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Ecological Flow Regime as an instrument for environmental impact assessment in an area impacted by the mining industry

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***Abstract* – Mining is an extremely important industry for Peru. However, its environmental impacts can be harmful, especially if they affect bodies of water near communities. In this sense, new environmental management instruments are being implemented. In this work, the ecological flow of a river affected by mining activity will be evaluated using the Tennant-Montana method. Taking the Santa River basin as a case study, the results showed that mining does not represent an activity that represents an exhaustive demand for water in the evaluated basin.**

***Keywords*-- Ecological flow, Environmental management, Mining activity, Santa River, Tenant-Montana methodology.**

I. Introduction

The mining industry is a very important economic activity in Peru, contributing almost 15% to the national gross domestic product (GDP). However, since mining operations are mainly carried out in high Andean areas, there is a risk of socio-environmental conflict due to the impacts on bodies of water [1].

The mining industry reuses water within its operations, disposing only a small percentage in bodies of water close to its operations. This eliminated effluent is previously treated to comply with current environmental legislation. However, old mining in Peru has left a large amount of mining waste (tailings) disposed near water streams and rivers [2]. Mining companies implement their environmental management programs based on the scope of their operations. The relative importance of an environmental impact depends on its direction, geographic extent, magnitude, duration, frequency and reversibility.

Regarding water demand, several instruments for measuring water resources have been used, such as: elevation of the groundwater table, water pressure and water quality, among others [3]. However, the topic of ecological flow of a body of water has been little or not at all explored [4].

In order to preserve a minimum quantity of good quality water in rivers, which allows maintaining a natural and healthy ecosystem, it is necessary to determine their ecological flow (EF) [5,6]. There are various methodologies for assessing ecological flows, each of which uses different criteria and thresholds. These methodologies include hydrological, hydraulic, hydrobiological (habitat simulation), holistic and hybrid approaches [7-9]. On the other hand, the Tennant method (Montana) that has been developed for river flow studies for special regions in the USA has been used by other countries successfully [9-12].

This paper proposes to work with data from the Santa River in Peru using hydrological methods, which have as their main input data the records of daily, weekly, monthly or annual flow measurements. In this case, the Santa River, which is part of the Pacific basin, of the Pacific hydrographic region in the Ancash region, Peru, has a predominant mining activity zone and is therefore considered suitable for carrying out the study in question.

Subsequently, with the defined methodology and the validated field data, the results obtained can be analyzed to define and evaluate the impact of mining on the ecological flow of the Santa River; where it will be confirmed that this industry does not require massive consumption of water resources nor endanger the continuity of the ecosystem of the studied basin.

II. Methodology

A. *Case study*

Peru has three hydrographic basins: the coastal basins that drain their waters into the Pacific Ocean, the basins that drain into the Amazon, which flows into the Atlantic, and the endorheic basin of Lake Titicaca [13]. For the study analysis, the Santa River was chosen, which belongs to the Pacific basin. The Santa River is the second river with the highest flow on the Peruvian coast.

The Santa River basin is located on the central coast of Peru, in the department of Ancash; politically it comprises 12 provinces and 69 districts. It is bordered by the Cordillera Blanca to the east, which is the longest glacial chain in Peru, and by the Cordillera Negra to the west, which is a mountain chain lacking glaciers. It has an area of 11,596.51 km^2 and a perimeter of 960.302 km (Figure 1). The average length is approximately 320 km and an average width of 38 km [14].

Its main river, the Santa, has a length of 316 km and an average slope of 1.4%, whose source is the Ancash lagoon, which is located at the south-east end of the Callejón de Huaylas, at an approximate height of 3944 m.a.s.l. between the coordinates 09°56’40¨ south latitude and 77°11’44¨ west latitude. The Santa River basin has a maximum altitude of 6768 m.a.s.l. corresponding to the Huascarán snow-capped mountain, an average altitude of 2100 m.a.s.l. (Caraz) and a minimum altitude of 0 m.a.s.l. corresponding to the mouth of the Pacific Ocean [15]. The Santa River has its origin in the Aguash Lagoon, which is located at the southeastern end of the Callejón de Huaylas, at an approximate height of 3,944 meters above sea level [16].

