro River.

Rivers thanks to rainfall are the main agents of transport and erosion; In this way the deposition of the sediments transported along the river occurs. The transport of sediments is carried out by two forms according to the type of soil and size of the particles; The material that moves suspended is called suspended sediments and the other form is when the material moves with the force of the water very close or close to the riverbed, these are called bottom sediments [1].

The production of sediments occurs by different natural events in the headwaters and in the route of the

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river altering the geomorphology, plants, water, biology, activities of human beings and as well as the hydraulic works found on the banks and in the riverbed [2].

The present work aims to determine the sensitivity of the soil parameters found in the experimental basin of the Ichu River using a distributed hydrological model of conceptual type that simulates in the best way the hydrological response to have as a database of information for the study of future constructions of hydraulic works; That is why in this research the objective of determining the sensitivity of soil parameters was proposed.

All data recorded at meteorological stations within the Ichu River experimental basin and satellite stations distributed throughout the basin have been taken into account.

2. Materials and Methods

For Mao [3] rivers flow from the basin area. However, effluents also transport sediments, which have been eroded at the basin or hydrographic network level, so rivers act as a means of transporting sediments, since they perform the work of transporting sediments from the upper part of the basin to the sea, through erosion, transport and deposition of sediments. These sediments can be transported in different ways in suspension or dragged to the bottom of the river, depending on the size of the particles and the shear pressure that the current can exert on the channel. When transported from below, particles of sand or larger diameter materials will move underground, slide, jump or roll. On the other hand, sedimentary particles of smaller diameter are transported by suspension, that is, in the water column, due to the flow [4].

2.1 MHDT (TETIS Distributed Hydrological Model)

Physically based distributed models, are physics-based models, employ complete equations such as amount of motion, balance and energy. The TETIS model performs simulations in natural basins using tanks and has the sediment submodel, as input data requires information on climatic variables such as precipitation, temperature and information distributed in space.

Runoff production is based on performing a water balance in each cell in six tanks as shown in the diagram of Fig. 1 [5].

The function of these tanks is to perform a simulation of a hydrological cycle with the morphological characteristics of the basin, the physical phenomena and the events that occur in it, this is done cell by cell throughout the basin until reaching the water balance at the point of interest.

2.2 Sub-model Sediment

The TETIS sediment sub model is based on the formulation developed in the CASC2D-SED model, which was modified by Rojas [5]. This CASC2D-SED model simulates hillside sediment processes in two dimensions. In the TETIS model, it simulates a sediment cycle of a distributed type with the characteristics and soil type.

When soil particles erode, they become part of the stream and are transported downstream. Any particle passing through any control point in the basin has necessarily been eroded upstream and washed away by the flow [7]. Production, transport and deposition rates are controlled by two characteristics: sediment availability in the basin and the ability to support the flow. The transport of materials is restricted by the availability of silt in the basin, while the transport of coarse materials is restricted by the carrying capacity of the stream [8].

Hillside sedimentation process and transport capacity according to Julien [8]:

$$q_s = 23210\ S^{1.66}\left(\frac{Q}{W}\right)^{2.035}\frac{K}{0.15}CxP$$

where Q is flow, W is the unit of width, S is the slope, C, K and P are factors of the universal equation of soil loss.

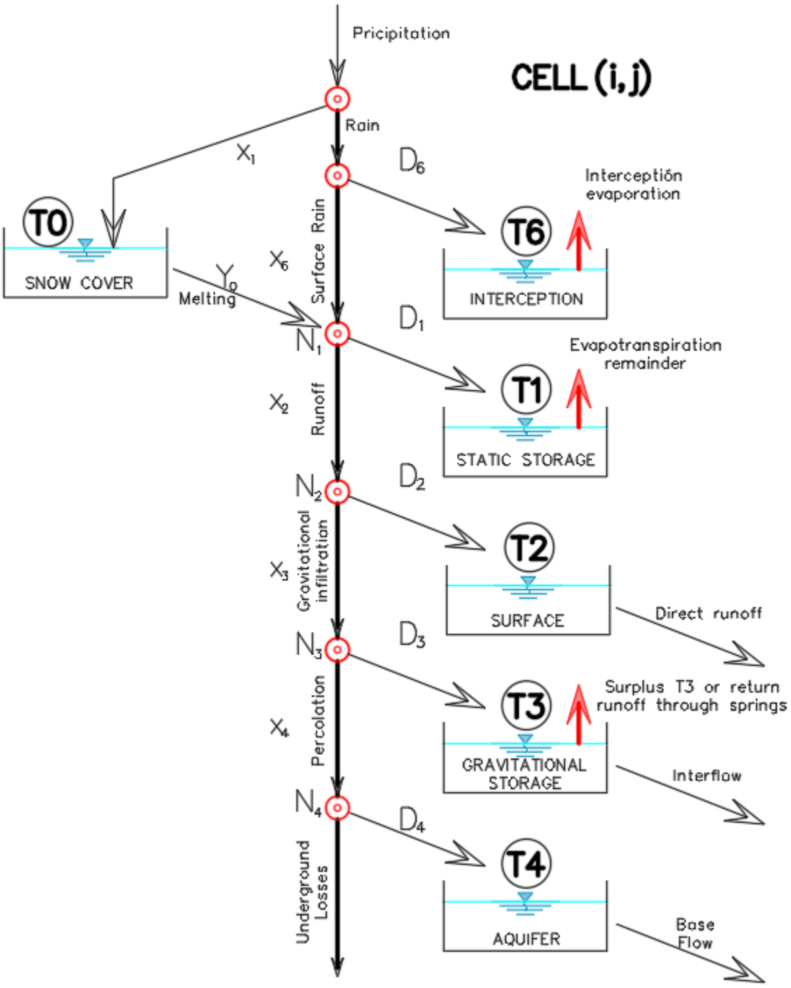


Fig. 1 Conceptual scheme of tanks of the TETIS model.

