Modern Environmental Science and Engineering (ISSN 2333-2581)
July 2018, Volume 4, No. 7, pp. 665-675
Doi: 10.15341/mese(2333-2581)/07.04.2018/010
Academic Star Publishing Company, 2018
www.academicstar.us

Analysis Hydrologic-Economic and Alternatives Current and Planned Damming in Locumba Basin, Tacna-Peru

Pino Vargas Edwin[1], Collas Chavez Manuel[2], Alfaro Ravello Luis[1], and Avendaño Jihuallanga Cesar[1]

1. Escuela Ingeniería Civil. Universidad Nacional Jorge Basadre Grohmann, Tacna, Perú

2. Autoridad Nacional del Agua, Lima, Peru

Abstract: Locumba river basin is located in the Tacna Region, which is the most arid area of Peru. This scenario determined by nature has been exacerbated by human activities, such as rapid population growth, the expansion of the agricultural frontier, the generation of hydroelectric energy and the growth of mining activities, which is why a set of works to increase the water supply, being the most representative the 8 km long Kovire tunnel that allows the transfer of the Maure river springs, which is a transboundary basin with areas of Peru, Bolivia and Chile. The upper part of the basin is characterized by being a humid area with an intense livestock and agricultural activity with 7554 hectares under irrigation; and it is also the provider of water resources for the mining units of Toquepala and Cuajone operated by the mining company SPCC. The middle and lower part of the basin is characterized by its aridity, but it is important for the Aricota lagoon, located at an altitude of 2800 masl that is currently exploited for the purpose of generating hydroelectric energy, with an operation rule that prioritizes the demand of water for power generation in response to the demand for water for agricultural use in the Locumba Valley and in Ite irrigation with 2790 hectares under irrigation. The conflict to the use of water for the increase of the demand by the different sectors, the different public and private institutions have been carried out dam studies unilaterally or isolated in the upper part of the basin to take advantage of the water availability of the rainy season , which is why a hydrological and economic analysis has been developed using the WEAP (Water Evaluation and Planning System) aimed at quantifying the effects of damming alternatives and a comparison of water storage costs of the dams projected in the Southern zone of Peru.

Key words: Locumba Basin, Laguna Aricota, simulation, WEAP, Locumba Valley, surplus water, water deficits

1. Introduction

The Locumba river basin (CL) is located in the Tacna Region and covers territories of the provinces of Candarave, Jorge Basadre and a small area of the Mariscal Nieto province of the Moquegua region. In the middle part of the Locumba river basin (CL), the Aricota lagoon is located and is a fundamental element because it stores the avenue contributions of the rivers Callazas and Salado and is also the source of water that allows the generation of hydroelectric energy in the Aricota I and II power plants and the water supply for the irrigation sectors of Curibaya, Chulibaya and Ticapampa; and for the valley of Locumba and Irrigacion de Ite.

The locumba river basin is a cattle basin, in the high Andean area there are irrigation sectors of Candarave, Quilahuani, Cairani, Huanura, Santa Cruz, Patapatani, Calleraco and others with an area under irrigation of 7554 hectares where 73% is alfalfa, in smaller proportion, there are the crops of beans, potatoes, corn, and fodder oats. The upper Andean part has sufficient water supply in the rainy season due to the increase in water availability of the rivers Callazas, Salado, Tacalaya and Quebrada Honda, but in the dry season it decreases to a minimum and only has a 60% coverage of water demand, which is the cause of conflicts between the agricultural and livestock user of Candarave and the mining user representing SPCC.

Corresponding author: Pino Vargas Edwin, Professor; research areas/interests: Modeling the hydrology. E-mail: epino68@hotmail.com.

The middle and lower part of the basin are totally arid and the water resources that meet their requirements come from the upper part of the basin and above all from the regulated waters of the Aricota lagoon. The Locumba Valley and the Ite irrigation are the most representative of the lower basin with an extension of 2790 hectares under irrigation with water from the Aricota lagoon and the Ilabaya river that covers all of its requirements and with water surpluses that are lost to the ocean for the Ite intake sector. It is very important to emphasize that even in the most critical years of drought in the lower Locumba river there are always surplus water that is lost in the ocean because the waters of the Aricota lagoon are exploited for the sole purpose of hydroelectric power generation, which is contradictory with the protection and/or preservation of natural resources especially in the Tacna region, which is the most arid in Peru.

Due to the scarcity of temporary water in the upper part of the Locumba river basin, different public and private institutions have developed studies of water damming projects, such as: Callazas, Calientes-Santa Cruz, Kullko, Turunturun, expansion of the dam Kularjahuira and Coltani, without taking into account the effects that they may cause downstream; This is why a hydrological analysis of the impacts of the proposed repression and a comparative analysis of the costs of the projected dams in the Tacna region and in the southern zone of Peru have been made.

2. Data and Methodology

2.1 Study área

The Locumba river basin is located in the Tacna Region and has an area of 5,742.34 km^2, of which 505 km^2 corresponds to the wet basin and which provides a significant resource to the surface runoff that has its headwaters in the upper part of the basin, extending to the Pacific Ocean [1]. It has a population of 17422 inhabitants, of which 7550 inhabitants are in the province of Candarave and 9872 in the province of Jorge Basadre [2]. Shows the location of the study área (Fig. 1).