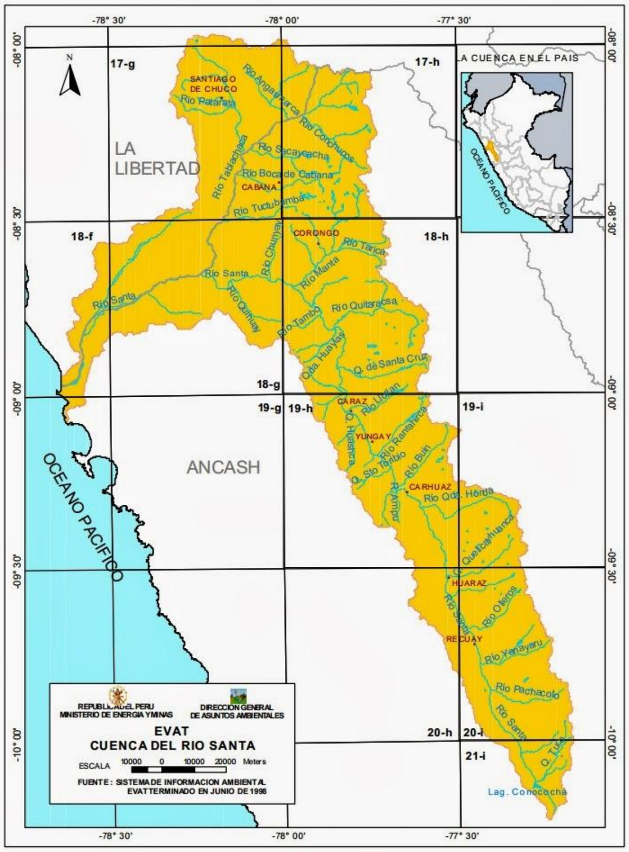

Fig. 1 Santa River Basin, Ancash region, Peru [16].

The Santa River flow rate is recorded by the National Water Authority of Peru (ANA) and has 15 hydrometric monitoring stations. Of the total number of stations available, three of them are located on the main axis of the Santa River, with the remaining ones located on different tributaries throughout the entire basin (Figure 2). The three stations closest to the Rio Santa are: Condorcerro, Balsa and Recreta [17,18].

The volumes of water granted as water use licenses for valleys that the Santa River supplies, such as the Santa Valley, Lacramarca, Nepeña, Guadalupito, Chao, and Virú, are reported. It is important to mention that this balance does not take into account the water consumption that will be generated by the hydroelectric plants and their effect on the river flow [17,18].

1) *Water Supply*

The water supply of a basin also corresponds to the volume of water available to satisfy the demand generated by human social and economic activities.

- **Water Source**

The water availability of this basin amounts to 4788.45 hm^3/year, as can be seen in the Table I [17].

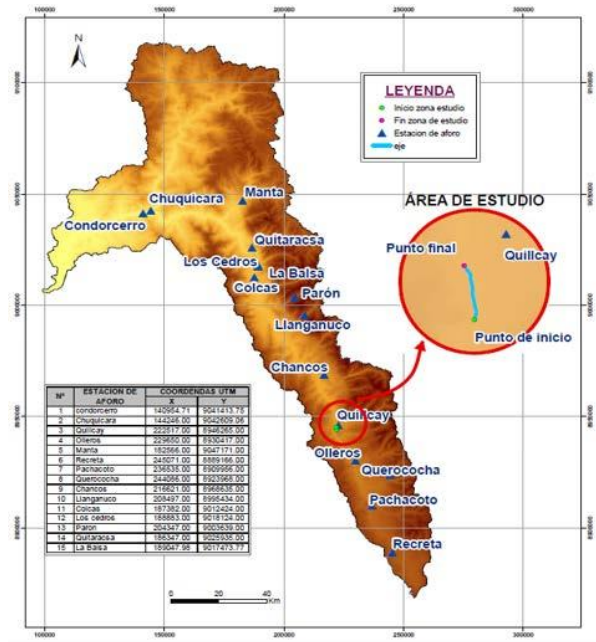

Fig. 2 Environmental monitoring stations in the Santa River basin [18].

TABLE I
TRIBUTARY WATER RESOURCES IN THE SANTA RIVER BASIN [17].

