CASUPÁ DAM AND RESERVOIR: SUSTAINABLE WATER SUPPLY FOR THE MONTEVIDEO METROPOLITAN AREA

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ABSTRACT

The design of the Casupá Creek Dam, which is a tributary of the Santa Lucia River, is being developed with the objective of ensuring a 100% water supply guarantee for the city of Montevideo and its Metropolitan Area, having the year 2045 as time horizon. The reservoir will add 100 hm^3 of storage capacity to the river basin and this is generated by means of an RCC gravity dam that will complement the current Paso Severino dam. The aim is to store natural waters, provide moderate base flows throughout the year and peak flows when natural flows begin to decrease, without resorting to transfers from other basins. Apart from the regulation of river flows, one distinctive feature of the project is linked to the need of ensuring water quality with a continuous flow throughout the year, avoiding the stagnation of waters along the river course, something that leads to the proliferation of cyanobacteria and potentially triggers toxins. This paper provides a general description of the project, which includes a comprehensive watershed management plan and a reservoir management model that incorporates water quality as a paramount variable, given the fact that it is aimed at ensuring urban water supply.

1. DESCRIPTION OF THE CASUPÁ PROJECT

Obras Sanitarias del Estado (OSE), is a state Agency that is responsible for the supply of drinking water in Uruguay. Nowadays, the water supply to the Montevideo Metropolitan Area currently relies on the Paso Severino dam and the reservoir at the Canelón Grande Creek. In order to ensure the supply of the Montevideo and its Metropolitan Area, OSE has proposed the construction of a new dam, located in the Santa Lucía river basin. The purpose of the Casupá project is to improve this system in terms of quality, reliability and water security (ICOLD, 2016).

The basic problem is not a deficit of resources in the water basin, but rather a lack of regulation. Over the last decades, different studies have been carried out to solve the problem and ensure the water supply to the metropolitan system (OSE, 1999 & 2013). These studies concluded that a reservoir is needed to allow the regulation of the upper area of the basin, storing natural waters in order to ensure moderate base flows throughout the year and peak flows when natural flows begin to decrease.

1.1 The Casupá dam and reservoir

In this way, the Casupá dam and reservoir was put forward as a solution to the needs of the water supply system to the Montevideo metropolitan area many years ago (OEA, 1970). Current designs for Casupá (OSE, 2020) consider an RCC gravity dam with a maximum height of about 31.50 m over the foundation and a crest length of 750 m. The typical cross section of the dam has vertical slopes upstream and 0.8H:1V downstream, whereas the dam body is divided into blocks by transverse joints every 20 m. The total concrete volume of the dam body including the spillway is 117,681 m³, of which 76,435 m³ correspond to RCC and the rest to conventional vibrated concrete.

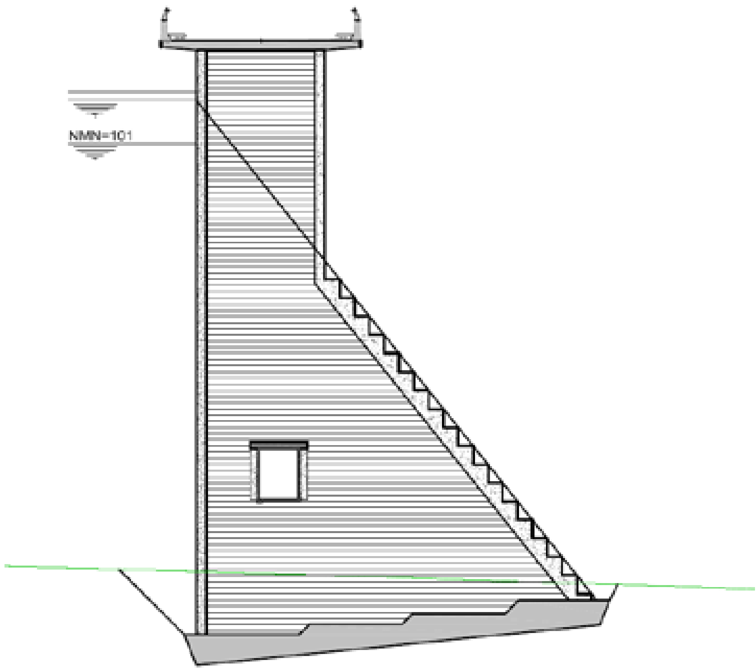

Figure 1 : Typical cross-sections of Casupá Dam.

