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The water-energy nexus: Analysis of the water flow of the Coca Codo Sinclair Hydroelectric Project

Nexo agua – energía: Análisis del flujo hídrico del Proyecto Hidroeléctrico Coca Codo Sinclair

Sebastián Jiménez-Mendoza[1], Francisco Terneus-Páez[1,2,*]

Abstract

This article analyzes the interrelation between water and energy, taking as a case the analysis of the water flow of the Coca Codo Sinclair Hydroelectric Project. It investigates the case of this emblematic project, where the water used for consumption would decrease the inflow to the driving tunnel, which would risk its power generation capacity. A bibliographic research is used for this purpose. It is concluded that the Chalpi Grande project and the subsequent phases of the Ríos Orientales; and the Cayambe Pedro Moncayo irrigation projects and the Pesillo Imbabura potable water would reduce the inflow rate by up to 11% and, therefore, their energy production, demonstrating the need to plan the use of these resources considering their nexus.

Keywords: Water-energy nexus, Coca Codo Sinclair Hydroelectric Project, consumptive use of water.

Resumen

Este artículo analiza la interrelación existente entre el agua y la energía, tomando como caso el análisis del flujo hídrico del Proyecto Hidroeléctrico Coca Codo Sinclair. Investiga el caso de este proyecto emblemático, donde los usos consuntivos del agua disminuirían el caudal de entrada al túnel de conducción, arriesgando con esto su capacidad de generación eléctrica. Se utiliza para ello una investigación de tipo bibliográfica. Se concluye que el proyecto Chalpi Grande y las fases siguientes de ríos orientales; y los proyectos de riego Cayambe-Pedro Moncayo y de agua potable Pesillo-Imbabura afectarían el caudal de entrada hasta en un 11 % y con ello su producción de energía, con lo cual queda en evidencia la necesidad de planificar el aprovechamiento de estos recursos considerando su nexo.

Palabras clave: Nexo agua – energía, Proyecto Hidroeléctrico Coca Codo Sinclair, uso consuntivo del agua.

[1,*]Department of Energy and Mechanics, Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador http://orcid.org/0000-0001-7031-5954
[2]Doctorate Program in Technological Management – Escuela Politécnica Nacional, Quito, Ecuador.
Autor para correspondencia ✉: cfterneus@espe.edu.ec http://orcid.org/0000-0001-5372-0288

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1. Introduction

The water-energy-food nexus has been under discussion since the Bonn Conference in 2011, in which it was recommended that these resources are considered in an integrated fashion, and concentrating in assuring that the interdependence between them is explicitly identified in decision making [1]. Three years later, during the Global Water Security & Sanitation Partnership (GWSP) conference, the research and political communities around the world issued a call to develop strategies to address this nexus in a comprehensive manner [2]. With the current growth rate of the world population, the agricultural sector faces the challenge of doubling the production of food for 2050 [3]. About 71% of worldwide water withdrawals are due to such sector [4]. Since for 2050 it will be required 55% more water to increase the generation of electricity and to meet consumption of households, it is projected that more than 40% of world population will live under severe hydrological stress [5]. Nevertheless, few authors have addressed the issue of how to turn the mainly theoretical concept of the water-energy-food nexus, into practical evaluation approaches. Albretch *et al.* [6] state that, despite the promising conceptual approach, the use of the aforementioned nexus to systematically evaluate the connection of the resources has been limited. Middleton *et al.* [7] mention that the water-energy-food nexus has not been practically integrated yet. Similarly, Leck *et al.* [8] ask for the practical application of such nexus in future scientific research work.

Denise Lofman *et al.* [9], regarding the nexus between water and energy, state that it will be difficult to simultaneously fulfill the needs of the users and protect these valuable resources, regarding agricultural, industrial and residential issues. Pittock Jamie *et al.* [10] showed the significant influence of the nexus between the supply of hydroelectric energy and food on the water basin. According to Fisher *et al.* [11], the water-energy nexus for the generation of electricity causes more severe problems such as pollution and CO_2 emission. Lubega *et al.* [12] state that it is possible to measure the water energy nexus using models that relate electric energy and municipal water consumption.

