Chapter

# Interconnection among River Flow Levels, Sediments Loads and Tides Conditions and Its Effect on the Coastal Wetlands Reduction

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## Abstract

When the river supplies water to vulnerable environments, such as marshlands, it is vital to establish the expected impact mostly under a changing climate, and moreover, if a dam is being projected to solve energy demands. Soil characteristics, specifically sediment composition, are exposed to changes that modify this type of ecosystem and are rarely investigated. For this, a discharge period for an average historical year was analyzed to evaluate the magnitudes of the flows, with or without a dam. Also, it helped to identify the modification of the hydrodynamic regime between the sea and the lagoon system, particularly during the dry season but also checking the behavior in the rainy season. Results showed that the main problem with the construction of the dam on the San Pedro-Mezquital river would be the effect of a controlled flow that reaches the wetlands of the alluvial plains, affecting the sediment load in the estuarine and coastal ecology. However, after a readjustment period, the dam neither significantly changes the previous flood conditions of the coastal plain nor the sediment load will be a problem. However, if an additional sediment load is required to maintain the coastal microhabitats, there are different ways to provide it.

**Keywords:** marshlands, river connectivity, wetlands, Marismas Nacionales, dam

## 1. Introduction

A river needs to be understood as part of a changing system, so it cannot be studied in isolation. In this way, the benefits throughout the basin at different levels (high, middle, and low) and scales can be observed, which will favor the development of social and ecosystem services. However, to achieve comprehensive management of a basin, it is important to understand some of the main obstacles to river management, such as the changes that have originated through several actions, such as land use management (changes of coverage and use), climate change, development of aquatic resources and expansion of the industrial sector, dams, among others. These actions have considered changes in the runoff pattern, the quality of the discharges to the river, the size distribution, and the load of transported sediments, as well as changes in the structure of fluvial and riparian micro-habitats.

Hydrological processes are governed by a large number of biophysical and climatic variables. No matter how small, any change made to sensitive and highly vulnerable ecosystems generates large changes. Thus, when the change is not so small and considers the installation of a dam, there is a modification that alters the energy flows, such as the precipitation and temperature, and, in consequence, the evapotranspiration (ET), groundwater recharge, runoff, and water bodies storage [1, 2]. This implies that the cause/effect relationship of the realized changes will have significant environmental implications, such as the loss of biodiversity, alterations in hydrological processes, and land degradation. When it comes to natural or artificial reservoirs, runoff can be attenuated or restricted, although secondary runoff associated with overflows can even occur, changing the ecosystem upstream and downstream in the river [3]. The main responsible for this type of change is associated with humans and their productive activities [2], including river regulation and global warming change, which are the main drivers of changes in the flow regime of rivers identified by [4]. In particular, a dam that, on one side, it will provide several benefits to people, such as diversion of water to agricultural or urban areas, electricity production, aid in navigation, and flood control [5, 6]. However, on the other side, there are also negative changes affecting the estuarine and coastal ecology, which has resulted, in many places, in the loss of habitats such as wetlands. In particular, vegetative populations, such as riparian or coastal vegetation (e.g., mangroves), show a structure defined by the availability of freshwater, nutrient recycling, tidal flows, frequency of flood periods, physical characteristics of sediments, and water chemistry [7–9]. As these ecosystems could be highly affected by the changes in the rivers and their plains, a geomorphological analysis is necessary, and it includes the vegetation and environment, as formations of geoforms making the system highly unstable). In general, the installation of dams is associated with the loss of natural structures, changes in the grain size distribution (structure and substrate of the river bed), and interruption of the sediment transport of the river bed (continuity of the river). Thus, it is important to consider that inducing a discontinuity in longitudinal migration will likely lead to fragmentation of the aquatic fauna. Also, special attention needs to be made to the hydrology alterations caused by river regulation and climate change. The continued temperature increase, as well as the reduction of water supply (precipitation), have the potential to modify the timing and magnitude of a river flow [10, 11]. Duan and Cai [12] noticed that global warming had affected the snow accumulation in winter; and its melting in spring, resulting in short timing with peak runoff and the increment of discharges earlier in the water year; thus, there are changes in the annual flow [13]. For instance, Duan and Cai [12] observed that flood risk was reduced in cold watersheds corresponding to high latitudes and altitudes. In contrast, an increase in flood risk was registered by Allamano et al. [14] due to the increase in temperature and precipitation intensity. It will be common for rain-dominant basins to present floods related to storms in the wet season [15]. Precipitation is characterized by frequency and duration, which defines its magnitude, as well as soil moisture. Thus, a reduction/increment of high flow magnitude is significantly connected to changes in precipitation characteristics, climate warming, and the spatial heterogeneity of the terrain [12]. Maskey et al. [4] pointed out that there is no single climate model that explains the behavior of the hydrological processes. Still, it is necessary to understand both impacts and effects caused by the water bodies to set realistic managed environmental flows that cope with their ecological goals. Although, Maskey et al. [4] found that "the flow regimes downstream of a dam are likely more altered by reservoir operations than by climate change." Also, an intermittent flow created, as a result of the reservoir operations, affects the static instream flow requirements that might impact the movement, establishment, and environmental signals for aquatic life.