Total surface erosion:

$$E_t = \int_t \int_x q_s dxdt$$

In the TETIS model, as shown in Fig. 2 the transport capacity depends on the size of the material, as well as the availability of sediments, there is an equilibrium that depends on the size of the material between the suspended load and the bed load. It can be said, if the bearing capacity is maintained, the soil is eroded relative to the percentage of grain size corresponding to the original material.

In Fig. 3 the transport capacity that has been calculated is first used for the propagation of sediments downstream, by size fraction according to the percentage present in suspension and as bed material. Then, if the transport

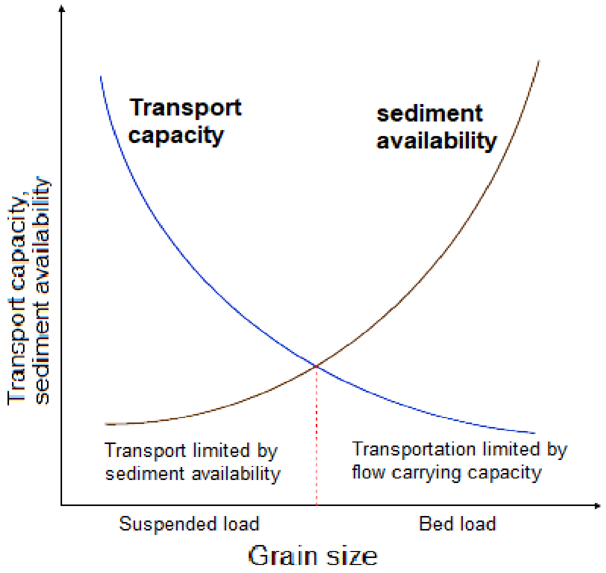


Fig. 2 Supply curve and transport capacity.

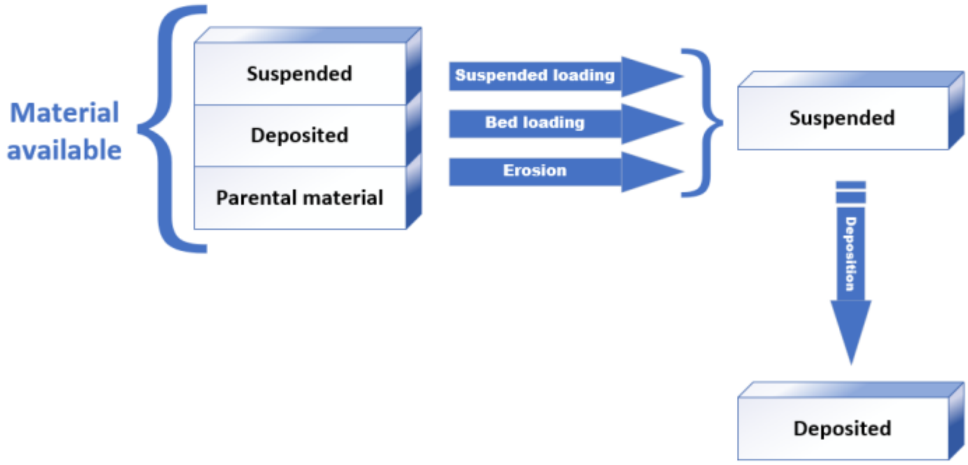


Fig. 3 Diagram of hillside processes in TETIS.

Table 1 Average grain size and velocities.

Description	Diameter (mm)	Speed (mm/s)
Sand	0.350	36.00
Silt	0.016	0.22
Clay	0.001	0.00086

capacity remains, the soil is eroded proportionally to the percentage of the corresponding size fraction of parental material.

In sedimentation process in gullies and channels, the equation of Engelund and Hansen is used:

$$C_{wi} = 0.05\left(\frac{G}{G-1}\right)\frac{V * Sf}{\sqrt{(G-1) * g * dsi}} * \sqrt{\frac{Rh * Sf}{(G-1) * dsi}}$$

2.3 Model Parameters

As initial data you need distributed information on the three parameters (factors *C*, *K* and *P*) of the Universal Soil Loss Equation (USLE) formula and soil textures (percentages of sand, silt and clay). The calibration of TETIS is done through the adjustment of three corrective factors. α, is a coefficient for the correction of transport capacity on slopes. $\beta 1$ and $\beta 2$, are coefficients used to calibrate the transport capacity in gully and the transport capacity in channel respectively.

Table 1 shows the average values of the particle size and its velocities used in the TETIS distributed model in its sediment submodel.

3. Application

The basin of the Ichu River is located in the provinces of Castrovirreyna and Huancavelica, in the department of Huancavelica. It is geographically located between coordinates 12°32′ to 13°05′ south latitude; and 74°45′ to 75°15′ west longitude, the basin has an area of 1,380.17 km^2 which ranges from the lowest area in Mariscal Cáceres at an altitude of 2,856 m a.s.l. and the highest area or the head of the basin is located in the district of Santa Ana (Castrovirreyna) at a maximum altitude of 5,233 m a.s.l. according to the study carried out. Within this basin that is born the Ichu River with the union of the Astobamba River and the Cachimayo River, has a length of 90.72 km of main channel, which flows into the Mantaro River in the district of Mariscal Cáceres.

3.1 Meteorological and Hydrological Stations

The data of the stations have been necessary for the processing of the model within the basin, the database of the six meteorological stations and a hydrometric station that are administered by the UNH (National

University of Huancavelica) has been used, the ones that have a record from 2016 to the present. Likewise, the synthetic stations that have a database are registered from 1981 to the present at a daily level and with a total of 43 stations distributed in the basin of the study area.

Table 2 shows the location of the coordinates of the synthetic stations that satellite rainfall data have been obtained from CHIRPS 2.0 where the validation study is based on 403 stations of the main rainy seasons in Peru, where these have a resolution of 0.05 °equivalent to 250 m.