Various current trends raise the urgency to address the water-energy nexus in an integrated and proactive manner. In the first place, climate change has begun to affect precipitation and temperature patterns. Secondly, population growth and regional migration trends indicate that it is probable that there is an increase in the number of inhabitants in arid zones. At last, new technologies in the energy and water fields may change the demand of these resources [13].

According to the International Energy Agency [14], worldwide water consumption will increase 60% by 2040, thus affecting hydroelectric plants whose water withdrawals will raise less than 2%. Due to the population growth and the modifications in the feeding patterns, food consumption is increasing in almost all regions on earth. It is expected that for 2050 it will be necessary to produce 200 million tons of meat and 1 billion additional tons of cereal to fulfill the increasing food demand. For this reason, agriculture is responsible for 90% of the consumptive use of water [15].

As a consequence of the aforementioned global issues, Ecuador is in the need of addressing and planning the use of its hydrological resources. Article 30 of Ecuador's Law of Hydrological Resources states that: "The State and its institutions in the scope of their competences are responsible of the integrated administration of the hydrological resources in each basin. As a consequence, they are obligated to regulate the uses of water, and take actions to preserve its quantity and quality by means of a sustainable management based on technical regulations and quality parameters" [16].

On the other hand, article 313 of Ecuador's Constitution states that: "The State reserves the right to administer, regulate, control and manage strategic sectors; energy in all forms are considered strategic sectors. . . " [17]. The purpose of this paper is to analyze the case of the Coca Codo Sinclair Hydroelectric Project CCSHP), as an example of the nexus between water and energy, where the consumptive uses of water would reduce the inflow to the transmission tunnel, thus putting at risk electric generation capacity of this emblematic project.

The rest of the paper is structured as follows. Section 1.1 presents a historical overview of the CCSHP, and section 2 (methodology) discusses reports of feasibility and projects that make consumptive use of water. In addition, section 3 analyzes how such projects would affect the inflow to the CCSHP and, at last, section 4 concludes showing the need of planning the water-energy nexus in an integrated manner.

1.1. The Coca Codo Sinclair Hydrolectric Project

The CCSHP is a construction considered as emblematic by the Ecuadorian government. It was built in the origin of the Coca River, in the province on Napo [18]. It was named after the North American geologist Joseph Sinclair who, when going through the such river in the east of Ecuador, identified a sharp curve later called Codo (elbow) Sinclair by local people. This researcher stated that in this place the river had the potential to generate electric energy [19].

The CCSHP was one of the most important projects of the National Electrification Plan, in the basin of the Quijos and Coca Rivers, during the 1970s and 1980s. The Ecuadorian Institute of Electrification (INECEL, Instituto Ecuatoriano de Electrificación) was the company in charge of conducting the studies associated to the project. In particular, two studies were carried out in 1976: pre-feasibility by the Brazilian company Hidroservice, and total available capacity by the Italian consulting companies Electroconsult and Rodio, the Belgian Tractionel and the domestic Ingeconsult, Inelin, Astec y Caminos y Canales [20].

In order to optimize the selected alternative, a feasibility design was carried out between April 1990 and June 1992, corresponding to two continuous stages that would generate a power of 432 (MW) and 427 (MW), respectively, for a total of 859 (MW). This study included adjustments to the project because of an earthquake close to the volcano Reventador in March 1987, which significantly changed the face of the land. The State modified such study in 2007, and redesigned the project to reach a power of 1500 MW [18].

The CCSHP was announced in January 15 2007, being considered of high national interest, and it was included in the Master Plan of Electrification. In that year, two companies were in charge of managing the project: the National Council of Electricity (Conelec) during the first trimester, and the Minister of Electricity and Renewable Energies (MEER) in July. Nevertheless, it is important to remark that the company Termopichincha, of the Ecuadorian State, was designated as the operator of the project in September 2007. Later, Termopichincha and the Argentinian company ENARSA constituted the Consortium Coca Sinclair S.A. [20].