The central area of the dam is the highest and includes the ogee spillway, the outlet works and the water intake. The channel used for the river diversion during construction goes through one block located next to the one that accommodates the water intake. The spillway has a useful length of 42 m with a total length of 48 m and is divided into three blocks of 17, 14 and 17 m; whereas the two blocks used of the outlet works and water intake are 20 m long.

The dam creates a reservoir with a maximum useful volume of 100 hm³ at the normal operation level of 101.0 masl (meters above sea level) and it can be filled up in about 4.5 months. The crest is located at elevation 106.0 masl, thus creating a 5 m freeboard. In addition, the water basin yields and average of 380 hm³/year, whereas the water supply demand is estimated at about 21 hm³/year, having the year 2045 as time horizon.

To allow the construction of the dam, the diversion for the Casupá Creek is considered in two stages; a first provisional stage on the right bank, with a rock-carved channel, and a second stage with a channel that goes through the dam body. The temporary 1st stage is designed for a maximum flow of 215 m³/s, corresponding to a return period of 2 years, whereas the 2nd stage is prepared for a 10-year event of 603 m³/s. This main diversion of the Casupá Creek is made up of a 3-way reinforced concrete channel with a width of 5.50 m in each channel, from its beginning to the crossing with the dam structure after which a small stilling basin is envisaged to reduce energy before the water continues with a channel carved into rock, all the way down to the outfall downstream.

1.2 Outlet works and water intake

The water intake has been conceived using a well-type structure attached to the upstream face of the dam, including two 1.75 m diameter pipes. This design aims at reducing pressure losses and controlling water velocities in the hydraulic system, thus minimizing future maintenance costs.

This structure ensures the water supply rates defined in the basic project at 11 m³/s (8 m³/s for the water supply of Montevideo and 3 m³/s of environmental flows). The design includes two 1200 mm Howell Bunger valves at the downstream end of the water intake, before delivering flows back to the Casupá Creek.

Two different intakes are arranged at different elevations; the lower one at 89.0 masl and the upper one at 96.3 masl. During operation, when the level of the reservoir reaches the elevation near the minimum level of the upper intake, the lower intake might be used, removing the stop-log gate and introducing the grid from the dam crest, where a small valve house is included.