2.2 Analysis Data

The Locumba river basin has a natural partial regulation in the Aricota lagoon located in the middle part of the basin and receives the contributions of the rivers Callazas, Salado and since 1996 the contributions of the Maure river transfer through the tunnels of Kovire and Ichicollo. It has a storage capacity of 804 Hm^3 (cubic hectometres) and 0.3 Hm^3 in the Kularjahuira dam. The Aricota lagoon has been exploited for the purpose of hydroelectric generation since 1967, and was close to depletion in January 1997, registering a volume of only 20.63 Hm^3. It currently has a stored volume of 213,764 Hm^3 (January 2015). Due to the restrictions that have been imposed, the operating flow has been reduced to 1.5 m^3/s on average.

Due to the overexploitation to which Aricota was submitted for the generation of hydroelectric energy, it was on the point of exhaustion, which is why the Tacna

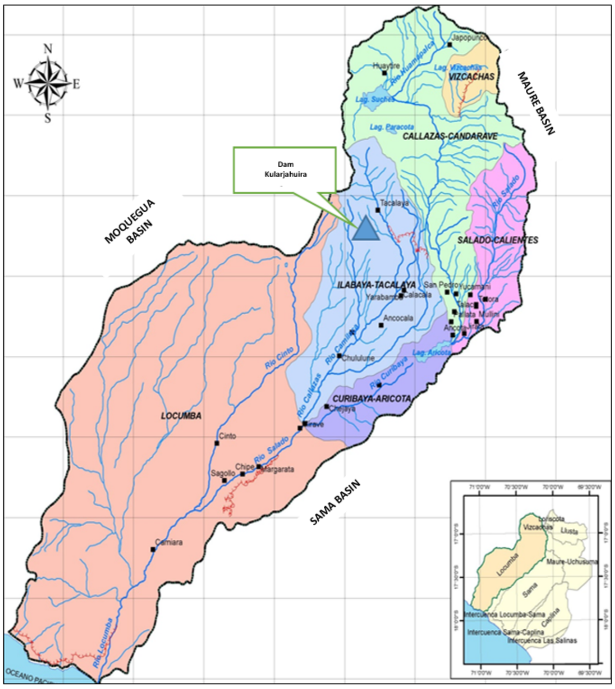

Fig. 1 Map of sub-basins of the Locumba River (Source: Tacna Special Project).

Special Project built a set of works for its consolidation such as: Tacalaya bypass canal, temporary water transfer of the Vilacota lagoon, temporary exploitation of the groundwater of the Vizcachas aquifer, Bocatoma Ancoaque, Kovire tunnel, Cano dam and Ichicollo tunnel, whose operation has allowed to avoid its depletion and has a relative recovery. See Fig. 2 shows the historical record of the storage volume of the Laguna Aricota. In Fig. 3 the hydraulic diagram of the set of works that has avoided its exhaustion.

The database of the hydrometeorological variables, such as: precipitation, discharges, relative humidity, wind speed and sun hours, has been compiled on a monthly basis by the different institutions such as: SENAMHI, PET, SPCC and the Valley Users' Meeting. Locumba

The total annual rainfall in the Locumba basin varies from 10 mm in the coastal zone to 445 mm/year. Table 1 shows the total monthly rainfall of the pluviometric stations located in the upper area of the basin.

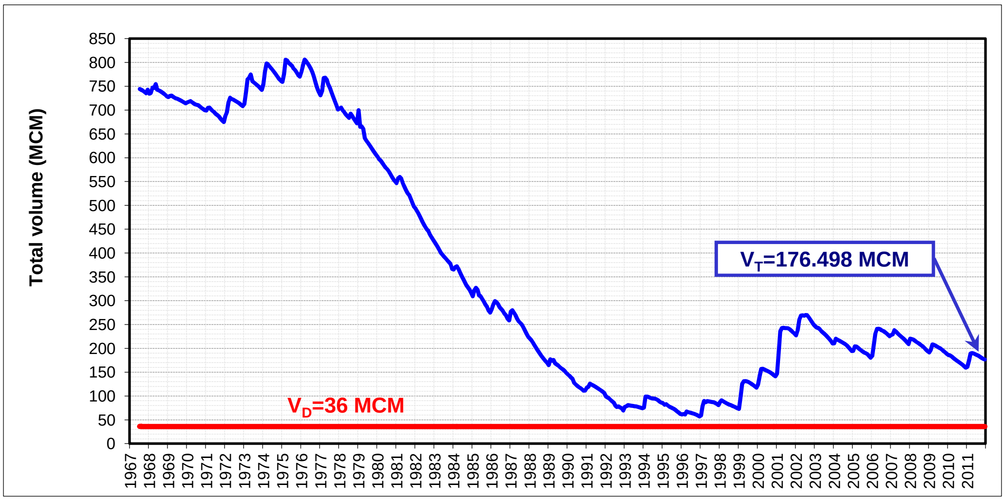

Fig. 2 Decline in the volume of the Aricota lagoon during the exploitation period.