Tributary to a watercourse - Average supply (hm^3/year)			
La Balsa	1209.85	Palo Redondo	67.68
Chuquicara	1080.19	Recreta	66.50
Quitaracsa	255.04	Collota	56.15
Chancos	248.09	Queracocha	52.78
Alto Manta	246.42	Parón	42.35
Quilcay	235.71	Rajucolta	42.11
Colcas	168.06	Bajo Manta	41.23
Olleros	149.27	Santo Toribio de Shupluy	36.86
Condorcerro	135.81	San Luis - Yungar	35.39
Pachacoto	129.07	Chinchayhuasi	34.33
Medio Bajo Santa	87.96	Aguascocha	27.45
Ampu	83.09	Lag. Rajucolta	17.17
Llanganuco	79.33	Cullicocha	6.49
Medio Alta Santa	76.52	Bajo Santa Valle	6.20
Los Cedros	71.33		
Total = 4788.43 (hm^3/year)			

- **Precipitation**

The Santa River basin is divided into two sectors: the “dry” basin (sea level up to 1800 meters above sea level) where rainfall is less than 250 mm. And the “wet basin” (between 1800 and 4200 meters above sea level) where average annual rainfall ranges between 250 mm and 1200 mm respectively. The dry sector of the basin does not contribute flow to the runoff [17]. The total multi-year precipitation (mm) in the Santa River Basin is presented in the Table II.

TABLE II
TOTAL MULTI-YEAR PRECIPITATION (MM) IN THE SANTA RIVER BASIN [17].

Tributary to a watercourse - Precipitation (mm)			
Aguascocha	993.60	San Luis-Yungar	808.10
Pachacoto	974.00	Colcas	802.60
Chancos	959.40	Santo Toribio de Shupluy	800.70
Queracocha	955.80	Recreta	779.20
Quilcay	946.20	Quitaracsa	770.40
Lag. Rajucolta	941.70	Chuquicara	764.50
Olleros	930.60	Rajucolta	760.90
Cullicocha	918.00	Alto Manta	725.80
Parón	914.80	Condocerro	568.40
Llanganuco	894.80	Medio Alta Santa	560.00
Collota	847.90	Bajo Manta	536.10
Los Cedros	842.10	Palo Redondo	269.00
La Balsa	826.00	Medio Bajo Santa	228.40
Ampu	816.10	Bajo Santa Valle	76.40
Chinchayhuasi	814.80		
Total = 22026.30 (mm)			

- **Flow**

The months of greatest flow in the Santa River are from December to April (rainy season) so they are the months of greatest interest for study. While the period of minimum flow (low water) is between June and September, the remaining months correspond to transition months. The Santa River discharges 71.06% of its total annual volume during the rainy season, which corresponds to 3058.15 MCM; and the dry season (4 months) discharges 11.95% of this volume, which is equivalent to 514.28 MCM [15,17]. The multiannual average flow of the Santa River Basin is presented in Table III.

TABLE III
MULTIANNUAL AVERAGE FLOW OF THE SANTA RIVER BASIN [17].

Tributary to a watercourse - Average flow (m^3/s)			
La Balsa	38.68	Palo Redondo	2.16
Chuquicara	34.49	Recreta	2.13
Quitaracsa	8.12	Collota	1.79
Chancos	7.90	Queracocha	1.68
Alto Manta	7.86	Paron	1.35
Quilcay	7.51	Rajucolta	1.34
Colcas	5.36	Bajo Manta	1.32
Olleros	4.76	Santo Toribio de Shupluy	1.18
Condorcerro	4.34	San Luis – Yungar	1.13
Pachacoto	4.11	Chinchayhuasi	1.10
Medio Bajo Santa	2.81	Aguascocha	0.88
Los Cedros	2.70	Lag. Rajucolta	0.54
Ampu	2.66	Cullicocha	0.21
Llanganuco	2.52	Bajo Santa Valle	0.20
Medio Alto Santa	2.45		
Total = 152.85 m^3/s			

2) Water Demand

The area near the Santa River has a population that implies a demand and consumption of water resources. According to the consulted bibliography, four types of water demands have been identified: population, agricultural, industrial and/or mining, and energy.

- **Population Use**

Table IV shows the water demands in the basin, as well as the water deficits during dry periods (June to November) [17].

TABLE IV
WATER BALANCE ACCORDING POPULATION DEMAND [17].

Tributary to a watercourse	Total	Served	Deficit
Bajo Santa Valle	9.85	9.85	0.0
Quilcay	7.28	7.28	0.0
La Balsa	4.63	4.63	0.0
Chuquicara	1.46	1.46	0.0
Shupluy	0.60	0.60	0.0
Corongo	0.14	0.14	0.0
Others [a)]	0.00	0.00	0.0
Total = 23.96 hm^3/year			

[a)] The other tributaries did not contemplate water demand per population.