Table 3 shows the location of the weather stations that are located in the Ichu River basin, stations that are managed by the Professional School of Civil Engineering of the UNH [9].

Table 4 shows the gauging point of the hydrological station, it has a record of levels at the daily level and is transformed into flows with the equation formulated by Ayala [10]:

$$Q = 12.911(H - 0.012)^{3.03}$$

Table 2 Synthetic weather stations in the Ichu River basin.

Number	*Latitude (°)*	*Longitude (°)*	*Elevation (masl)*
Es-1	-75.175	-12.825	4,975
Es-2	-75.175	-12.875	5,074
Es-3	-75.175	-12.925	4,678
Es-4	-75.125	-12.825	4,539
Es-5	-75.125	-12.875	4,344
Es-6	-75.125	-12.925	4,890
Es-7	-75.125	-12.975	4,896
Es-8	-75.075	-12.675	4,706
Es-9	-75.075	-12.725	4,660
Es-10	-75.075	-12.775	4,601
Es-11	-75.075	-12.825	4,157
Es-12	-75.075	-12.875	4,994
Es-13	-75.075	-12.925	4,751
Es-14	-75.075	-12.975	4,744
Es-15	-75.075	-13.025	4,723
Es-16	-75.025	-12.675	4,372
Es-17	-75.025	-12.725	4,455
Es-18	-75.025	-12.775	3,781
Es-19	-75.025	-12.825	4,534
Es-20	-74.975	-12.625	4,350
Es-21	-74.975	-12.675	4,152
Es-22	-74.975	-12.725	4,555
Es-23	-74.975	-12.775	4,174
Es-24	-74.975	-12.825	4,528
Es-25	-74.925	-12.575	3,150
Es-26	-74.925	-12.625	3,888
Es-27	-74.925	-12.675	4,332
Es-28	-74.925	-12.725	4,278
Es-29	-74.925	-12.775	3,639
Es-30	-74.925	-12.825	4,257
Es-31	-74.875	-12.575	3,824
Es-32	-74.875	-12.625	3,165
Es-33	-74.875	-12.675	3,880
Es-34	-74.875	-12.725	3,905
Es-35	-74.875	-12.775	3,781

Table 2 to be continued

Es-36	-74.875	-12.825	4,248
Es-37	-74.875	-12.875	4,523
Es-38	-74.825	-12.625	4,500
Es-39	-74.825	-12.675	3,775
Es-40	-74.825	-12.725	3,877
Es-41	-74.825	-12.775	3,995
Es-42	-74.825	-12.825	4,281
Es-43	-74.775	-12.675	4,502

Table 3 Weather stations in the Ichu River basin.

Number	Latitude (°)	Longitude (°)	Elevation (masl)
E. M. Huancavelica	-12.789	-74.979	3,685
E. M. Sacsamarca	-12.799	-74.992	3,959
E. M. Chuñuranra	-12.791	-75.037	3,781
E. M. Lachocc	-12.859	-75.101	4,217
E. M. Cachimayo	-12.917	-75.186	4,649
E. M. Pucapampa	-13.035	-75.091	4,598
E. M. Lachocc	-12.859	-75.101	4,217

Table 4 Hydrological station.

Number	Latitude (°)	Longitude (°)	Elevation (masl)
E. H. Huancavelica	-12.7846	-74.9721	3,678

3.2 TETIS Hydrological Model

For modeling in Tetis the hydrological, geomorphological, sedimentological parameters and initial conditions are necessary to represent the characteristics of the basin. The basin of the Ichu River has a climatic variability and diversity of distribution in the texture of the soil, for this we start from obtaining a Digital Model of Elevations (DEM) with a scale of 12.5 by 12.5 meters and then perform the processing in a GIS software rescaling to a resolution of 100 by 100 metros to standardize and thus obtain the entry raster in extension asc. In Fig. 4 we have the DEM of the Ichu River basin.