The studies were approved by Conelec in 2008. The hydroelectric company Coca Codo Sinclair S.A. from Quito, put the consulting company ELC-Electroconsult, from Milan, Italy, in charge of the conceptual redesign studies to reach 1500 MW. In 2009 ELC-Electroconsult presented the corresponding final feasibility study. Then, Coca Codo Sinclair S.A. hired SINOHYDRO to do the engineering, and it started the construction [20]. Six years later, on November 18 2016, the CCSHP was inaugurated.

Once the construction was finalized, the CCSHP is constituted by: a water catchment dam with a maximum height of 31.8 m; a spillway with a diversion dam of 13.5 m high and a net width of 160 m; a sand removal equipment with 8 chambers; a 24.8 km long transmission tunnel, with excavation and interior diameters of 9.1 m and 8.2 m, respectively, and a design diameter of 222 m^3/s; a compensating reservoir which comprises a rock-fill dam with a concrete wall of 58 m high, corresponding to a reservoir with a usable volume of 800000 m^3; two 1400 m long concrete pressure pipes with internal diameters of 5.8 and 5.2 m, respectively, a design flow of 139.25 m^3/s) each, and a steel coating in their final section, carry the water from the compensating reservoir to the powerhouse; the powerhouse is a cavern of dimensions 26 × 46.8 × 219.5 m excavated in rock, containing 8 vertical shaft Pelton turbines each with 6 injectors and a power of 187.5 MW, which turbinate the water of the Coca River, that forms where the Quijos and Salado Rivers meet, as can be seen in Figure 1 [21].

Figure 1. Location of the CCSHP [22].

The installed power of a hydroelectric plant, also known as effective nominal power is given by [23].

$$Pi = \eta t \times \eta g \times \eta tr \times \lambda \times Q \times H \qquad (1)$$

Where:

Pi = Effective nominal power (W)
Q = Flow rate entering the pressure pipe (m^3/s)
H = Nominal net height (m)
ηt = Efficiency of the Pelton turbine
ηg = Efficiency of generator
ηtr = transformer efficiency

The data taken from appendix f of the feasibility report of the CCSHP by ELC-Electroconsult [24] are.

H = 604,1 (m)
P = 1500 (MW)
ηt = 91 %
ηg = 97,52 %
ηtr = 99,5 %

Substituting these values in equation (1) and solving for Q results in:

$$Pi = \eta t \times \eta g \times \eta tr \times 9,81 \times Q \times H \times 1000$$

$$Q = \frac{Pi}{\eta t \times \eta g \times \eta tr \times 9,81 \times H \times 1000}$$

$$Q = \frac{1500000000}{0,91 \times 0,9752 \times 0,995 \times 9,81 \times 604,1 \times 1000}$$

$$Q = 286,6 (m^3/s)$$

Since the CCSHP is a run-of-river plant with daily regulation [24], the turbinated flow to generate 1500 MW, i.e. the flow that should enter the two pressure pipes, is 286.6 m^3/s, i.e. 143.3 m^3/s each. According to Synohidro Corporation, (2009), the CCSHP only can generate this power during four hours daily, however, the design flow rate of the pressure pipes is 139.25 m^3/s, namely 278.5 m^3/s both [24].

In 2017, after one year of operation, the CCSHP had produced 66.7% of the expected energy. Between January and December, the plant contributed a total of 5838 GWh to the national interconnected system, below the expected average generation of 8734 GWh [25].

2. Materials and methods

This research is bibliographic, with a descriptive scope. The feasibility studies presented by Inecel in 1992, which shows the historic behavior of the Coca River flow, and by ELC-Electroconsult, which redesigns the study by Inecel, were analyzed. In addition, the projects that would affect the flow coming into the CCSHP, because of the consumptive uses of water, were examined.

2.1. Feasibility studies

In the following, two feasibility reports of the CCSHP will be analyzed. The first one was carried out by Inecel and approved in 1992, and the second was conducted by ELC-Electroconsult and approved in 2009.