- **Agricultural Use**

The agricultural demand of the Santa River basin is 1489.77 hm^3 with a deficit for this type of use of 117.85 hm^3. The values are summarized in Table V [17].

TABLE V
WATER BALANCE DEMAND OF THE SANTA RIVER BASIN [17].

Tributary to a watercourse	Total	Served	Deficit
La Balsa	166.6	129.14	37.47
San Luis – Yungar	43.16	15.68	27.48
Ampu	39.08	21.04	18.04
Recreta	35.02	24.28	10.74
Shupluy	20.42	12.24	8.18
Paron	47.31	40.47	6.84
Chinchayhuasi	13.84	7.35	6.48
Bajo Santa (Valle)	150.4	149.12	1.28
Colcas	62.10	61.17	0.93
Medio Bajo Santa	752.55	752.23	0.33
Chuquisaca	82.70	82.63	0.07
Rajucolla	6.47	6.46	0.01
Collota-Quitaracsa	3.59	3.59	0.00
Corongo	24.07	24.07	0.00
Llanganuco	0.94	0.94	0.00
Olleros	3.45	3.45	0.00
Quillcay	32.13	32.13	0.00
Other[a)]	---	---	---
Total Deficit = 117.85 hm^3/year			

[a)] The other tributaries did not take into account.

- **Industrial and Mining Use**

The water demand required by this sector amounts to 5.39 hm^3. The values of required and deficit of water are summarized in Table VI [17].

TABLE VI
WATER BALANCE ACCORDING INDUSTRIAL AND MINING DEMAND [17].

Tributary to a watercourse	Total	Served	Deficit
La Balsa	1.13	0.91	0.22
Chuquicara	2.28	2.27	0.01
Bajo Santa (Valle)	1.87	1.87	0.00
Chinchayhuasi	0.09	0.09	0.00
Paron	0.09	0.09	0.00
Chancos	0.02	0.02	0.00
Other[a)]	---	---	---
Total Deficit = 0.23 hm^3/year			

[a)] The other tributaries did not take into account.

- **Energy Use**

In the Santa River basin, there are hydroelectric plants such as Cañón del Pato (the most important), Quitarcsa I, Santa Cruz, C.E. Pariac, C.E. Huinac and the mini power plant of the Santa Mountain Guides House. We should also mention the Virú Hydroelectric Plant that uses the waters of the Santa River to produce energy [17]. The total nominal power and flow required of hydroelectric plants is presented in Table VIII.

TABLE VII
TOTAL NOMINAL POWER AND FLOW REQUIRED OF HYDROELECTRIC PLANTS [17].

Hydroelectric Plant	Total nominal power (MV)	Flow (m^3/s)
Cañón del Pato	267	78
Quitarcsa I	114	15
Virú	7.5	9
Other[a)]	---	---
Total Flow = 102 m^3/s		

[a)] The other hydroelectric plants have not been considered due to their low flow demand.

- **Other uses.**

Other uses include other activities such as fish farming, recreation, tourism, among others. The total demand for this type of use amounts to 26.62 hm^3 [17]. Table VIII summarizes water demand based on water use.

TABLE VIII
GLOBAL WATER BALANCE DEMAND IN THE SANTA RIVER BASIN [17].

Types of use	Consumption	Volume (%)
Agricultural	1489.76	96.56
Population	23.96	1.55
Mining Industrial	5.39	0.35
Energy	0.19	0.01
Others	23.50	1.52
Total	1542.8	100

3) Environmental problems in the Santa River basin

Among the activities with the greatest impact on the basin and which have a direct impact on its ecosystems, the following have been identified:

- Change in land use due to the growth of agricultural areas, urban growth and infrastructure development.
- Deficient sanitation systems (treatment of wastewater and solid waste).
- Forest fires.
- Informal tourism activity.
- Mining activity, mainly informal mining.
- Overgrazing of high Andean grasslands.
- Poor hunting and fishing.
- Use of agrochemicals.

Total volume of unauthorized wastewater discharges in the Santa River is presented in Table IX.