### 1.1 Tidally-driven connectivity

Streams, rivers, lakes, wetlands, and marshes are aquatic ecosystems that interact because of their ability to import and export material and energy altering the fluxes of these materials. These interactions require connectivity, where various transport mechanisms in a heterogeneous landscape define the degree to which components of a river system are joined or connected to other water bodies [16, 17]. Connectivity between freshwater and marine aquatic habitats offers benefits, such as migration of coastal habitats and species, protection of inland habitats against storms, waves, and seawater, food production, biodiversity protection, flood protection, and erosion control. In general, connectivity in these ecosystems is defined by characteristics of the physical landscape, climate, biota, and human impacts. The last one has partially restricted or completely obstructed tidally-driven aquatic habitats in coastal areas due to human developments (reclamation, species invasion, and environmental pollution), and infrastructure [18]. Thus, many coastal habitats have been disappearing because there is not enough space for inland movements. It is not only a longitudinal consideration, but it also requires studying the lateral and vertical movement since the first links ditches and floodplains, and the second the surface and subsurface [18]. It is important to contemplate the three of them in order to achieve good projects of maintenance or adaptation of these areas. In addition, it is necessary to consider that wetlands in riparian or floodplain areas can have bidirectional lateral hydrologic flows, whereas the type of connection between them only influences wetlands in non-floodplain areas. Also, it is necessary to consider whether vertical movement corresponds to an expansion or contraction of the river network since each one can affect the duration and timing of flow in this network [16].

An interesting aspect related to rivers is the transport of nutrients, sediments, chemicals, organic particles, microbes, detritus of various size classes, and living organisms downstream through wetlands, deltas, estuaries, and other downstream systems. Leibowitz et al. [16] identified the proportion of the material from (or reduced by) streams and wetlands, the residence time of the material in the downstream water; and the relative importance of the material to river function or ecosystem services as the main factor that influences at the material and energy fluxes from streams, and wetlands downstream. As connectivity can be defined as the degree to which components of a system are connected and interact through various transport mechanisms, it varies over time and space, and there are several methods to characterize or quantify it at the watershed scale, such as field hydrological monitoring, hydrological models, connectivity index, remote sensing approach (e.g., LIDAR data or aerial imagery) and graph theory [18]. Park and Latrubesse [19] used remote sensing to map the seasonal water extent and quality variabilities. Also, they identified channel-floodplain connection thresholds and validated results using field measurements. They confirmed that hydrological connectivity processes happen mainly through floodplain channels having specific river level thresholds over space and time characterized by different recharging conditions (through sequential river pulses), water residence, and recessional periods. In addition, Freeman et al. [20] identified that changes upstream of a river affect directly downstream ecosystems, which are also associated with sea conditions, such as flooding, frequency by the tidal and cumulative flooding time. The last two are also responsible for the ecological structure and functions of coastal ecosystems, such as estuaries, mangroves, and tidal flats [21]. Thus, the main goal of this research was to quantify the impact of a dam operation in both river and marshland systems as a function of their connectivity by looking at its spatial (part of the basin) and temporal (dry and wet seasons) variations. For this, the hydrology was modeled for a period of discharges to evaluate the magnitudes of the flows, with or without the dam. This allowed identifying the modification of the hydrodynamic regime between the sea and the lagoon system during the dry and wet seasons.