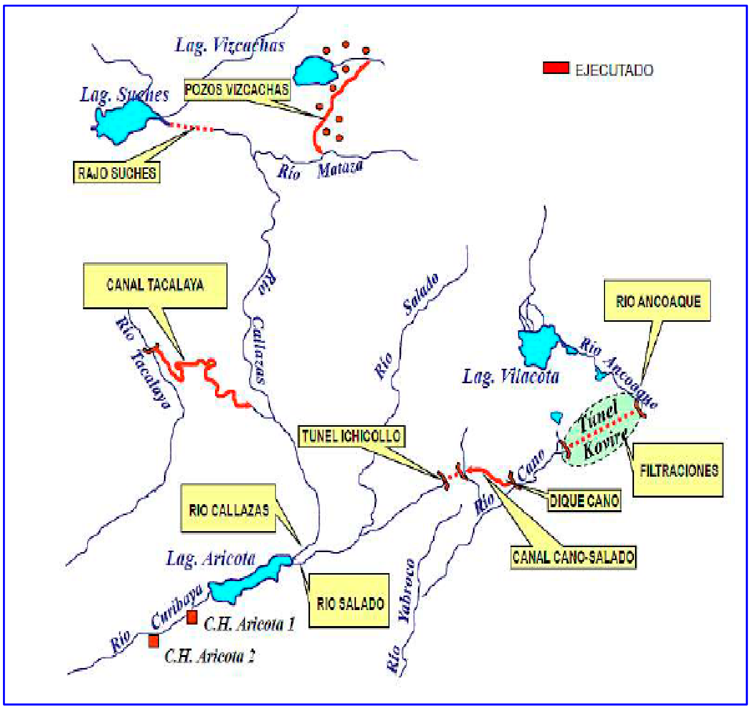

Fig. 3 Hydraulic diagram of contributions to the Aricota lagoon built by the Tacna special project.

Table 1 Total monthly precipitation of the upper part of the Locumba river basin.

Year	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	Total
Tacalaya	7.7	8.9	19.5	55.8	119.0	119.3	84.9	19.1	3.5	2.0	1.5	4.5	445.9
Quebrada Honda	1.3	2.1	4.6	27.9	85.7	85.2	60.2	6.4	0.5	1.7	1.0	1.6	278.2
Suches	5.0	8.7	32.3	50.4	95.5	98.4	69.5	19.2	2.8	2.7	1.2	3.2	389.0
Candarave	2.2	1.6	2.1	13.8	95.5	98.4	69.5	19.2	2.8	2.7	1.2	3.2	312.4

2.3 Historical Discharge

As regards the hydrographic network of the upper part of the Locumba river basin, it is constituted by the contributions of the Callazas river, which has a basin area of 1015 km^2, and an average flow of 1,135 m^3/s and of the Salado river It has a basin area of 375 km^2 with an average flow of 0.835 m^3/s. It is important to indicate that since 1996, the contributions of the Maure river have been transferred through the Kovire and Ichicollo tunnels with an average flow of 0.574 m^3/s.

The lower part of the Locumba river basin is made up of the contributions of the Curibaya rivers, which have a basin area of 225 km^2 and Ilabaya that has a basin area of 955 km^2. Downstream from the confluence of the Ilabaya and Curibaya rivers, the sporadic contributions of the Cinto River are available, and all of these contributions are recorded at the old bridge gauging station, which has an average flow of 2,713 m^3/s. In the final part of the basin there is the Ite channel gauging station and the surplus water that is lost in the Pacific Ocean at an average volume of 13.1 Hm^3/year. The details are presented in Table 2.

Table 2 Discharges of rivers from the Locumba basin.

River	Station	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	Prom
Callazas	Pallata	0.592	0.545	0.525	0.642	1.600	3.217	2.799	0.922	0.692	0.665	0.723	0.704	1.135
Salado	Yesera	0.429	0.380	0.372	0.485	1.537	2.423	2.046	0.539	0.455	0.463	0.441	0.444	0.835
Tacalaya	Tacalaya	0.168	0.152	0.153	0.168	0.240	0.369	0.372	0.261	0.218	0.200	0.192	0.184	0.223
Callazas	Coranchay	1.372	1.356	1.376	1.490	2.054	2.966	2.982	1.884	1.526	1.422	1.396	1.375	1.766
Ilabaya	El Cairo	0.210	0.170	0.155	0.193	0.789	2.115	1.781	0.561	0.415	0.391	0.351	0.278	0.617
Curibaya	Ticapampa	2.105	1.986	1.996	1.987	2.029	2.101	2.040	2.087	2.144	2.087	2.018	2.077	2.055
Qda Honda	Qda Honda	0.066	0.060	0.057	0.069	0.145	0.339	0.286	0.137	0.090	0.081	0.078	0.072	0.123
Locumba	Puente Viejo	2.379	2.220	2.142	2.166	2.979	4.254	3.577	2.660	2.582	2.559	2.540	2.495	2.713

3. Methodology

The hydrological analysis has been carried out through the application of the WEAP (Water Evaluation and Planning System) software, where a model has been developed following the recommendations of the “Hydrological and water resources modelling” developed by the Global Change Center and the Stockholm Environment Institute (2009), which stipulates the following steps:

Spatial delimitation/scheme: The existing sub-basins have been delimited taking into account the closure points of the sub-basins. The main typical management points that have been considered are: gauging station, dam (existing or projected), confluence of major rivers, location of water extraction channels. Fig. 4 shows the main hydrological network of the Locumba river basin and the water demands existing in the basin, which has been developed schematically in the WEAP.