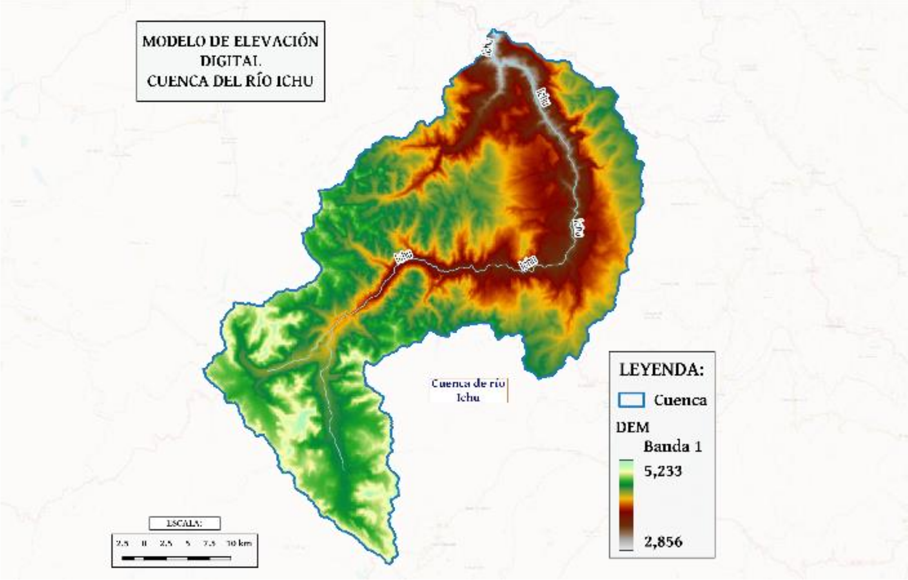
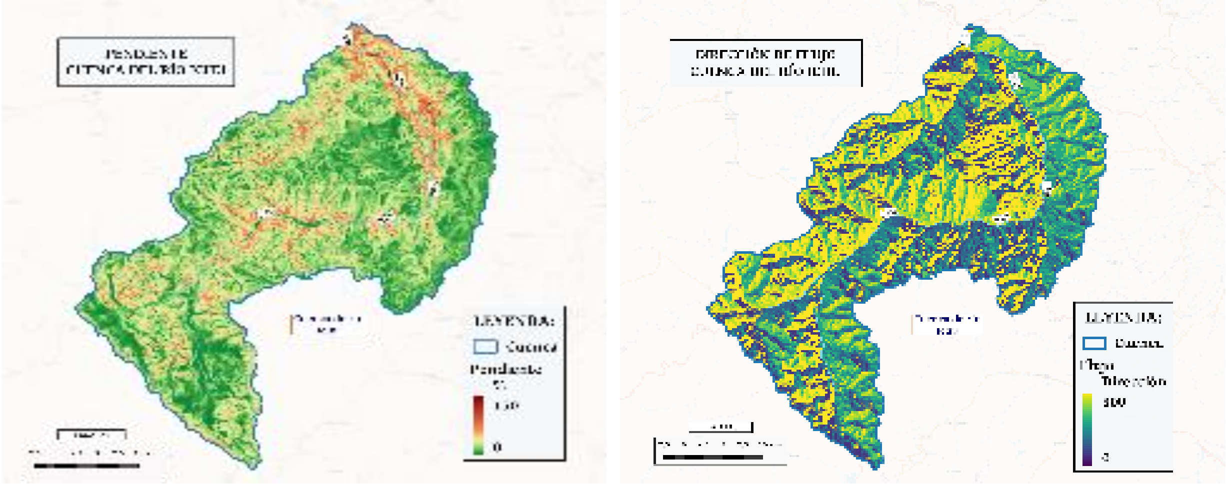
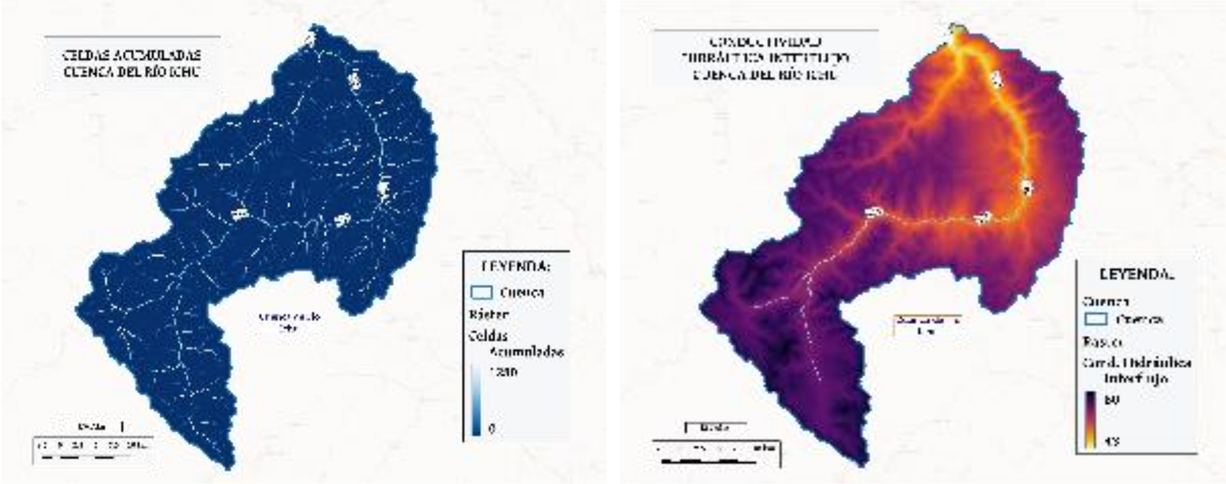


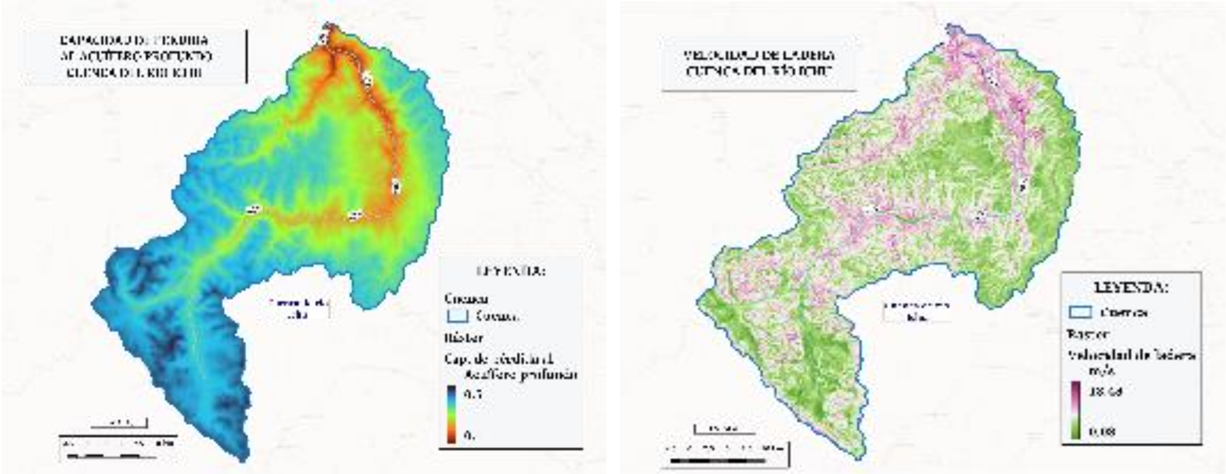
Fig. 4 DEM.



(a) Pending (b) Flow direction



(c) Cumulative cells (d) Interflux



(e) Deep aquifer (f) Hillside speed

Fig. 5 Geomorphological parameters.

The initial parameters that can be seen in Fig. 5 were generated from the DEM with a resolution of 100 m by 100 m, then to analyze with thesame size characteristicsusing an algorithm in R programming language.