2.1.1. Feasibility study of 1992

This feasibility study was carried out by Inecel. To calculate the flow rates of the project, historic data from 1972 to 1987 was considered for the San Rafael cascade and for the Coca River in the El Salado sector [18]. Since the study was conducted in the same river station for an interval of fifteen to twenty years, which include dry, typical and rainy periods, this methodology is widely accepted [26]. Figure 2 illustrates the curve obtained by Inecel, showing the general duration of daily flow rates in El Salado [19]. On the other hand, Figure 3 shows the monthly average flow rates recorded in the Coca River station, in the El Salado sector, along the aforementioned periods.

This way Inecel determined that the average flow rate in the El Salado sector is 292 m^3/s, after taking out 3 m^3/s that were used by the aqueduct Papallacta-Quito, which corresponds to a specific contribution greater than 80 $l/s/km^2$. The steady daily flow rate of 127 m^3/s is guaranteed 90% of the time [18].

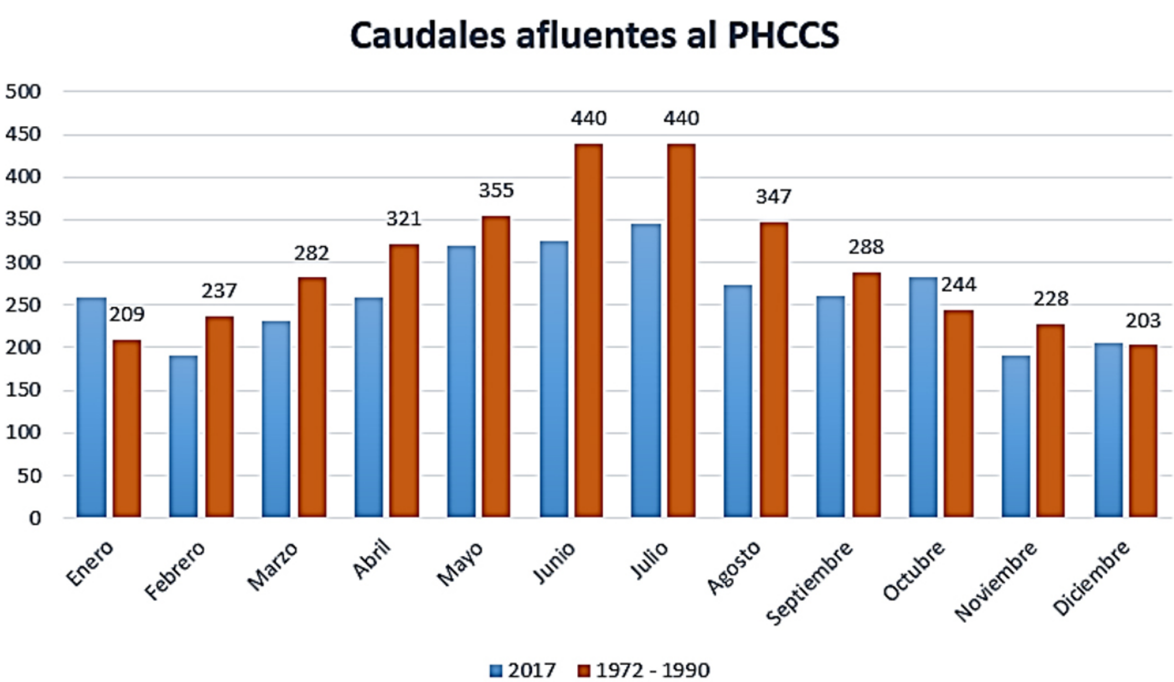

Figure 2. Comparison between the flow rates of the period 1972-1990 and 2017.

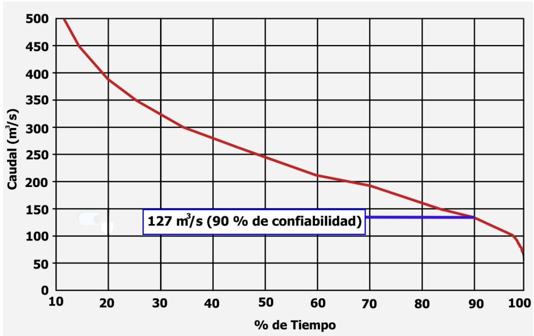

Figure 3. Curve of general duration of daily flow rates in El Salado [19].