## 2. Study area

The study area is in the state of Nayarit, which has the largest number of mangroves together with the state of Sinaloa, sharing the Teacapán-Agua Brava-Marismas Nacionales lagoon system [22]. The rivers that drain the system are Cañas, Acaponeta, Rosamorada, Bejuco, San Pedro, and Santiago, with 161,515 km$^2$. This study area is located in the physiographic province of the coastal plain of the Pacific, in the sub-province of the delta of Santiago. Along the river, lands of the deltaic landscape system characterized by marshes with coastal lagoons and parallel bars of old coastlines can be found (**Figure 1**). The soil types correspond to fluvisols, cambrisols, and feozem with some gleysols. The feozem is well-drained, fertile, and productive soils. Thus, these plains are excellent for agriculture. In general, more of the landscapes are converted into agricultural lands.

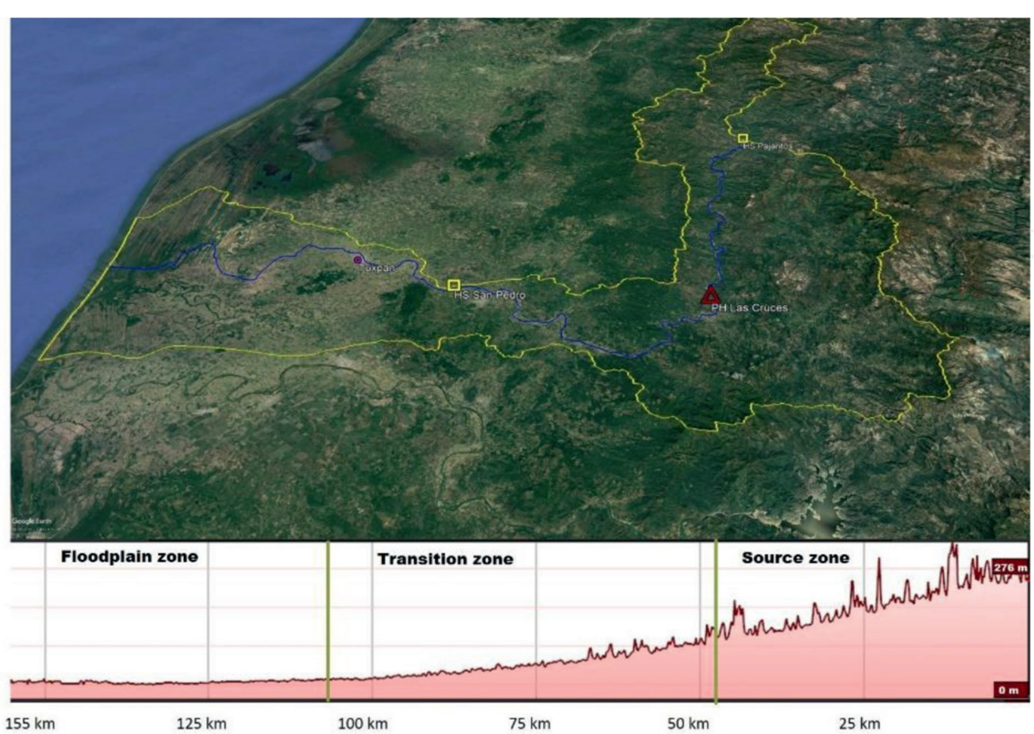


**Figure 1.**
*General scheme of the San Pedro river from the Las Cruces Hydroelectric Project (PHLC) to the Marismas Nacionales zone.*

Climate is sub-humid and warm with summer rainfall and semi-warm sub-humid. The average annual precipitation is between 1000 and 1500 mm, reaching more than 2000 mm in September and October. However, rainfall is also associated with the presence of the Mexican monsoon and the occurrence of hurricanes and tropical storms, which may appear between June to October each year. Vegetation includes agriculture occupying 10.67% of the alluvial plains with a low slope (less than 1 m) of the high plateau with deep and moderately deep soils. On both river banks, two irrigation districts (DR) are developed: 052 and 043 are at the present.