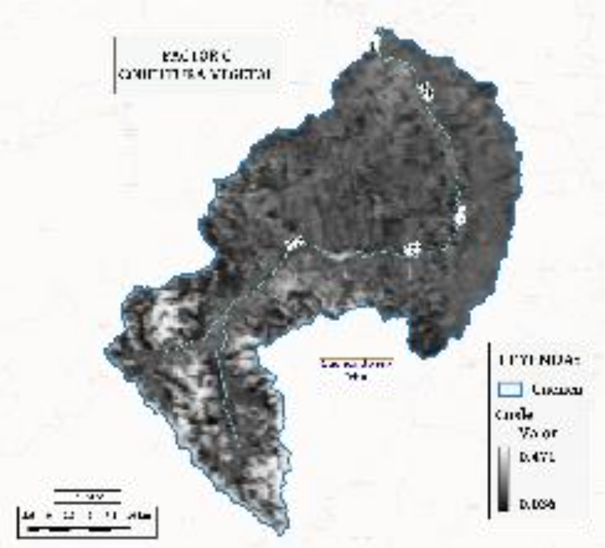


Fig. 6 USLE Parameter *C*.

3.2.1 Factor C

Calculation of the vegetation cover factor (C), corresponds to a part of the USLE equation and is used to know the relative effectiveness of soil management systems and crops for the estimation of prevention and reduction of soil loss, to obtain the map of the factor C (Fig. 6) the equation of Lin [11] has been used:

$$C = \frac{1 - NVDI}{2} = 0.5 - 0.5NVDI$$

$$C = \left(\frac{1 - NVDI}{2}\right)^{1+NDVI}$$

where:

NDVI: Normalized Difference Vegetation Index.

The value of *C* that approaches 0 means that there is no coverage vegetal and if the value approaches 1, there is a coverage effect.

3.2.2 Factor K

Soil Erodability factor calculation measures susceptibility to erosion, from soil compositions such as: texture, organic matter, structure and permeability.

For Yali [12] if the value of K approaches 0 it means that the hard soil to be eroded (mainly water bodies) and if the value of K is equal to 1, there is lto ease of soil erosion.

To obtain the map of the K factor (Fig. 7) the equation of William [13] has been used, which proposes the following relationship:

$$\boldsymbol{K = f_{csand} * f_{cl-si} * f_{orgC} * f_{hisand}}$$

$$f_{csand} = 0.2 + 0.3EXP\left[-0.256m_s\left(\frac{m_{silt}}{100}\right)\right]$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3}$$

$$f_{orgC} = \left(1 - \frac{0.25orgC}{orgC + EXP[3.72 - 2.95 * orgC]}\right)^{0.3}$$

$$f_{cl-si} = \left[1 - \frac{0.7\left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + exp\left[-5.51 + 22.9\left(1 - \frac{m_s}{100}\right)\right]}\right]$$

where:

m_s: sand fraction content (0.05-2.00 mm) in %;

m_{silt}: content of the silt fraction (0.002-0.05 mm) in %;

m_C: content of clay fraction (< 0.002 mm) in %;

orgC: organic carbon content (SOC) in %.

3.2.3 Factor P

The factor calculus of Erosion Control Practices (P), and this effect of soil erosion control practices according to Wischmeier & Smith [14], was defined as the relationship of soil loss with a specific conservation practice with soil loss in a crop.

When the value of P is lower, it means that the conservation practice will be more effective in the face of soil erosion.

In this case, the values of Table 5 have been used, carrying out the zoning within the Ichu River basin, the areas where there are crops in overuse, underuse and

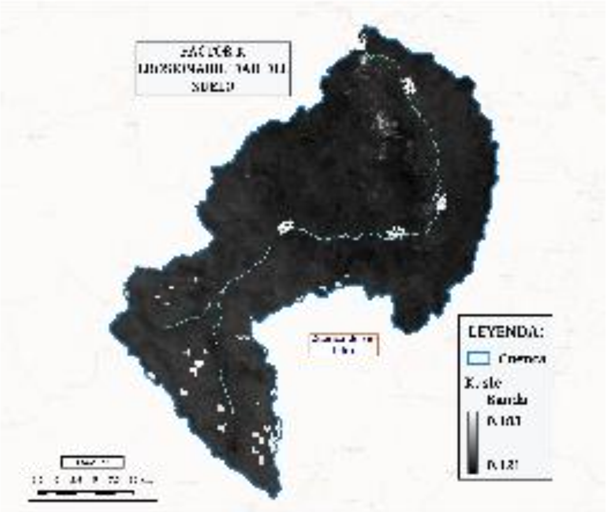


Fig. 7 USLE *K* parameter.

Table 5 P-factor values for different erosion control practices (Wischmeier & Smith, 1978).

Earring	Contour	Crop in strips	Terrace
0.0-7.0	0.55	0.27	0.10
7.0-11.3	0.60	0.30	0.12
11.3-17.6	0.80	0.40	0.16
17.6-26.8	0.90	0.45	0.18
26.8 >	1.00	0.50	0.20

conforming use of soils have been identified, but not the conservation practices that are carried out in the current, because there are no parameters that can be determine on a certain scale, neither entities dedicated to conservation. The farmers of the crops in the basin carry out an excessive erosion to produce the different crops and have approximated according to the average values.

To obtain the soil textures, an algorithm has been made in GEE, using a remote sensing technique, the raster of sand, silt and clay has been generated, see in Fig. 8.