The Inecel company decided that the flow rate should be captured in two stages, the first of 63.5 m^3/s and the second of another 63.5 m^3/s, thus reaching a total of 127 m^3/s. In both stages the plant capacity factor remained equal to 0.8 [21].

2.1.2. Current feasibility study of the CCSHP

The current feasibility study of the CCSHP was carried out by ELC-Electroconsult, and was based in the hydrological study conducted by Inecel in 1992, which recorded the historic flow rate of the Coca River [21].

ELC-Electroconsult pointed out that in order to generate the 1500 MW installed in the powerhouse, keeping the same losses of the feasibility study, a flow rate of 278.5 m^3/s is required in the pressure pipe, which corresponds to a flow rate of 222.7 m^3/s entering the compensating reservoir. Subtracting an average flow rate of 0.7 m^3/s from Granadilla creek, leaves a flow rate of 222 m^3/s, which will be directed from the El Salado site to the dam through the transmission tunnel [21].

In order to obtain a maximum flow rate of 278.5 m^3/s in the pressure pipe while maintaining a plant capacity factor of 0.8, it was required to increase from 460000 m^3 to 800000 m^3 the usable volume of the compensating reservoir, keeping the same minimum and maximum levels, i.e. 1229.50 y 1216 meters above mean sea level (mamsl), respectively [21].

On the other hand, CENACE has the information shown in Table 1, about the flow tributary to the compensating reservoir of the CCSHP. Figure 3 also shows the monthly average flow rates in the Coca River station corresponding to 2017; it can be seen that these rates are smaller than the historically obtained during the period 1972-1990.

It is important to consider the significant changes undergone by the face of the sector, mainly due to the construction of the road between Valle de Quijos and Lago Agrio handed in 1972, which promoted the colonization of the sector. This caused the transformation of the forest area into pastures and the wood exploitation, which surely affected the climatic conditions of this river basin and the flow of its rivers [27]. The latter were also affected by the consumptive uses of water.

Table 1. Flow rate tributary to the compensating reservoir of the CCSHPS [25]

Menths	**Flow rate (m^3/s)**	
	2016	**2017**
January	-	258,75
February	-	190,21
March	-	230,37
April	-	258,11
May	697,9	320,35
June	707,38	324,84
July	560,6	344,57
August	506,23	272,94
September	394,34	259,8
October	298,5	283,55
November	148,03	190,05
December	135,89	205,16

2.2. Consumptive uses of water

According to the Organic Law of Hydrological Resources and Water Utilization, a consumptive use is one in which the water is not returned to the site from which it was withdrawn, nor in the same way in which it was removed [16]. This kind of use can be identified in four projects as shown in Figure 4: one already existing, two under construction and one scheduled. These projects, which capture or will capture the water from the flow entering the CCSHP, are the following:

Existing:

- Papallacta Project from the Public Metropolitan Company of Potable Water and Sanitation, of Quito Metropolitan District (EPMAPS).

Under construction:

- Chalpi Grande Project or phase one of the Ríos Orientales Project (Proyecto Ríos Orientales, PRO) of the EPMAPS.
- Cayambe-Pedro Moncayo Irrigation and Pesillo-Imbabura Potable Water Project.

Scheduled:

- Future phases of the Ríos Orientales Project (PRO) of the EPMAPS.

Each of these projects is now described.

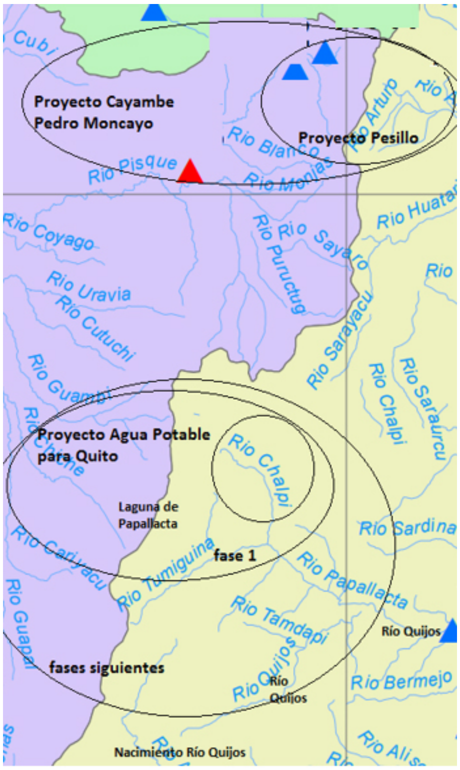

Figure 4. Location of the projects under construction [28].