TABLE IX
VOLUME OF UNAUTHORIZED WASTEWATER DISCHARGES [17]

Sector	Flow (m^3/year)
Sanitation (domestic-municipal)	44475220.8
Mining	6016142.4
Industrial	614952.0
Tourism	201830.4
Paron	54308145.6

- **Mining activities in the Santa River basin**

The geology of the Santa River basin has allowed mining activities to develop due to its metallic and non-metallic deposits. Figure 3 shows the four largest mining operations in the Santa River basin. These companies are: Minera Barrick S.A., Minera San Simon S.A., Minera Austria Duvaz S.A.C. and Minera Lincuna S.A. However, the tributaries of the Santa River are seriously affected by old mining practices that have generated environmental liabilities, as well as by unprocessed or untreated urban effluents and solid waste that alter the quality of the waters in the basin. Significant concentrations of heavy metals such as iron, lead, zinc, copper, cadmium, arsenic and antimony have been measured in areas affected by mining tailings such as Ticipampa [19].

B. Methodology

1) Data required

For the respective evaluation, it will be necessary to have the following information:

- hydrometric information of three environmental stations: Parón, Llanganuco and Queracocha.
- location map of the Santa River basin and the active and nearby mining units.

2) Application of Tennant Methodology

To estimate the value of the Ecological Flow in the Santa River basin, the following steps were taken:

- Collect and organize information from Hydrometric Stations. The consistency of this data was verified with the ANOVA test.
- Once all the data has been processed and the homogeneity of the average annual flows has been verified, the data from each hydrometric station will be divided into two periods from 1954 to 1978 and from 1979 to 2003.
- The Classified Flow Curve (CFC) is applied, also known as the Flow Duration Curve (FDC).
- For each set of years, the average monthly flow, average annual flow, maximum and minimum regime values, average, standard deviation, and coefficient of variability will be determined.
- For each of these periods, the Ecological Flow will be determined by applying the Tennant methodology.
- In addition, the Reference Ecological Flows will be determined. In this case, the provisions established by the highest competent authority in matters of water resource management will be used: the ANA.

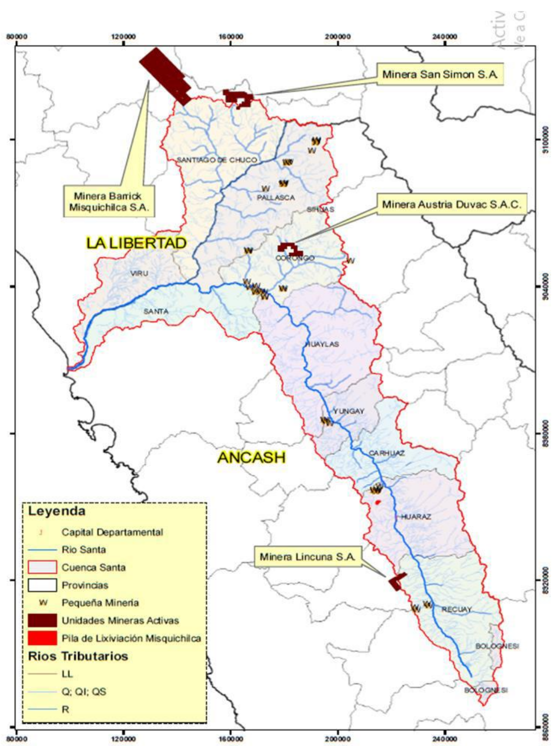

Fig. 3 Active mining operations in the Santa River basin [15].

3) *Additional considerations*

The methodology of Tennant follows the following criteria [20,21]:

- 10% of the average annual flow is the minimum recommended to maintain a habitat that allows the survival of most forms of aquatic life (both flora and fauna) in the short term.

- 30% of the average annual flow is recommended to maintain a habitat suitable for the survival of the various forms of aquatic life.

- 60% of the average annual flow is recommended to generate a habitat with excellent to exceptional characteristics for most forms of aquatic life, during the initial growth periods.

III. Results

Below are the results obtained from the analyses carried out:

A. *Consistency Analysis of Hydrometric Station Information*

For the analysis of data consistency, reviews were applied through:

➢ Visual Analysis of Hydrograms

The analysis of the Figure 4 shows that the levels of variation in the average annual flows of the Parón station are moderate, in many cases even minimal. In the case of the Llanganuco station, it presents a variation in the average annual flows greater than that of the Parón station. Meanwhile, at the Queracocha station, the average annual flows are more stable in the first years (1954-1990) than in the last ones (1991-2003), where there is a moderate variation in the average annual flow.