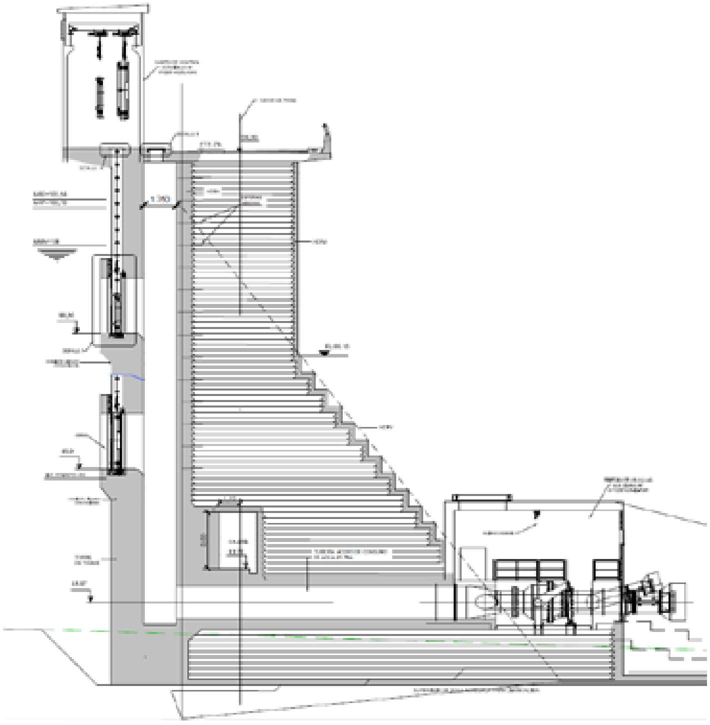

Figure 2 : Water intake structure in one of the Casupá Dam blocks (OSE, 2020)

Following the results of the Reservoir Management Model used during the design (OSE, 2020), the 96.30 elevation intake corresponds to the minimum reservoir volume (45 hm^3) necessary to meet water supply demands and the dead volume due to sedimentation. The 88.50 m level corresponds to the level of sediments expected at the end of the reservoir service life, allowing the emergency operation of the water intakes in the event that the bottom outlet works are covered by sediments. This design also guarantees the minimum environmental flow with a 90.89 m reservoir elevation.

Outlet works are another important element whose main objective is to carry out seasonal flushing (ICOLD, 2009 & 2010), thus allowing sediment loads to remain close to the pre-dam conditions. Another relevant purpose of the outlet works is lowering reservoir levels in case of flood events or safety needs. Their operation is carried out with two metal 1,200 mm diameter ducts controlled by Howell Bunger valves at the downstream end. The outlet works minimum elevation is 82.87 masl.

1.3 Geological and geotechnical aspects

The development of the basic and detailed design of the Casupá project has included the execution of several geotechnical campaigns to minimize uncertainties regarding the design of the dam body and the foundation treatments.

The Project area is part of the San José Belt, formed by a volcano-sedimentary association of rock structures defined as "Paso Severino and associated plutons". The dam site presents numerous outcrops of quartzites and quartz sandstones with medium to fine grain, very well selected and very consolidated. Its grains are sub-rounded, of high sphericity and they mainly consist of quartz (90%) and lithics (1%), whereas the cement is siliceous, constituting 5% -10% of the total rock. Overall, this has led to the need of designing all concrete mixtures to avoid expansive reactions, such as the alkali-aggregate type.

In general, the rock fracturing present in most outcrops is important, where surface fractures appear closed, often with iron oxides. There are two preferential fracturing systems, N190 and N350 (dip direction), the direction (strike) of both plans is close to the axis and the inclination (dip) is 60° downstream in the N190 plan and 30° upstream for the N350 plan. The spacing of these fractures is around 0.5 m.

Figure 3 : Rock outcrops at the Casupá dam site.

The general conditions of the rock mass are satisfactory after removal of the surface layer (generally 5 m), and the value of the deformability modulus for the rock mass is estimated at 4,000 MPa. However, these general conditions are locally depleted at certain points, where it has been difficult to recover samples when drilling boreholes or very weathered materials have been found. Specifically, there are about 160 m along the axis where the rock is intensely fractured (RQD<40 and RMR>21) and a previous treatment has been proposed by means of high energy and low pressure grouting, to be executed inside of previous drills, in order to wash and mix less competent materials with cement grout.

1.4 Numerical and physical models

These geotechnical conditions in the foundation have also determined the stability calculations and the cross-section eventually designed for some blocks of the dam, all of which have followed international recommendations (ICOLD, 2001 & 2013) and Spanish regulations and guidelines (MOPTMA, 1996 & SPANCOLD, 2003).

On the one hand, a 2D transient thermal model assesses the maximum temperatures reached during the construction stage, plus the minimum and maximum expected thermal gradients in the concrete are obtained, both for short and long-term conditions.

The cross-section of the dam is also analyzed using a static 2D mechanical-structural model, from which the expected strains and stresses in the various load scenarios are obtained. Safety coefficients against sliding of the dam and safety factors for maximum stresses in the concrete have been obtained. This model includes several sensitivity analyses considering the most relevant resistance parameters for the stability of the dam at representative cross-sections.