2.2.1. Papallacta Project

This project was inaugurated in 1990 by the EPMAPS, and consisted of supplying potable water to the city of Quito, in the province of Pichincha. In a sentence on September 22 1987, by means of the concession under trial number 1503, the company obtained authorization to capture the flow from rivers Papallacta, Chalpi Grande, Tuminguina and Blanco Chico, with rates of 1.70 m^3/s, 3.20 m^3/s, 2.20 m^3/s and 0.90 m^3/s, respectively [29, 30].

For the feasibility studies of the CCSHP a value of 3 m^3/s was taken into account; however, the concession granted to EPMAPS considered 8 m^3/s [30].

2.2.2. Ríos Orientales Project (PRO)

The growing demand of potable water in the city of Quito was analyzed in the 1970s; fulfilling such demand required the implementation of new projects, as well as reducing unaccounted losses and per capita consumption. EPMAPS decided to design some projects, the most important of which was the Ríos Orientales Project (PRO) that would supply water to the Metropolitan District of Quito and to its 22 rural parishes beyond year 2055, by means of the capture, gravity transmission and treatment of 31 rivers. The PRO would use water from the hydrological basins of rivers Valle Vicioso, Antisana, Cosanga, Quijos and Papallacta, located along Quijos and Archidona cantons in the province of Napo [31]. On January 16 2002, by through concession under trial number 296-96-CTD [29], EPMAPS obtained authorization from former National Council of Hydrological Resources (CNRH), now Senagua, to capture the waters from the rivers that would feed the project, which are summarized in Table 2 [31].

Table 2. Flow rates approved by the CNRH to EPMAPS in January 2002 [31]

River	Flow rate (m^3/s)
Río Valle Vicioso	5,01
Río Tolda	0,74
Río Chuzalongo	0,3
Río Bajo	0,16
Río Antisana	4,49
Río Javas	0,71
Río Cosanga	1,13
Río Quijos Sur	2,14
Río Quijos Norte	1,36
Río Blanco Grande	1,19
Total	**17,23**

Based on technical, economic-financial and environmental aspects, construction of the Ríos Orientales Project (PRO) would be executed in phases as illustrated in Figure 5 [32]. The first phase would use the concession granted in 1987, while the second and future stages would use the concession of 2002, which was summarized in Table 2.

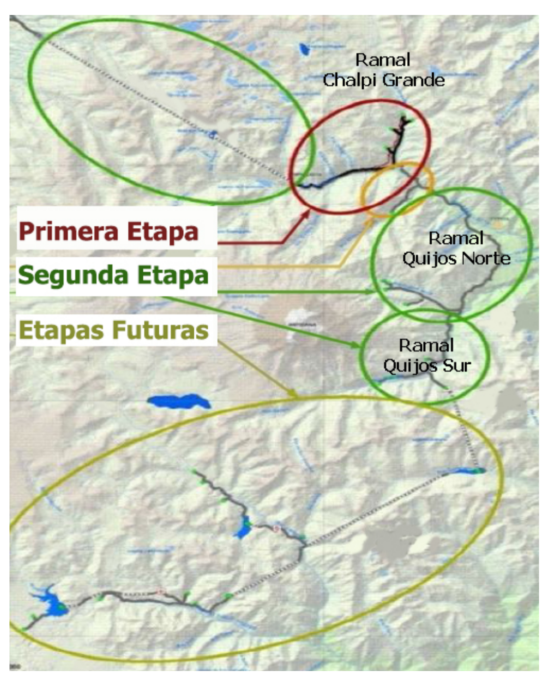

Figure 5. Phases of the Ríos Orientales Project [33]

The first phase, which is Ramal Chalpi Grande-Papallacta, comprises a canal that will capture a total flow of 2.21 m^3/s from tributaries Chalpi A (1.23 m^3/s), Encantado (0.64 m^3/s), Chalpi B (0.27 m^3/s) y Chalpi C (0.07 m^3/s), that constitute Chalpi Grande River, as shown in Figure 6, and transfers it to the reservoir in Papallacta [33].