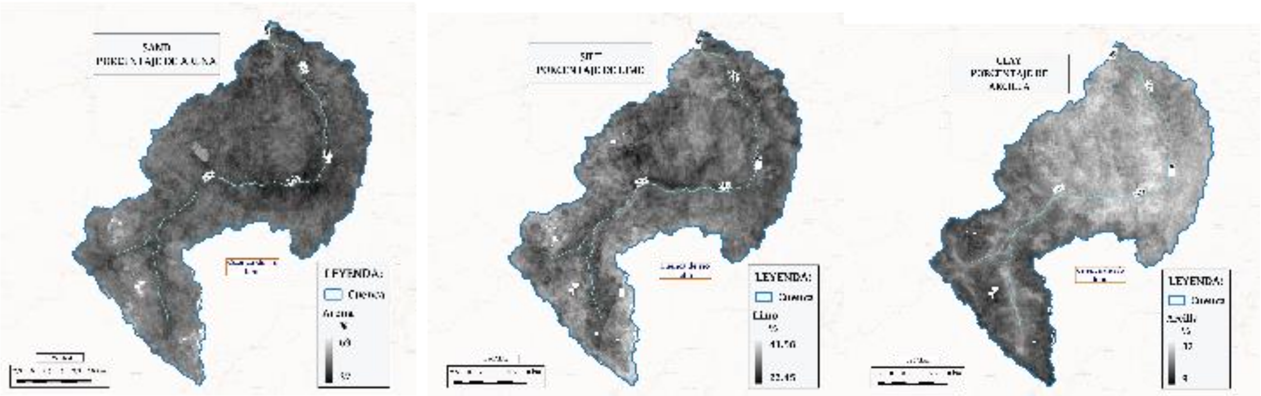
Next, we proceed to launch the simulation with the initial conditions.

3.3 Model Calibration

The TETIS model was calibrated at the gauging point, at the Hydrological Station located in the city of Huancavelica. In the simulation prior to the automatic calibration stage, for the period from January 1981 to December 2021 at the gauging station, the results shown in Fig. 9 were obtained, which highlights the value of the Nash Sutcliffe coefficient equal to 0.2122, classifying in an insufficient fit.

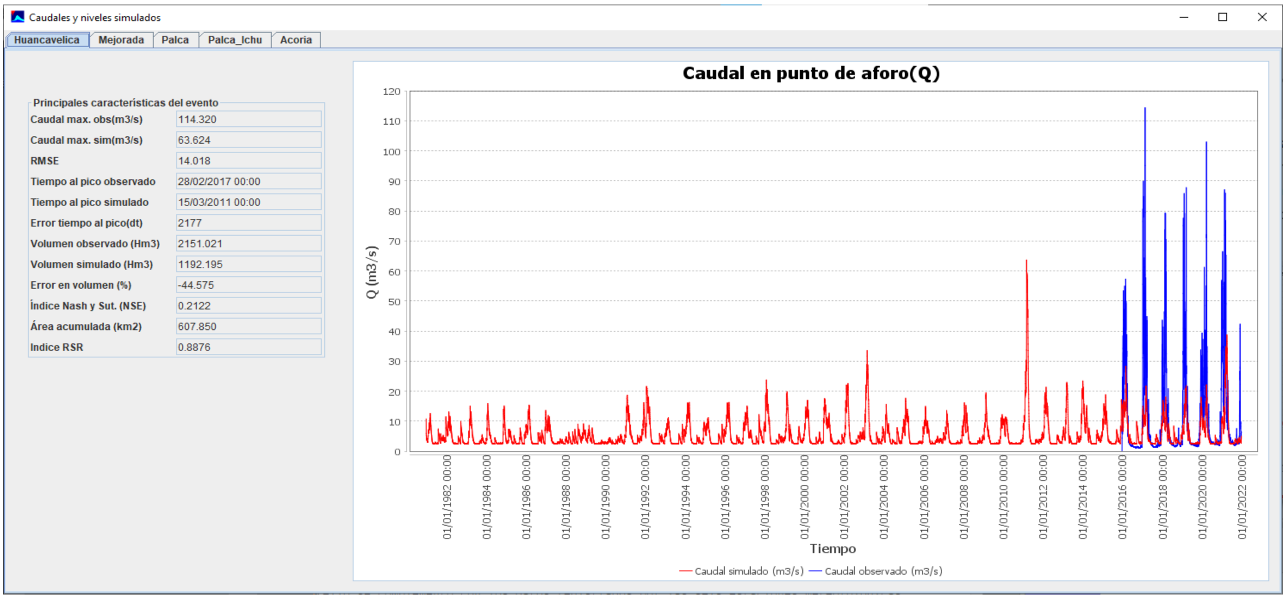
By performing the calibration process with the estimated Corrective Factors (FCs) after the first simulation with the uncalibrated FCs and using the Shuffled Complex Evolution-University of Arizona (SCE-UA) optimization algorithm that applies the TETIS model [15]. The set of corrective factors shown in Table 6 was obtained, the results are presented in Fig. 10, obtaining a coefficient of Nash Sutcliffe equal to 0.5046 in the gauging station, which corresponds to a good fit.

The process of water balance, represented in the TETIS model was satisfactory becoming good, according to the Nash classification, was obtained by using the objective function efficiency coefficient of Nash Sutcliffe equal to 0. 5046, observing a good fit between the maximum flows observed and the simulated maximum flows. Table 6 shows the uncalibrated corrective factors and the calibrated optimization algorithm (SCE-UA) of the TETIS model, as well as the characteristics of the simulated event in Table 7.