In addition, a refined structural calculation has been developed for the central area of the dam, where singular cross-sections are located, such as the spillway, the outlet works and the water intake. For this area, a static 3D mechanical-structural model has been deemed necessary to verify the most critical hypotheses that were found with the 2D model. In this case, the 2D models have provided more conservative results than the 3D model, although the latter is considered to represent real conditions in a more reliable manner.

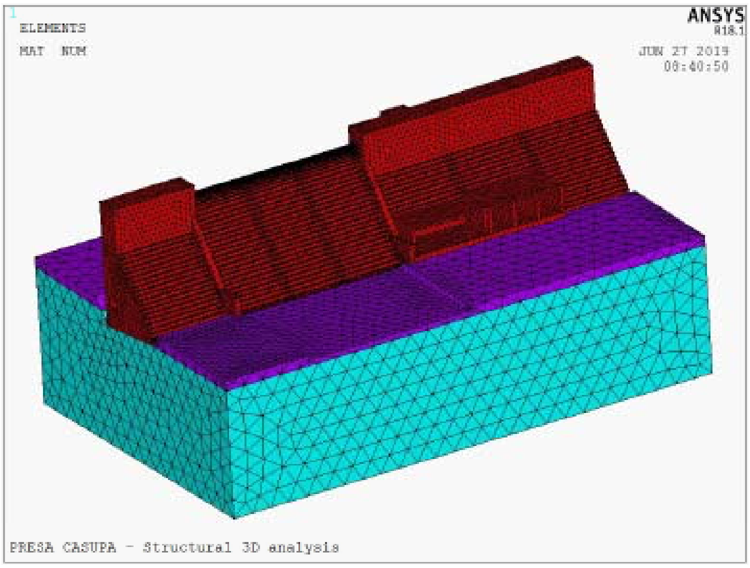

Figure 4 : Geometry of the ANSYS 3D numerical model for the central blocks of Casupá dam.

As a complement to the preceding calculations, a 2D geotechnical model has also been developed for the dam foundation, considering the typical cross-section. With this model, the flow net and seepage in the foundation has been estimated for several load scenarios, in conjunction with stability calculations in the foundation.

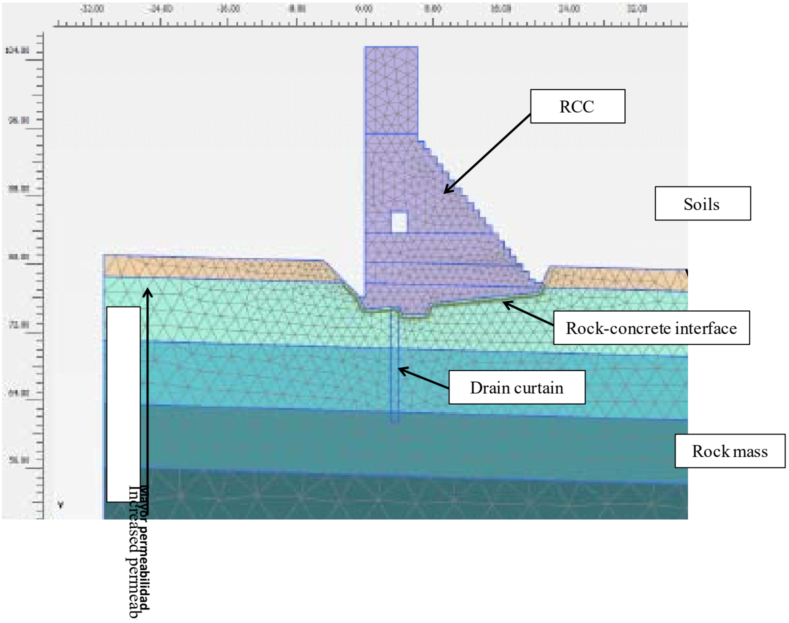

Figure 5 : Geometry and finite element mesh used in the 2D PLAXIS model for Casupá Dam.