Bojórquez et al. [23] identified that the deltaic plains are made up of alluvial material. The presence of dynamic processes is manifested in erosion (in the channel) and accumulation along the flood plain (terraces and dikes). This type of geomorphological landscape in the lower part of the San Pedro-Mezquital river basin, dividing it into (a) intermediate fluvial plain (second level of a fluvial terrace at heights of 5–10 m, from which the rivers overflow in extraordinary flows), (b) low plain with fluvio-marine influence, and (c) fluvial flood plain. In the latter, it is found in the current riverbeds with fluvisols subjected to the action of the systematic flooding of the Santiago, San Pedro, and Acaponeta rivers, where a rejuvenation process is active, which is manifested by the presence of fluvic material in the first 50 cm at the thick soil. In the Marismas Nacionales (MaNas, National Marshes) region, there are few evolved mineral soils of unconsolidated colluvial-marine contribution with moderate erodibility and salinization or sodification [23].

The MaNas is estuary's most important wetlands system, where the mangrove is the dominant vegetation (15–20% of the total of this valuable ecosystem) with species reaching up to 20 or 30 m tall and occupying almost 175,000 hectares [24]. Other vegetation types are halophytic and tular vegetation; the distributions of mangroves and halophytic vegetation clearly respond to a hydraulic regime of flooding. However, these areas have been affected by human beings who have modified the riverbed not only in the mangrove area but also upstream with deforestation and the creation of dams or canals to guarantee agricultural activities. Blanco y Correa et al. [24] noted that from the total area of the estuary, around 135,000 ha (77%) suffered from tidal disturbance; between 5000 and 10,000 ha (from 2.8 to 5.5%) have disappeared under the sea due to coastal erosion, and 5000 ha (2.8%) represented effects from the hydro-sedimentary imbalance of its river. Thus, more than 15,000 ha (8.86%) have an accumulated and synergistic environmental deterioration of at least four to six decades of interaction with different factors, such as poor water, sediment quantity, and quality.

As the MaNas area is important for its high biodiversity and ecosystem services, it is required to take care of its mangroves and, in general, of the entire wetland system. In this way, the real impact that river systems have in the face of natural and anthropic changes, such as altering rivers' capacity to recover or presenting different losses in the hydrological basin needs to be considered. Some actions to protect these ecosystems are the reduction of the possible erosion of beaches, eutrophication of bodies of water, loss of habitat, loss of soil fertility, and reducing the vulnerability to storms or tidal waves, among others.

It is important to recognize that in the MaNas area, the contribution of water is associated with the rain and runoff from the San Pedro river and the effect of the underground movement of water, which means that it can move from neighboring lateral areas into and out of the areas bounded by the watershed. In other words, the hydraulic behavior of the MaNas zone owns complex hydrological connectivity due to the existing interaction between freshwater and marine water. There are associations between the periods of sedimentation and marine regression, which largely affects the sediments' character (differentiation of mechanical particles and/or carbon content in the thickness of the soil profile), the spatial distribution of salinity, and the predominant type of vegetation. This makes MaNas different from the rest of the basin, being the movement of subsurface water decisive. In fact, the drainage patterns of the lower courses of the San Pedro-Mezquital river changed due to the deposition of sediments and the construction of protection levees on the riverbanks. Although the dam will signify greater flood control, at the same time, it will introduce changes in the coastline, intensifying the erosive processes of channels, and the accumulation of sediments in the coastal lagoons.