(a) Percentage of arena (b) Percentage of silt (c) Percentage of clay

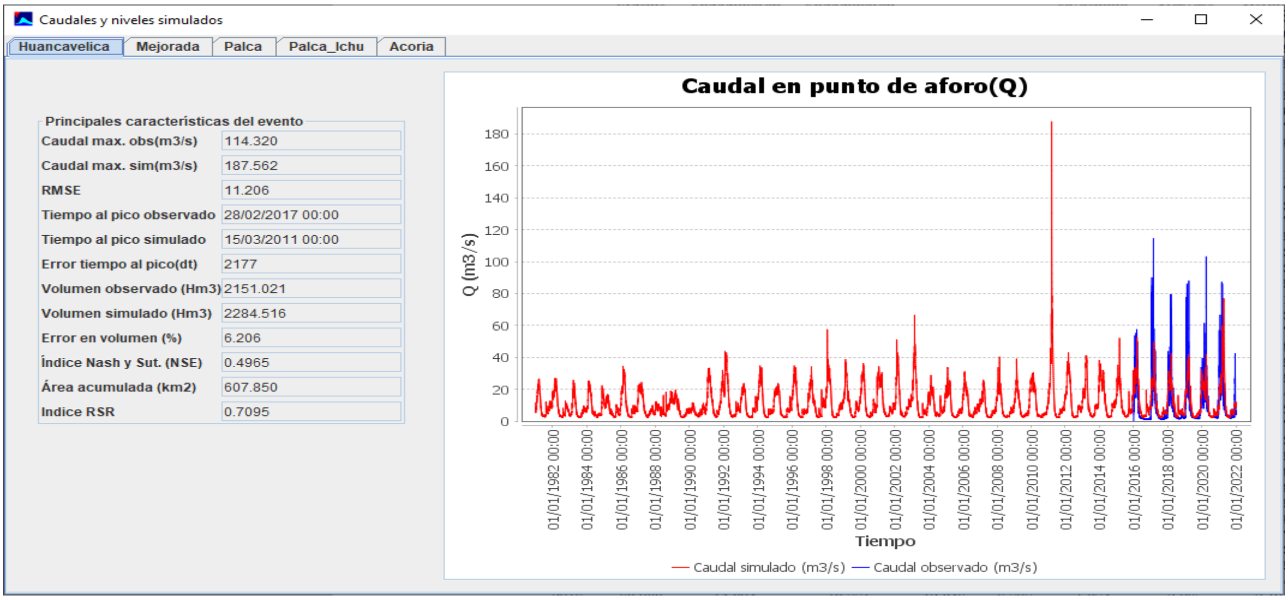
Fig. 8 Soil textures.



Principales caracteristicas del evento

Caudal max. obs(m3/s)	114.320
Caudal max. sim(m3/s)	63.624
RMSE	14.018
Tiempo al pico observado	28/02/2017 00:00
Tiempo al pico simulado	15/03/2011 00:00
Error tiempo al pico(dt)	2177
Volumen observado (Hm3)	2151.021
Volumen simulado (Hm3)	1192.195
Error en volumen (%)	-44.575
Índice Nash y Sut. (NSE)	0.2122
Área acumulada (km2)	607.850
Indice RSR	0.8876

Fig. 9 Uncalibrated results.



Principales caracteristicas del evento

Caudal max. obs(m3/s)	114.320
Caudal max. sim(m3/s)	187.562
RMSE	11.206
Tiempo al pico observado	28/02/2017 00:00
Tiempo al pico simulado	15/03/2011 00:00
Error tiempo al pico(dt)	2177
Volumen observado (Hm3)	2151.021
Volumen simulado (Hm3)	2284.516
Error en volumen (%)	6.206
Índice Nash y Sut. (NSE)	0.4965
Área acumulada (km2)	607.850
Indice RSR	0.7095

Fig. 10 Calibrated results.

Table 6 Corrective factors.

Corrective factors	Uncalibrated	Calibrated
FC-1 Static storage	0.50	0.01
FC-2 Evapotranspiration	1.00	1.30
FC-3 Infiltration	0.50	0.10
FC-4 Direct runoff	1.00	1.80
FC-5 Percolation	0.50	0.03
FC-6 Interflujo	10.00	20.00
FC-7 Deep underground flow	1.00	0.50
FC-8 Base flow	200.00	150.00
FC-9 Speed in river network	0.50	0.70
FC-0 Precipitation escalation	1.00	1.10

Table 7 Simulated event features.

Events	Uncalibrated	Calibrated
Maximum flow obs. (m^3/s)	114.32	114.32
Maximum flow rate yes (m^3/s)	63.062	187.562
Mean square error (RMSE)	14.02	11.206
Time to observed peak (h)	28/02/2017 00:00	27/02/2017 23:00
Simulated peak time (h)	15/03/2011 00:00	15/03/2011 15:00
Peak-time error (%)	2,177	2,177
Observed volume (hm^3)	2,151.021	2,151.021
Simulated volume (hm^3)	1,192.229	2,284.516
Volume error (%)	-44.574	6.206
NSE (Nash-Sutcliffe Index)	0.2122	0.5046
Accumulated area (km^2)	607.85	607.85