Finally, hydraulic models have also been developed for the spillway, a numerical CFD model and a physical one in the laboratory. Regarding the operation of the stilling basin, an excellent correlation between the physical and the numerical models was found, obtaining similar results in terms of water depths and pressures. Regarding the operation of the spillway, the numerical model was used to verify that the designed structure can be operated without the generation of dead flow areas, subpressures or turbulences that may affect the discharge capacity. Later, the physical model was used again to verify these conditions, using a more refined model to analyze the flow behavior next to the piers.

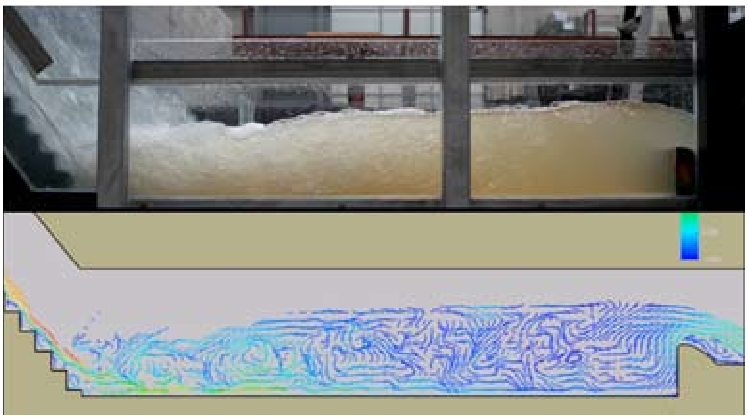

Figure 6 : Physical model and XFlow CFD numerical model for the Casupá dam spillway.

2. WATER BASIN MANAGEMENT AND ENVIRONMENTAL IMPACT ASSESSMENT

The Santa Lucía Chico river is partially regulated by the Paso Severino reservoir, with a storage capacity of 70 hm^3 and a 2,200 km^2 basin. However, the Santa Lucía river currently lacks regulation, especially in the middle stretch of the basin, where there is stagnation of waters along the river course, something that leads to the proliferation of cyano-bacteria and triggers toxins, thus seriously altering the organoleptic conditions of the water.

Therefore, the regulation of the upper area of the basin is required, storing natural waters to be able to provide moderate base flows throughout the year and peak flows when natural flows begin to decrease. The watershed management plan and the reservoir management model developed yield as a result the Casupá Creek reservoir, located on a tributary of the Santa Lucía River. It will store approximately 100 hm^3 with a 685 km^2 basin, involving the provision of ecological flows throughout the year, and specifically each time the river flow drops below 3 m^3/s. In this way, the dam will both fulfill the regulatory and the preventive function to mitigate algae blooms.

Casupá has been devised for the exclusive use of water supply and, if necessary, leaving open the option to other non-consumptive uses. In any case, the Paso Severino Dam assumes a complementary function and will supply water when the natural resources and the regulated ones do not cover the water demand. Based on the daily flows at different gage stations and the demand from the Montevideo Metropolitan System for the horizon year (2045), the following basic proposal for the operation of the basin is put forward:

- Base flow in Canelón Grande reservoir: 1 m³/s.
- Base flow in Casupá reservoir: 0.4 m³/s.
- Complementary flow in Casupá reservoir: 2.6 m³/s.
- Base flow in El Soldado reservoir: 0.25 m³/s.
- Complementary flow in El Soldado reservoir: 0.75 m³/s

On the other hand, the water demand for the horizon year (2045) yields the following results:

- Minimum volume in Paso Severino reservoir: 42,93 hm³
- Minimum volume in Casupá reservoir: 41,95 hm³
- Minimum volume in El Soldado reservoir: 10,56 hm³
- Minimum volume in Canelón Grande reservoir: 2,24 hm³