Temporal delimitation: Based on the availability of information on climatological and hydrological data collected from the Locumba river basin, the time step has been taken at monthly level and a simulation period of 1964-2013.

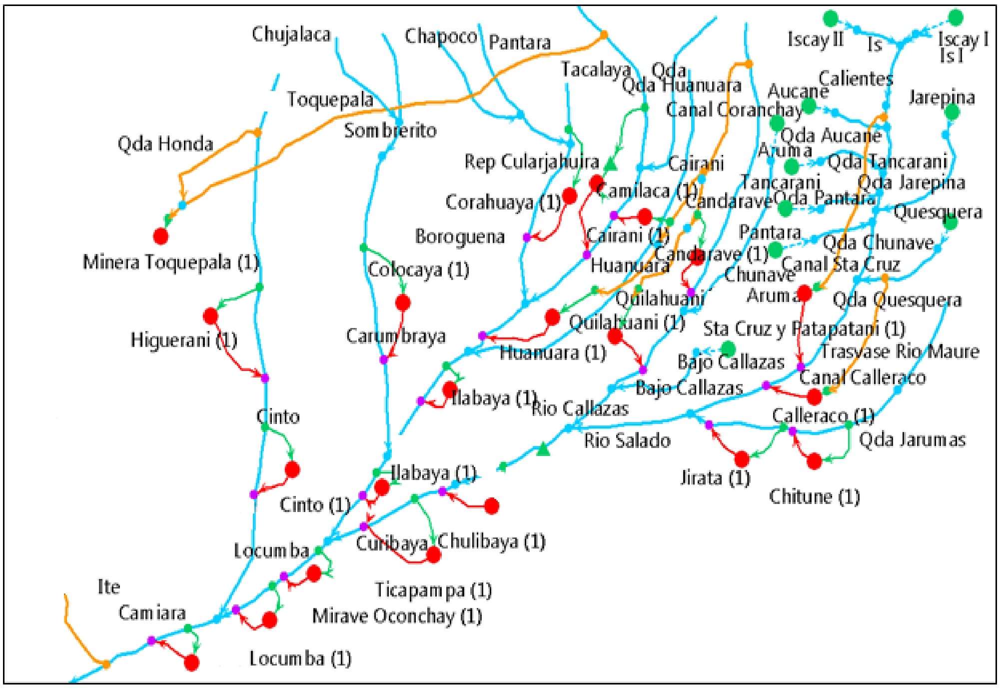

Fig. 4 Hydrological simulation scheme of the Aricota lagoon using the WEAP software.

Construction of the model: In the stage of construction of the model, the water supply has been determined on the basis of the inflow of hydrometeorological data in each catchment area named in the model as catchments, which have been defined through the delimitation of sub-basins. It has been essential to estimate the areas of distribution of vegetation cover within each catchment area. The climatic data required to make the model have been: precipitation, temperature, humidity, wind and latitude. Finally, in the analysis of water supply it has been necessary to incorporate the information related to the physical infrastructure of control and use existing within the basin, such as: Ancoaque Intake, Kovire tunnel, Cano-Salado channel, Cano-Salado canal and tunnel Kovire and Ichicollo that allows the transfer of the sources of the river Maure (river of Peru-Bolivia international course) and Tacalaya channel.

In order for the model to develop the water balance at each node or point of interest it has been necessary to enter information on the water demands of: Candarave, Quilahuani, Cairani, Huanuara, Ilabaya, Borogueña, Camilaca, Santa Cruz, Calleraco, Patapatani, Curibaya, Valle de Locumba, Cinto and irrigation Ite, population use of Candarave, Locumba, Ilo and industrial concentrate basically for mining use of the SPCC of the Toquepala mining unit.

3.1 Calibration of the WEAP Model of the Locumba River Basin

In the calibration stage of the model, the hydrological parameters values have been defined, which have allowed reproducing as closely as possible the historical records of the volumes of the Aricota lagoon, for which the existing water extractions have been taken into consideration. The Coranchay intake, in the numerous existing catchments in the Calientes streams to meet the water demands of Santa Cruz and Patapatani, as well as the transfer of the Maure river springs. To verify the benefits of the model, comparisons have been made between the historical and simulated records of the Aricota lagoon. On the basis of these comparisons, statistical indices have been calculated to estimate the accuracy of the model and thus adjust the parameters to achieve the best response of said statistical measures.

The calibrated parameters of the model are: Kc (cultivation coefficient), Water storage capacity in the root zone (Sw), Deepwater storage capacity in the deep zone (Dw), runoff resistance factor (RRF) , Root zone conductivity (Ks), Deep zone conductivity (Kd) and Preferential flow direction (f). The values of the calibrated parameters are presented in Table 3.

Table 3 Values of the calibrated parameters in the Locumba river basin.