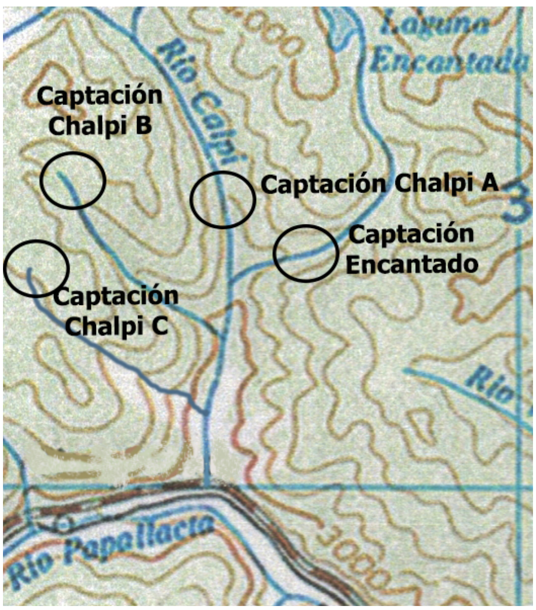

Figure 6. Phase 1 of PRO [34].

In July 2018, the manager of the EPMAPS pointed out that the project exhibited a progress of 26%, and will be finalized in 2021 [35].

The second phase, which is Ramal Quijos-Papallacta-Paluguillo, will start in 2040 and is intended to capture a total flow of 4691 m^3/s from rivers Quijos Norte, Tablón, Cristal, Pucalpa, Azufrado, Semiond, Quijos Sur and Blanco Grande [36].

The future phases will start in 2041, and are intended to obtain flow from rivers Cosanga, Antisana, Valle Viscoso and their tributaries [32].

2.2.3. Cayambe-Pedro Moncayo Irrigation and Pesillo-Imbabura Potable Water Project

The purpose of this project is to capture water from rivers Arturo, Boquerón, San Pedro, San Jerónimo and Montoneras, through the headrace tunnels that connect Arturo River with Boquerón River, Boquerón River with San Pedro River, and San Pedro River with La Rápida River, as shown in Figure 7 [37]. In the first trial, the 220-96, the Resolution enacted by Quito Water Agency in April 15 1999 favored the Pichincha Provincial Government, who got the right to use the waters from rivers Azuela, Arturo, Boquerón and San Pedro, for a total flow rate of 3325 m^3/s [38].

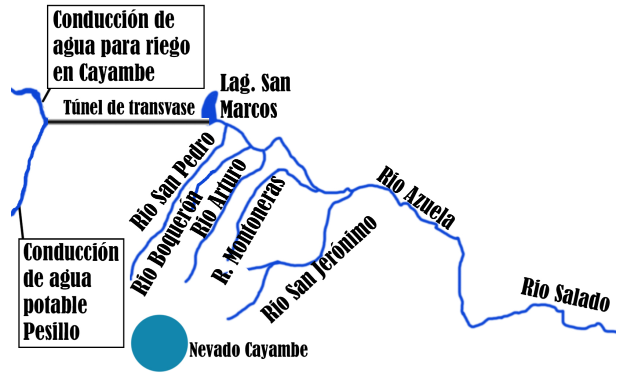

Figure 7. Location of the Cayambe-Pedro Moncayo and Pesillo-Imbabura Project ([33]).