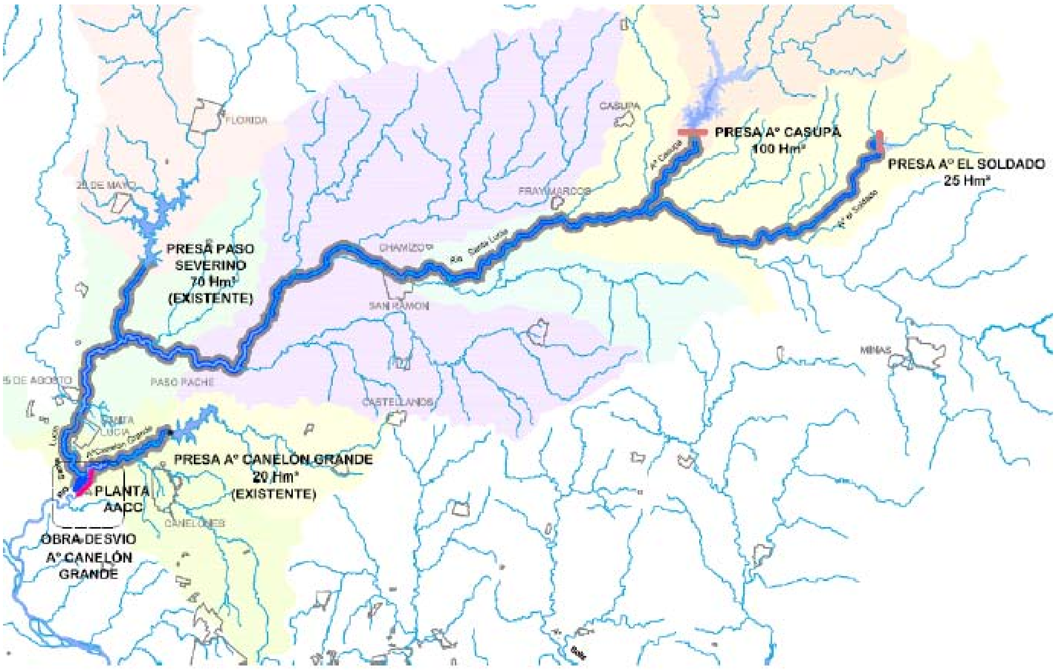

Figure 7 : Regulation scheme chosen for the Santa Lucía river basin. Source: OSE, 2013.

In compliance with the Uruguayan regulations, the Casupá design has identified and evaluated environmental impacts, defining the necessary mitigation measures for all stages of the project. The environmental and social impact study is structured in four parts:

- The identification of potentially negative impacts, with a description and classification of them.
- The evaluation of the environmental impacts identified as potentially significant. For those in which the medium to high importance is confirmed, mitigation measures are proposed, and then the residual impact is evaluated.
- The third part addresses the social impacts of the project, which are evaluated separately due to their complexity.
- Finally, the study describes and assesses the positive impacts of the project.

Mitigation measures are both preventive and corrective in relation to flora, fauna, heritage and water quality, as well as for the population close to the reservoir. In this sense, an environmental monitoring plan is also set forth during the construction and operation of the dam, together with a social management plan.

Among all the issues addressed within the environmental impact assessment of the project and the water basin management model, the analysis of eutrophication and environmental flows are discussed below.

2.1 Eutrophication and water quality model

One of the major concerns in the design phase has been to preserve water quality in the reservoir, since its primary purpose will be water supply. It was clear the need to define measures to reduce phosphorus concentration in the lake or, failing that, consider measures to minimize eutrophication.

In this way, a mathematical model based on the matter balance has been developed considering reservoir scenarios with maximum, medium and minimum stored volumes. With respect to the total phosphorus concentration, both variable (a monthly average concentration) and constant (average of the average monthly concentrations) inputs have been considered, along with a global phosphorus loss rate. These simulations were performed for both wet, dry and normal years, and the total phosphorus values for these simulated scenarios range between 100 and 50 µg/l, the average value being 70 µg/l.