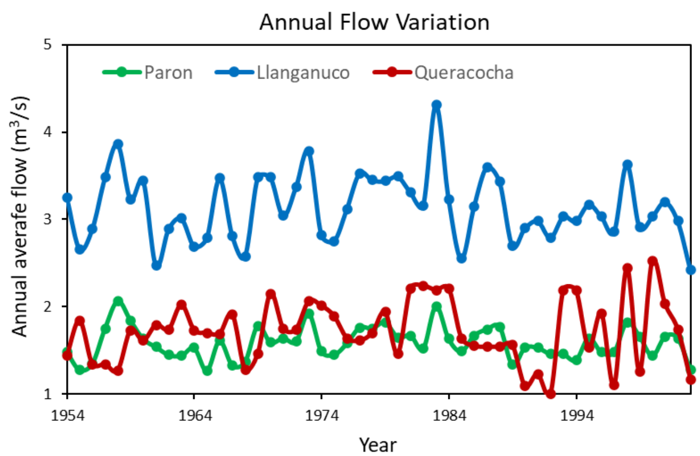

Fig. 4 Annual flow variation.

➢ Statistical Analysis, ANOVA test

The determination of the calculated *t* will be carried out using the following formula [22]:

$$t = \frac{(\overline{x}_1 - \overline{x}_2)}{s\sqrt{\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \qquad (1)$$

Where $\overline{x}_1$ and $\overline{x}_2$ are the means of the two groups, S is the combined standard deviation of the two groups, n_1 and n_2 are the sample sizes of the two groups [22].

$$F_c = \left(\frac{S_1}{S_2}\right)^2 \qquad (2)$$

Where S_1 and S_2 are the standard deviations of each group. The results are presented in Table X.

TABLE X
SUMMARY OF THE RESULTS OBTAINED THROUGH ANOVA STATISTICAL ANALYSIS.

hydrometric stations	Mean ($t \leq t_t$)	Standard Deviation ($F_c \leq F_t$)
Parón	$0.210 \leq 2.0106^{a)}$	$1.4630 \leq 1.9837^{b)}$
Llanganuco	$2.883 \geq 2.0106^{a)}$	Hypothesis Rejected
Queracocha	$0.415 \geq 2.0106^{a)}$	$0.2807 \leq 1.9837^{b)}$

[a)] t_t = t tabular = 2.0106; [b)] F_t = F tabular = 1.9837

B. Determination of Ecological Flow – Tennant Methodology

Next, the value of Minimum or Acceptable Ecological Flow, Good and Excellent, will be entered for the hydrometric station, based on what was found by the hydrological data (Figures 5, 6 and 7). In yellow, blue and green the ecological flows with minimum, acceptable and excellent values, respectively.

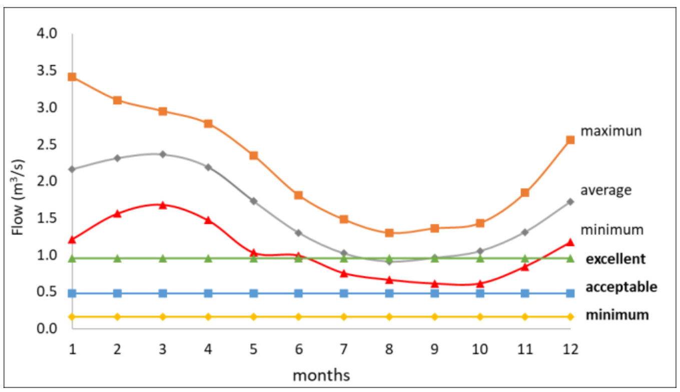

Fig. 5 Ecological Flow Curves - Parón Station.

Figure 5 shows that the measured natural flows are above the minimum and acceptable ecological flows. Also, from December to May, the natural flow values are above the ecological flow classified as excellent.

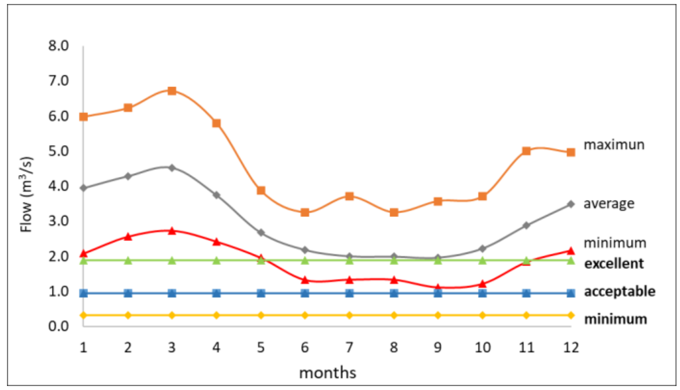

Fig. 6 Ecological Flow Curves - Llanganuco Station.