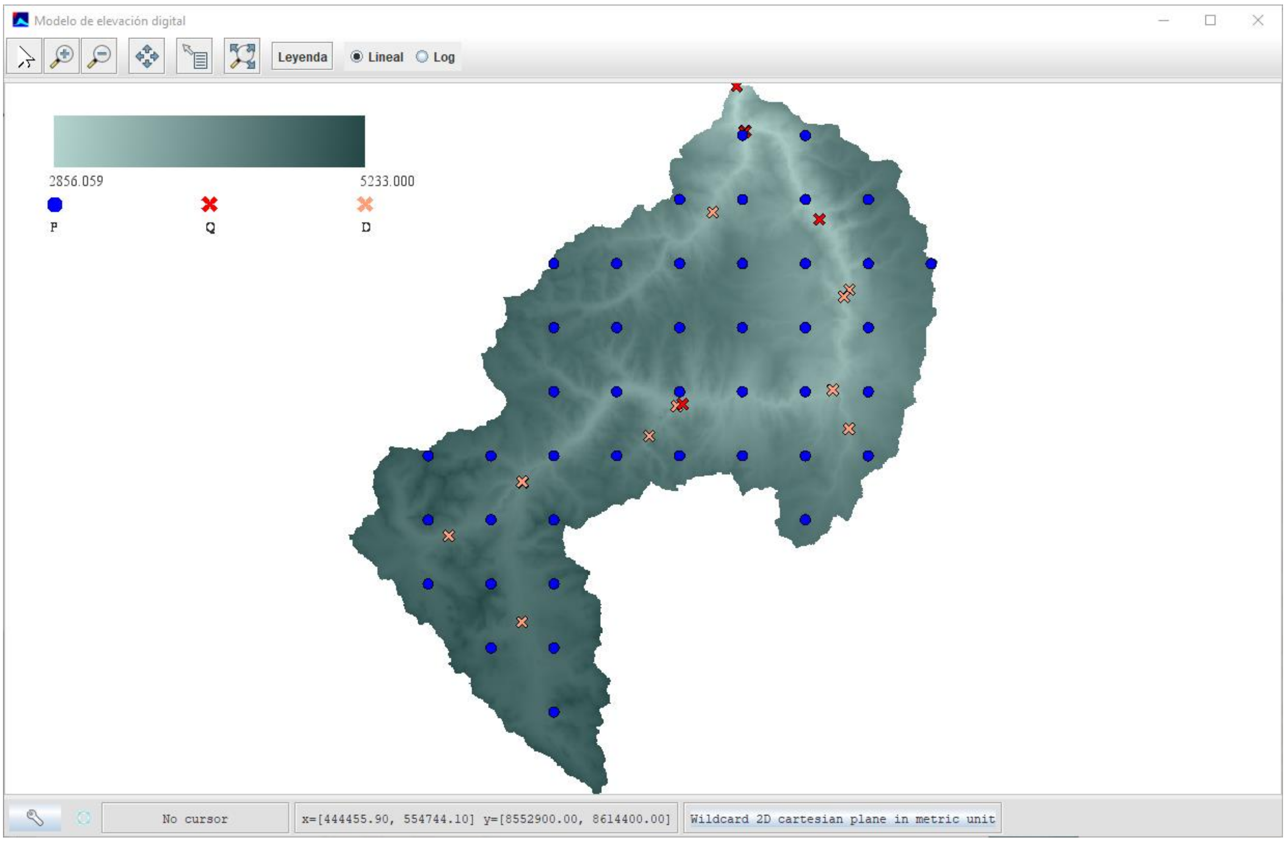
3.4 Model Validation

Fig. 11 shows how the TETIS model reproduces the events present in the simulated periods of interest, presenting an adequate temporal distribution of peak flows according to the calibration phase and a correct spatial distribution of the stations.

3.5 Amount of Sediment

Table 8 shows the result of the simulation in the production of sediments according to the variability of soil conservation at the gauging point located in the hydrological station.

Table 9 shows the results of the simulation of the amount of sediment at the gauging point located at the mouth of the Mantaro River, district of Mariscal Cáceres.



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x=[444455.90, 554744.10] y=[8552900.00, 8614400.00]

Wildcard 2D cartesian plane in metric unit

Fig. 11 Location of input sources and checkpoints.

Table 8 Input parameter values.

Parameters	Minimum value	Maximum value	Average value
Vol. de Arena (m^3)	364,251.21	519,256.23	441,753.72
Vol. de Limo (m^3)	248,169.19	354,849.12	301,509.16
Vol. of Clay (m^3)	289,354.29	395,236.74	342,295.52

Table 9 Output parameter values.

Parameters	Minimum value	Maximum value	Average value
Vol. de Arena (m^3)	912,301.14	1,592,786.65	1,252,543.9
Vol. de Limo (m^3)	824,542.95	1,367,845.62	1,096,194.3
Vol. of Clay (m^3)	521,553.84	964,519.95	743,036.90

Table 10 Summary of parameter results.

Factors	Base	Input 1	Input 2	(S)
Soil parameters				
Silt	1,694,297.62	912,301.14	1,592,786.65	0.6459
Sand	1,397,703.44	824,542.95	1,367,845.62	0.7139
Clay	1,085,332.41	521,553.84	964,519.95	0.5189

3.6. Analysis of Thestability of Parameters

The linear sensitivity model has been used for sensitivity tests of the soil parameters in the sediment sub-model TETIS. The sensitivity parameter (*S*) is calculated using the equation:

$$S=\frac{\left(\frac{O_2-O_1}{O_{12}}\right)}{\left(\frac{I_2-I_1}{I_{12}}\right)}$$

where:

I_1: The minimum value of the input parameter;

I_2: The highest value of the input parameter;

I_{12}: the mean value of I_1 and I_2;

O_1: The output value of I_1;

O_2: The output value of I_2;

O_{12}: the average value of O_1 and O_2.

The dimensionless sensitivity (*S*) parameter quantifies the sensitivity of the input parameter by comparing the relative normalized output change with a normalized input change. In this case compared from the amount of sediment calculated from the textures: silt, clay and sand.

3.7 Results of Sensibilidad

The verified parameters are shown in Table 10, overall average base values, input values and range of calculated sensitivity parameters (S). Input 1 and input 2 are the minimum and maximum values, respectively, of the sensitivity analysis. The total accumulated yield of the sediments it can be seen that the most sensitive was the sand fraction and the least sensitive was the clay fraction.

4. Conclusions

In the basin of the Ichu River the simulation was carried out with the hydrological model TETIS being good, the parameters were calibrated on the scale of the Nash-Sutclifle efficiency index of 0.5046 were obtained with a good fit, achieving validation of the water balance and in this way through the sediment submodel the amount of silt, clay and sand could be determined.

When determining the sensitivity and sediment production of the sand texture it is evident that the range is 0.7139, which is obtained with the comparison of the two gauging points and this also indicates that it is more sensitive.

The sensitivity in the texture dand clay, results in a range of 0.5189 in the points of capacity the variation is lower, this indicates that it is the least sensitive.

When determining the sensitivity in the percentage of silt, it can be seen in Table 10 in the gauging points the sensitivity can vary up to 0.6459, it is in the intermediate of silt and clay.

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