In order to know the necessary phosphorus reduction to avoid eutrophication in the reservoir, simulations were carried out for the most unfavorable scenario (constant phosphorus input for wet years with a minimum reservoir volume). In this way, it was concluded that the phosphorus input value that ensures a mesotrophic state in the reservoir must be smaller than 37 µg/l, way below the average 70 µg/l simulated.

Therefore, the imposition of a buffer zone in the reservoir margins was considered, resulting in a reduction of around 12% of the phosphorus load in the entire water basin (assuming an efficiency of 45% for this measure), such as shown in Table 1. Regardless of the initial concentration of phosphorus in the lake, it can be assumed that this mitigation measure will not be enough to obtain the required reduction.

Table 1 : Reduction in the contribution of Phosphorus (P) thanks to a buffer generated in the Casupá reservoir.

Water Sub-basins	**Surface**	**P load (1,000 kg/year)**	
	(ha=10,000 m^2)	**Without buffer**	**With buffer**
6050	19,319	5.68	5.68
6051	9,228	2.47	2.47
6052 reservoir	2,362	1.13	0.62
6052 rest	8,628	4.14	4.14
6053 reservoir	2,462	1.21	0.67
6053 rest	19,484	9.61	9.61
60542	5,853	6.00	3.30
TOTAL	67,336	30.24	26.48

In this way, additional measures to avoid the reservoir eutrophication have been considered:

1. Measures during the first filling of the reservoir:
   (a) Removal of vegetation in the potentially flooded areas by the reservoir as a measure to minimize the oxidizable organic load under water.
   (b) Planning of the first filling, prioritizing the wintertime for the first filling with cold, dense and well oxygenated waters, using outlet works to favor the renewal of the water in contact with the sediments. In spring and autumn, surface algae biomass must be controlled, and plankton must be allowed to pass through the water intakes. In summer, the circulation and renewal of deep waters must be accomplished, and reservoir levels must allow a balance between the diffusion of dissolved oxygen from the superficial layers to the deep water layers of the reservoir, so as to avoid anoxia scenarios and favor sediment mineralization.
   (c) Progressive and steady filling of the reservoir, with low residence times for the reservoir water, managing it by seasonal flushing and a selective withdrawal of water at different depths.
2. Measures to reduce nutrient contributions in the water basin, keeping under control any diffuse contributions through appropriate agricultural practices, restrictions on uses or restoration of the water ecosystem and riparian areas.
3. Adequate management of the reservoir waters and the natural aquatic communities by proper operation of the water intakes and outlet works, during the operation phase. Based on the water quality monitoring, seasonal management measures similar to those proposed for the first filling can be taken to control eutrophication in the reservoir: control of algae biomass on the surface during spring and autumn by operating the higher water intake, whereas in summer and winter it is necessary to allow the renewal of deep waters by means of operating the lower water intake and outlet works.

2.2 Environmental flows

Environmental flows downstream of Casupá reservoir have been modeled using a water resources management model, involving detailed operation rules for any reservoirs within the water basin. AQUATOOL software, developed in the Polytechnic University of Valencia (Spain), works as a decision support systems (SSD) for planning and managing water resources systems, including a water quality module.