Calibration parameters	Sub-basin Calientes	Sub-basin Callazas	Sub-basin Tacalaya	Sub-basin Honda
Kc_bofedal	1	1	1	1
Kc_escasavegetacion	0.4	0.4	0.4	0.4
Kc_pajonal	0.9	0.9	0.9	0.9
Kc_tundra	0.1	0.1	0.1	0.1
Ks	100	100	100	100
Sw	900	900	900	900
RRF	1000	1000	1000	1000
Deep Conductivity (mm/month)	25	25	25	25
Z2 (%)	10	10	10	10
Preferred Flow Direction	0.15	0.15	0.15	0.15
Z1 (%)	50	50	50	50
Deep water capacity (mm)	3000	3000	3000	3000

In order to establish the degree of correspondence between the observed and simulated values, the Nash-Sutcliffe and Bias efficiency indices [3] have been used, whose equations are:

$$Nash = 1 - \frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{0,i})^2}{\sum_{i=1}^{n}(Q_{0,i} - \overline{Q_0})^2}$$

$$Bias = 100 * [(\overline{Q_s} - \overline{Q_0})/Q_0]$$

In the case of the model developed, it has been calibrated based on the historical records observed or recorded in the Aricota lagoon, for which the period January 1968 to December 1987 has been taken into consideration, with a Nash index of 0.97 and Bias of 3.32. Fig. 5 and 6 show the simulated and observed volumes.

The validation of the model has been carried out for the period from 1988 to December 2012, where the Nash index is 0.94 and Bias is -0.51 [4-6].

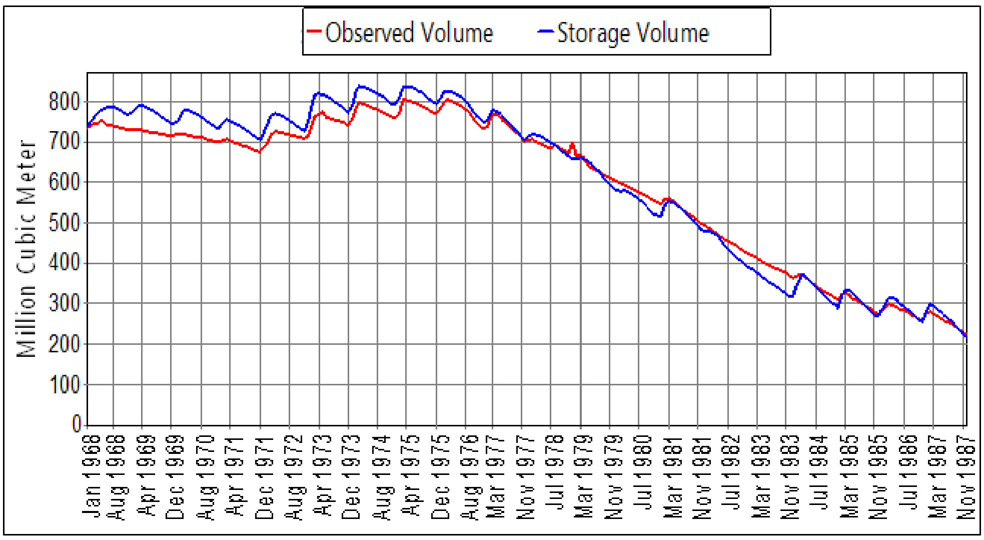

Fig. 5 Calibration of the model (1968-1987).

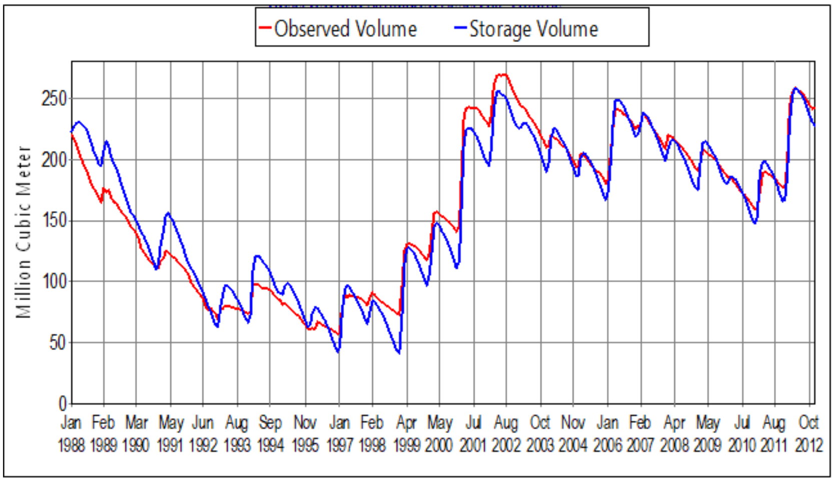

Fig. 6 Validation of the model (1988-2012).

3.2 Hydrological Simulation Scenarios of the Locumba River Basin

After the calibration stage, 3 simulation scenarios have been formulated:

Scenario I: Behavior of the Locumba river basin in the current scenario.

Scenario II: Behavior of the Locumba river basin considering the operation of the Callazas, Calientes-Santa Cruz and Coltani, Turunturun, Kullko and Ite dams. Fig. 7 shows the projected dams.