### 2.1 PHLC: reservoir characteristics

Las Cruces Hydroelectric Project (PHLC) curtain is located in the state of Nayarit on the San Pedro river, approximately 80 km from the river's discharge to its floodplain to later drain into the MaNas lagoon area and, finally, to the Pacific Ocean. **Figure 2** shows a general scheme of the PHLC contribution basin, having considered a tributary area of 24,879 km$^2$, as well as the general plan of the reservoir, which has a maximum flood length of approximately 60 km on the San Pedro river considering the elevation of the OMWL (ordinary maximum water level) at 238 masl.

The most important data of the reservoir concerning this study are: (a) OMWL capacity of 2267 × 10$^6$ m$^3$ and (b) extraordinary maximum water level (EMWL) capacity of 2485 × 10$^6$ m$^3$. **Figure 3** shows the runoff and sediment volumes at the inlet and outlet of the reservoir, as well as the hydrometric stations (EH) of Pajaritos

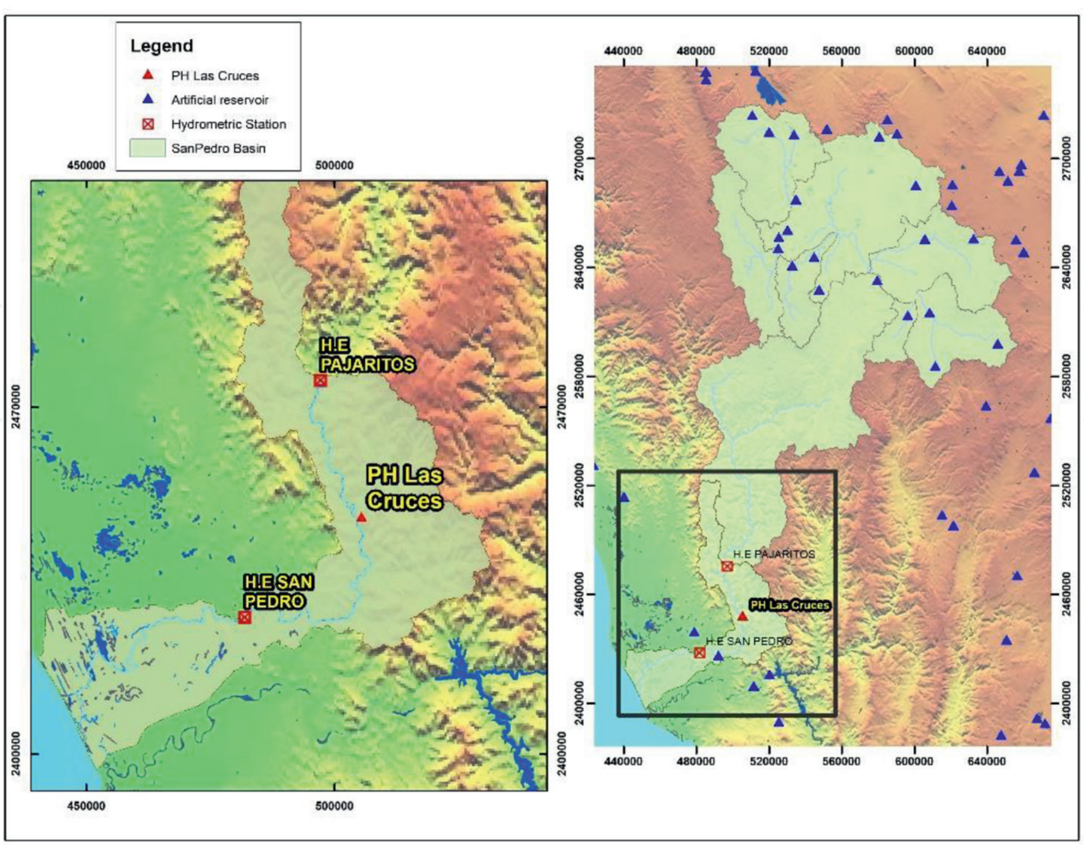


**Figure 2.**
*General plan of the reservoir and the contribution basin to the PHLC. Source: Ref. [25].*

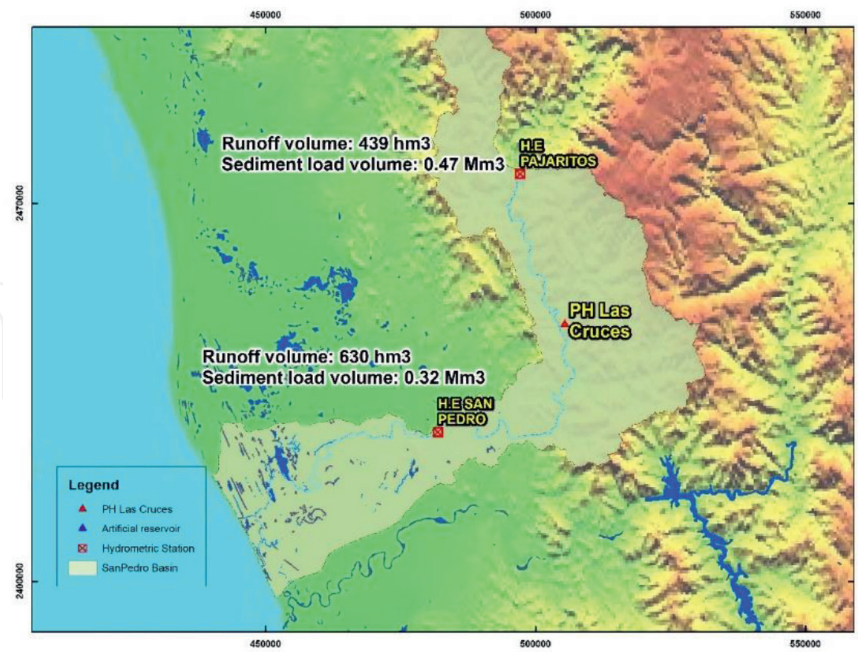


**Figure 3.**
*General plan of the reservoir: runoff and sediment load. Source: Ref. [25].*

and San Pedro. The bathymetry of the reservoir was obtained from the LIDAR information provided by [25], and the hydrometric information used to obtain the average monthly discharges was obtained from Ref. [26].

**Table 1** shows the monthly average discharge values and the monthly mean concentrations of transported fine solids obtained from the monthly sediment averages. The monthly mean concentrations of fine solids were obtained from the quotient of the monthly sediment volumes divided by the runoff volume.