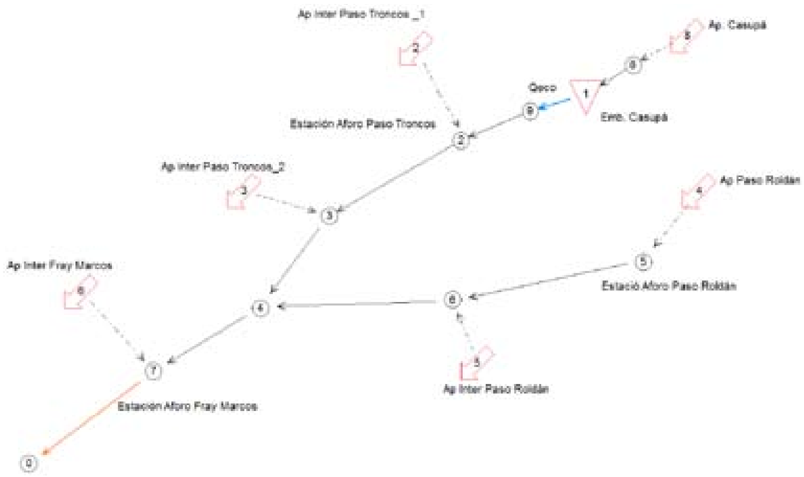

Figure 8 : General scheme of the Santa Lucía water basin management AQUATOOL model.

The scheme of the regulation model developed for the Arroyo Casupá river basin is included in Figure 8, developed all the way down to the Fray Marcos gaging station, located downstream of the river junction where the Casupá and El Soldado Creeks meet each other to create the Santa Lucía River. In addition, the management model has been developed including the following constraints:

- Because of the water supply demand, the minimum 60-day storage buffer in the Casupá reservoir must be equal to 41.955 hm^3, thus yielding a minimum monthly storage of 24.89 hm^3 (20.98 hm^3 for water supply and 3.91 hm^3 as dead storage for sediments)
- Due to sedimentation, the Casupá reservoir capacity must therefore be equal to 103.91 hm^3; ensuring a maximum useful storage capacity of 100 hm^3.
- A set of monthly environmental minimum flows with a 60% exceedance probability, determined by the Uruguayan ministry in charge of environmental issues.
- Due to water quality needs, a minimum flow of 3 m^3/s must be guaranteed at the Fray Marcos gaging station, the one located downstream of the Casupá and El Soldado Creeks river junction.

The results provided by the model determine that there is a 100% compliance regarding the minimum monthly environmental flows established by the Uruguayan Ministry, as shown in Table 2.

Table 2 : Water flows downstream of Casupá Reservoir resulting from the AQUATOOL model.

Variable	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March
Average Flow (m^3/s)	3.26	6.33	8.71	11.10	9.20	9.40	7.66	4.86	2.45	2.10	4.64	3.26
Minimum Flow (m^3/s)	0.85	1.08	2.75	4.36	3.80	3.36	1.69	0.87	0.42	0.40	0.26	0.60
ECO60* Flow (m^3/s)	0.85	1.08	2.75	4.36	3.80	3.36	1.69	0.87	0.42	0.40	0.26	0.60
Compliance (%)	100	100	100	100	100	100	100	100	100	100	100	100

* Monthly environmental flows with a 60% probability of exceedance required by Uruguayan regulations.

On the other hand, the minimum 3 m^3/s flow determined by water quality needs in the river section downstream of the Fray Marcos gaging station is also respected at all times. With respect to the minimum monthly reservoir volume needed to meet water supply demands, for the 40-year period simulation carried out, there has only been one month in which the reservoir volume remains below that required minimum; a result deemed totally acceptable in this design phase.

3. CONCLUSIONS

The basic and detailed design for the Casupá dam and reservoir project is nearing completion by the end of 2019, and this project constitutes an important milestone for dam engineering in Uruguay. The project was conceived at a conceptual level half a century ago and in the meantime, there have been several studies to implement it.

The dam design has been carried out following current technical guidelines and resorting to the current state of the art, always implementing conservative hypotheses and criteria, given that safety is a priority in this project.

This project will ensure a 100% water supply guarantee for the Montevideo Metropolitan Area, having the year 2045 as time horizon. One distinctive feature of the project is linked to the need of ensuring water quality with a continuous flow throughout the year, avoiding the stagnation of waters along the river course. The design tasks include a comprehensive watershed management plan and a reservoir management model that incorporates water quality as a paramount variable.

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