Scenario III: Behavior of the Locumba river basin in the current scenario operating the Vilavilani II Phase I project.

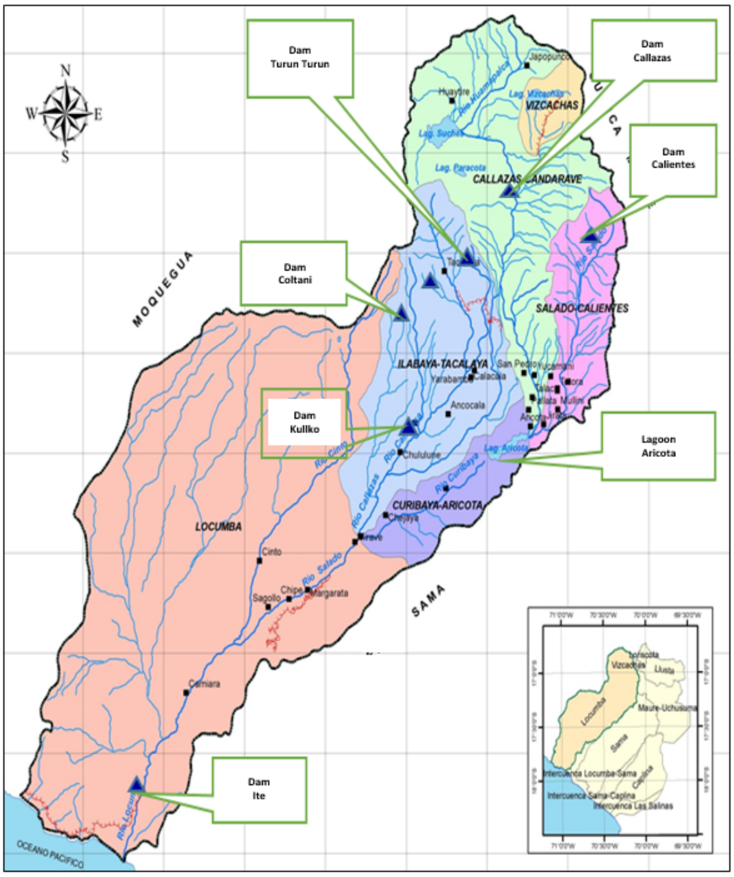

Fig. 7 Hydraulic scheme of the stage with projected dams.

4. Results

4.1 Projection of the Behavior of the Aricota Lagoon Maintaining The Current Scenario

The simulation carried out of the behavior of the Aricota lagoon for the period 2015-2045 shows a balance between entry and exit, with an average volume of 185 Hm^3, which could increase to volumes close to 360 Hm^3 due to the presence of wet years or to descend to volumes of the order of 150 Hm^3 due to the presence of dry years. Fig. 8 shows the projected behavior.

4.2 Water Balance of the Locumba River Basin in Current Scenario

In the upper part of the basin, the water supply is 86,226 Hm^3/year and is concentrated in the rainy season and in certain sectors the water demand has a 100% coverage, but in the dry season the water availability decreases and Water demand coverage only reaches 60%, so the deficit is of the order of 83,393 Hm^3/year. In the middle part of the basin the area under irrigation is limited and the demand for water is met 100% in the sectors of Curibaya, Poquera-Chulibaya due to the turbine waters of the Aricota lagoon, there is only deficit in the sectors of Toco and Chulibaya with a volume of 0.629 Hm^3/year. In the lower part of the basin, the water coverage is also 100% due to the extraction of water from the Aricota lagoon for the purpose of hydroelectric power generation, there is even excess water that goes to the ocean through the Ite intake sector a volume 13.1 Hm^3/year. In the Cinto valley, there is very low water coverage, and in the Ite irrigation in the last months of the year coverage is in the order of 70 to 80%.

4.3 Hydrological Analysis of the Locumba Basin Considering the Operation of the Projected Dams

The projected dams are spatially distributed in the upper, middle and lower part of the basin. In the upper part, the projected dams are: Callazas, Calientes-Santa Cruz, Turunturun and the extension of the Kularjahuira dam. The dams of Callazas and Calientes Santa Cruz are located upstream of the Aricota lagoon and their operation has a direct impact on the Aricota lagoon. The Callazas dam has a total volume of 11.5 Hm^3 and Calientes Santa Cruz of 5 Hm^3; the simultaneous operation of these 02 dams, according to the results of the hydrological simulation, will have an impact on the decrease in the volume of the Aricota lagoon, and in the year 2045, its storage volume could drop close to 83.1 Hm^3, which then it is a concern but reducing the leaks by Egesur that is the beneficiary of the turbine waters of the lagoon could mitigate its impact.