Figure 6 shows that the measured natural flows are above the minimum and acceptable ecological flows throughout the year. Also, from December to May, the natural flow values are above the ecological flow classified as excellent; the rest of the months the minimum natural flow value is above the acceptable value.

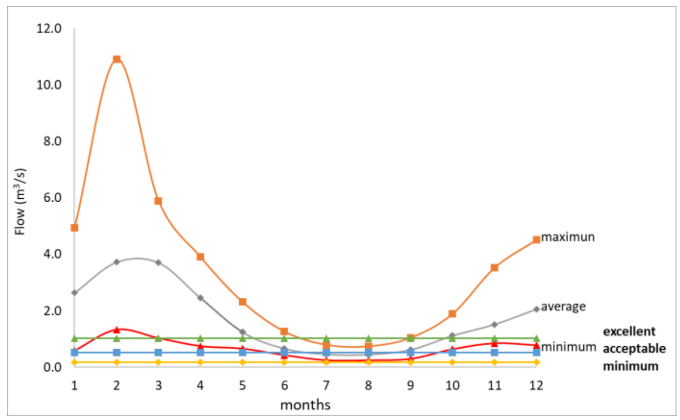

Fig. 7 Ecological Flow Curves - Queracocha Station.

Figure 7 shows that the measured natural flows are above the minimum ecological flow throughout the year. Also, only in the month of February is the natural flow above the ecological flow classified as excellent. The minimum natural flow is very close to the minimum ecological flow value during the months of July to September, months of greatest low water.

C. Ecological Reference Flow (ANA)

The value of the Ecological Reference Flow will be determined based on current Peruvian legislation (RJ N°098-2016-ANA) [23]. This legal norm establishes the study parameters if a hydrological/hydraulic method is used to determine the ecological flow.

This methodology establishes the following calculation process:

- The years to be worked on are defined and the series of average flows are ordered in columns, where each column will represent the value of a specific month.

- In a column to the left of the data series, the order number of each piece of data is placed (m), starting from 1 to N, where N represents the number of average flows.

- In another column to the right of the column where the order of each piece of data is indicated, the probability p=m/N*100 is calculated

- The other columns will be completed with the average flow data for the remaining months.

-Each column is ordered with the average flows in decreasing order (from highest to lowest).

- The values corresponding to p=95% are calculated; if this value is not found in the probability column, it must be interpolated between the closest values to determine this value (linear interpolation).

The results are presented in figure 8.

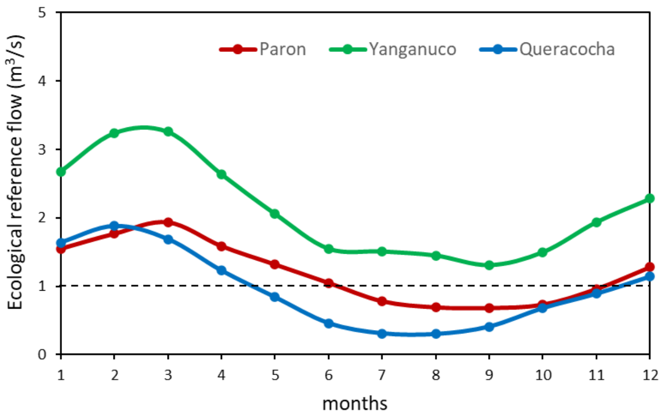

Fig. 8 Ecological reference Flow Curves.

Figure 8 shows the decrease in reference flow between the months of June and November in the Paron station. This behavior is characteristic of the dry season in the high Andean region of Peru. Minimum values less than 1 m^3/s are reported for the months of June to November. Figure 8 shows the decrease in reference flow between the months of June and November. This behavior is characteristic of the dry season in the high Andean region of Peru.

Figure 8 (Llanganuco station) also shows a decrease in flow due to the low water level. However, it is observed that the minimum values during the year are above 1 m^3/s.

In Figure 8 (Queracocha station), the minimum flow values are more evident in this season, all of them (except for the range of months from December to April) being less than 1 m^3/s. The flow rates are so low that maximum flow rates below 1 m^3/s are reached between the months of May and November.

D. Comparison of estimated flow rates

In order to evaluate the difference between applying the Tennant method or the ANA Reference method, a comparison of determined flow rates was made. In the case of the Ecological Flow, the average monthly values were used. The results are presented in the following figures.