In the second trial, the 1375-00, the Quito Water Agency granted the Pichincha Provincial Government the right to use the waters from rivers San Jerónimo, Montoneras, La Chimba and their tributaries. Among these rivers, only the first two affect the flow of Salado River that feeds CCSHP, with flow rates of 0.24 m^3/s and 0.08 m^3/s, respectively. In addition, Quito Water Agency granted the Imbabura Provincial Government the right to use the waters from rivers Montoneras and San Jerónimo, with flow rates of 0.1 m^3/s and 0.31 m^3/s, respectively [39]. Such flow rates together with the corresponding to rivers Arturo, Boquerón and San Pedro, which also flow into El Salado and were considered in the previous concession, add up to a total of 4.06 m^3/s [39].

On December 13 2017, the director of the Cayambe-Pedro Moncayo Irrigation and Pesillo-Imbabura Potable Water Project announced that it has a progress of 95.6 % [37].

3. Results and discussion

Figure 8 summarizes the past and future events that will affect the flow of the CCSHP.

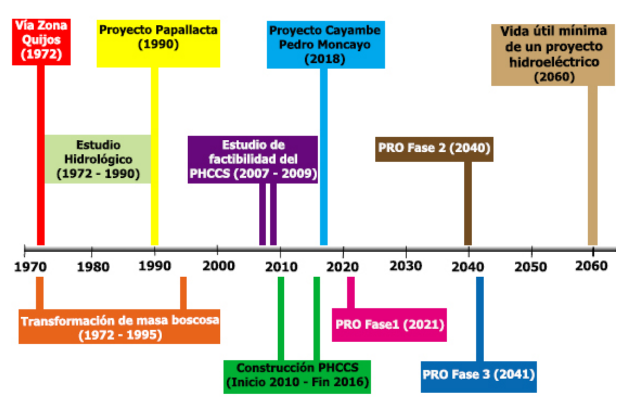

Figure 8. Chronology of events that affect the flow of the CCSHP.

From the analysis of the three projects, it follows that 20 m^3/s should be subtracted from the flow rate of Coca River in the El Salado Sector, due to the ecological flow (ELC-Electroconsult, 2009), and in the near future flow rates of 4.06 m^3/s from the Cayambe-Pedro Moncayo and Pesillo-Imbabura Project (for 2018) and of 2.21 m^3/s from Chalpi Grande Project, which correspond to phase one of PRO, should also be subtracted. Nevertheless, the concession of 1987 authorizes the use of up to 5 m^3/s, considering that 3 m^3/s have been already used in the Papallacta Project. At last, a total of 17.2 m^3/s corresponding to the second and third phases of PRO should be considered, which would initiate in 2040 and 2041, respectively. Table 3 explains in more detail the projects that would reduce the flow rate of the CCSHP. It should be considered that the service life of a hydroelectric project is generally 50 to 75 years [39].

Table 3. Projects that affect the flow of the CCSHP

Name	Year	Flow rate (m^3/s)
Ecological flow	2016	20
Irrigation project Cayambe-Pedro Moncayo and drinking water Pesillo-Imbabura	2018	4,06
Papallacta and PRO project (phase 1)	2021	≈ (2,21-5,00)
PRO (phase 2 and phase 3)	2040-2055	17,23
Total		≈ (23,5-26,29)

As it can be seen in Table 3, the inflow to the CCSHP would be reduced by a maximum of 26.29 m^3/s, which is equivalent to 11% of the design flow rate. Since the CCSHP is a run-of-river plant with daily regulation, such flow reduction would affect the generation of electricity in a similar percentage.

4. Conclusions

The energy generation capacity of the Coca Codo Sinclair Hydroelectric Project would be affected by the reduction of 222 m^3/s on the inflow, because of the future consumptive uses of water by the EPMAPS, due to the Chalpi Grande Project and the subsequent phases of the Ríos Orientales Project, which would take up to 2.2 m^3/s and 17.2 m^3/s, respectively. The flow utilized by the Cayambe-Pedro Moncayo Irrigation and Pesillo-Imbabura Potable Water Project, which is expected to finalize in 2018 and has a granted concession of 4.06 m^3/s, should be reduced as well. In the future, the flow entering the SSCHP would be reduced in up to 11%, thus affecting the generation of electricity. Therefore, it becomes evidently necessary to plan ahead the use of these resources considering their nexus.

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