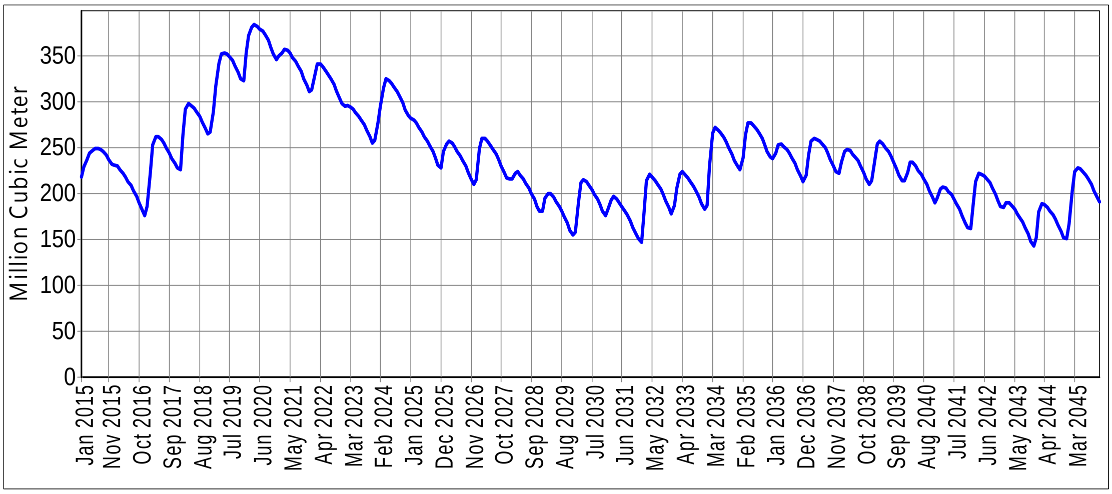

Fig. 8 Simulation of the Laguna Aricota 2015-2035.

The water supply in the scenario with project that is operating the Callazas and Calientes dams, will have a positive impact mainly in the irrigation sectors of Candarave, Quilahuani, Cairani and Huanuara and Santa Cruz and Patapatani, where water coverage will increase in a 40% on average in the dry season from October to December. The water supply in the upper part of the Locumba river basin will be 91,834 Hm^3/year.

The operation of the Turunturun dams (volume of 1 Hm^3), Coltani (Volume of 4 Hm^3), Kullko (8 Hm^3), and Kularjahuira (Volume 1 Hm^3), will also have a positive effect, because they will be able to increase the water supply of their areas of profit by 30% mainly in the dry season; but above all, it will not adversely affect the water supply of the Locumba Valley and Irrigation Ite, very on the contrary it will help to reduce the volume of water surpluses from 13.1 Hm^3/year to 4.5 Hm^3/year that are lost in the ocean by the water sector Ite intake.

4.4 Analysis of the Impact in the Aricota Lagoon of the Operation of the Vilavilani II Project

The Vilavilani II phase I project contemplates the derivation of the Maure river of 1 m^3/s in the rainy season with a priority rule of operation for the benefit of the city and valley of Tacna for population and agricultural use. The only source of transfer water for the Aricota lagoon will be the water filtrations existing in the Kovire tunnel that will be distributed to Sama and the users of Jirata, Chitune, Yaralaca and catchments, so the transfer of water to the Aricota lagoon in the dry period will practically be null. There will only be a transfer of water during the rainy season, as long as the supply exceeds 1 m^3/s, so the water transfer from the Maure river will be reduced from 0.574 m^3/s to 0.179 m^3/s, according to the obtained results, will have negative effects in the decrease of the volume of the lagoon and could cause its depletion in the year 2030. The pertinent details are presented in Fig. 9.

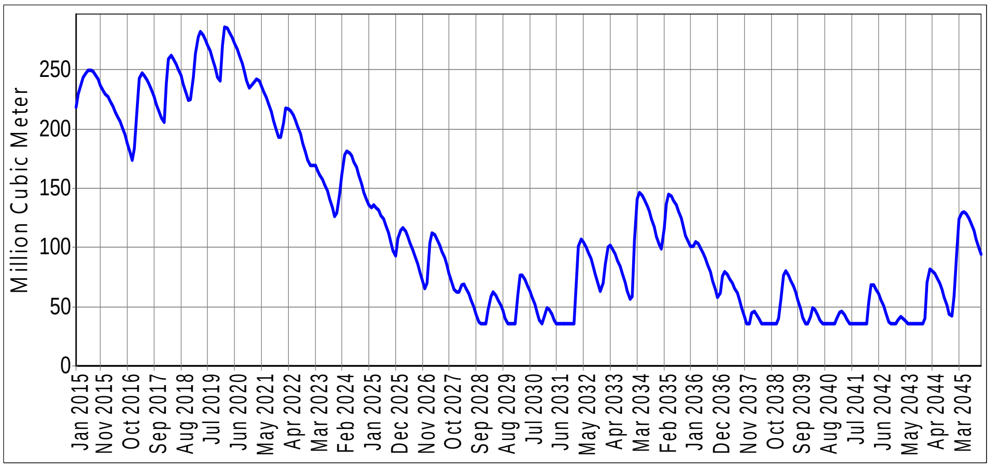

Fig. 9 Laguna Aricota with operation of the Vilavilani II Phase I project.