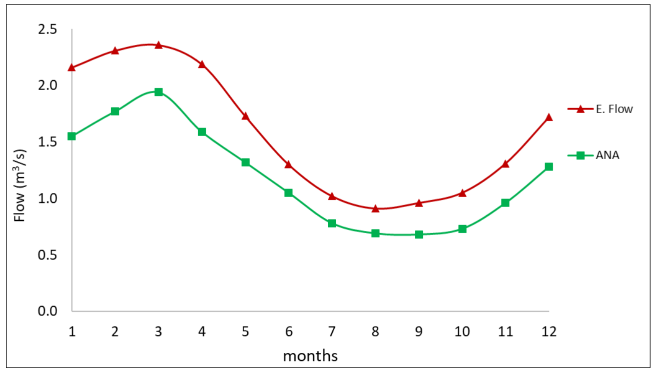

Fig. 9 Ecological and reference flows (ANA) of the Parón station.

Figure 9 shows the ecological and reference flows at the Paron station. It can be observed that both methods follow the same trend. The Tennant method offers more conservative flow values. The smallest difference between both methods is observed in the month of August (0.22 m^3/s), while the largest difference is reported in the month of January (0.61 m^3/s).

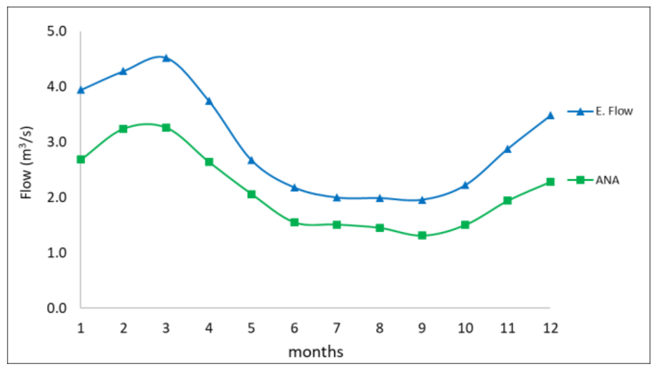

Fig. 10 Ecological and reference flows (ANA) of the Llanganuco station.

Figure 10 shows the ecological and reference flows at the Llaganuco station. It can be observed that both methods follow the same trend. The Tennant method provides more conservative flow values. The smallest difference between both methods is observed in the month of July (0.49 m^3/s), while the largest difference is reported in the months of January (1.26 m^3/s) and March (1.26 m^3/s).

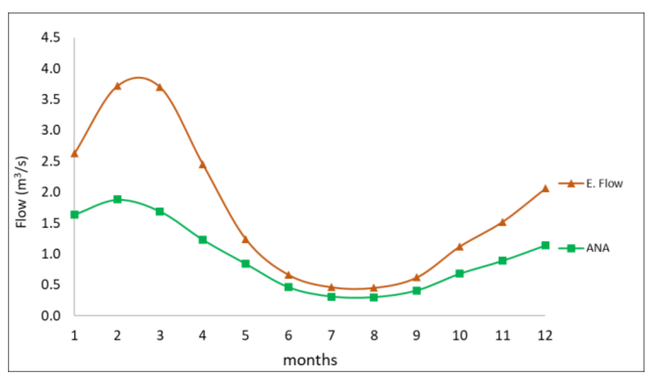

Fig. 11 Ecological and reference flows (ANA) of the Queracocha station.

Figure 11 shows the ecological and reference flows at the Queracocha station. It can be observed that both methods follow the same trend from April to December. High and unexpected values are observed for the months of February and March. The smallest difference between both methods is observed in the months of July (0.15 m^3/s) and August (0.15 m^3/s), while the largest difference is reported in the month of March (2.01 m^3/s).

IV. Conclusions

The Water Balance determined that the demand for water by the mining industry represents only 0.35% of the total consumption of the Santa River basin; a value that is insignificant when compared to the 96.37% demanded by the population surrounding the basin.

It has been shown that it is feasible to use the tenant method to calculate the Ecological Flow and its respective classifications for the Parón, Llanganuco and Queracocha stations.

The determination of the Ecological Flow demonstrated that this Environmental Management instrument does not consist of a single and exclusive value, but will depend on the hydrometric station (which will determine the level of rainfall) and the water consumption by the population or industry.

The application of Tennant's methodology to determine the ecological flow of rivers will allow for a more sustainable and appropriate management of water resources, facilitating coexistence between the different actors (population, mining industry, other industries and others) that settle in this same basin.

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