4.5 Analysis of the Cost of the Projected Dams in Tacna and Some Regions of Peru

Based on the costs of the dams declared viable by the National System of Public Investment (SNIP) in the regions of: Tacna, Moquegua, Arequipa, Ancash, La Libertad, Lima, Junín and Ayacucho, the cost of m^3 has been determined of water storage, from which it is concluded that the average cost in Tacna is S/33.4 nuevos soles/m^3 due to several factors, among them the rugged topography of the region, where high-altitude dams are required for a low volume of storage, the geological aspects related to local or regional faults due to the great volcanic chain, between other factors that increase the cost of dams; even so, the projected dam projects have an average IRR internal rate of return of

19%, which is why they have been declared viable by the Ministry of Economy and Finance. The cost of m^3 of water stored in the different regions of Peru is presented in Table 4.

Finally, for the cases of water damming projects of up to 5 MCM in the Tacna region, based on the approved projects, a relationship between storage volume and cost could be established, which would allow to know the cost of the dam at a level preliminary on the basis of a volume of dam. The detail is presented in Fig. 10.

5. Conclusions

The following conclusions can be drawn from the research carried out:

The Aricota lagoon located in the middle part of the Locumba river basin is a large natural regulation vessel, which is currently in equilibrium between the water supply of the rivers Callazas, Salado and the transfer of the headwaters of the Maure river through the Kovire and Ichicollo tunnels that together contribute an average annual volume of 93 Hm^3/year. According to the projection carried out in the next 30 years, the volume of this will average 237.5 Hm^3 with variations of decrease and increase due to the presence of dry years and wet years.

Table 4 Cost of m^3 of stored water of the projected dams.

Regions	Cost in Soles per m^3 dammed water
Arequipa	2.63
Moquegua	3.72
Ayacucho	11.14
Ancash y La Libertad	6.06
Lima y Junín	8.93
Tacna	33.4

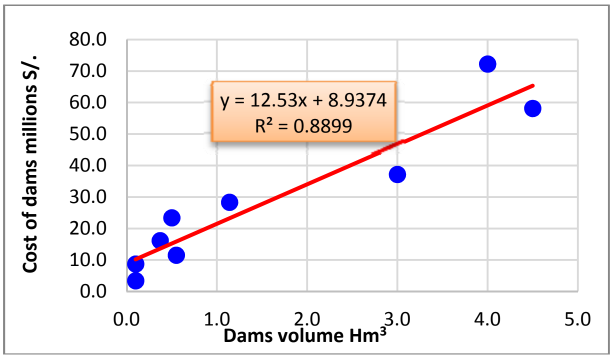

Fig. 10 Relationship between storage volume and cost in Tacna region.

The operation of new dams such as Callazas and Calientes for irrigation in Candarave and Santa Cruz located upstream of the Aricota lagoon will not deplete the water volume of the Aricota lagoon, but will reduce the volume of entry to the lagoon with an annual volume of 4 Hm^3/year and in 30 years of projected operation the volume could decrease to 83.1 Hm^3, which is worrisome, but a balance can be achieved by decreasing the flow rate of filtrations in 0.122 m^3/s of the Aricota lagoon through waterproofing works. This task can be assumed by the company EGESUR that benefits from the exploitation of the Aricota lagoon for the purpose of generating hydroelectric energy.

The operation and use of the Turunturun, Coltani, Kullko, Kularjahuira and Ite dams will not endanger the water availability of the Locumba Valley and Ite irrigation, because these dams will store water from the rainy season that is lost in the Pacific Ocean. the Ite intake sector, and will continue with 100% supply coverage of the Locumba Valley and will be able to reduce the surplus water that is lost in the Pacific Ocean from 13.1 Hm^3/year to 4.5 Hm^3/year in the Ite intake sector .

Finally, a comparison of m3 costs of dammed water has been made in the different regions of the country, from which it is concluded that the cost per m^3 of water in the Tacna region is of the order of S/33.4, in Arequipa of S/2.63, Moquegua of S/3.72, Ayacucho S/11.14 Ancash and La Libertad S/6.06 and Lima and Junín of S/8.93; This is due to several factors, including the rugged topography of the Tacna region and geological aspects.

References

[1] Autoridad Nacional del Agua, Dirección de Estudios de Proyectos Hidráulicos Multisectoriales, Lima: Ministerio de Agricultura y Riego, 2011.

[2] INEI, *"Población y crecimiento", En Dirección Técnica de Demografía y Estudios Sociales y Centro de Investigación y Desarrollo del INEI, Perfil*

sociodemográfico del Perú (2nd ed.), 2008, pp. 62-64, 87-100.

[3] S. Weglarczyk, The interdependence and applicability of some statistical quality measures for hydrological models, *Journal of Hydrology* 206 (1998) (1-2) 98-103, doi: 10.1016/S0022-1694(98)00094-8

[4] G. K. Devia, B. P. Ganasri and G. S. Dwarakish, A review on hydrological models, *Aquatic Procedia* 4 (2015) 1001-1007, doi: 10.1016/j.aqpro.2015.02.126.

[5] J. C. Abbott, J. A. Bathrust, P. E. Cunge, O'Connell and J. Rasmussen, An introduction to European hydrological system — system hydrologique European (SHE) Part 2, Structure of a physically based distributed modeling system, *Journal of Hydrology* 87 (1986) 61-77.

[6] Abu El-Nasr, J. G. Arnold, J. Feyen and J. Berlamont, Modeling the hydrology of a catchment using a distributed and a semi distributed model, *Hydrological Processes* 19 (2005) 573-587.