Annual precipitation throughout the San Pedro river basin shows high variability. However, there is a clear trend, with precipitation being greater as one move toward the outlet of the basin. In fact, the highest rainfall occurs in the MaNas area, where it reaches more than 1.5 m per year. The average annual discharge calculated at the EH San Pedro station was 87.2 $m^3\ s^{-1}$, the maximum 204.7 $m^3\ s^{-1}$, and the annual minimum 24.6 $m^3\ s^{-1}$. According to the records, the maximum annual average discharge was presented in 2008, whereas the minimum was in 2005. The San Pedro river basin recorded 53 floods from 1944 to 2004, causing significant socioeconomic damage [26]. It was determined that the flood season occurs mainly from July to November. These floods are associated with the fact that the San Pedro river basin is subject to extraordinary meteorological events. In particular, the rainfall in this area is due to the presence of the Mexican monsoon, which causes above-average rainfall, although not always with the same intensity during the months of June, July, and August. The monsoon is produced by a break in the atmospheric circulation in the northwest that generates the release of latent heat and a rise in temperature and wind and, consequently, an increase in humidity. The humidity flow begins in the so-called intertropical zone of convergence and is accentuated by the tropical waves caused by the trade winds, which come from the central Atlantic, generating a displacement of humidity toward the Pacific coastal zone. But, also, droughts occurrence was identified for two historical periods, from 1976 to 1980 and 1995 to 2001, with 5–7 successive years of null flow, respectively. Regarding the river regime, flows between 1000 and 1400 $m^3\ s^{-1}$ were observed in the case of very dry years, whereas in average years,

| Month | Discharge ($m^3 s^{-1}$) | Concentration (kg monsoom$^{-3}$) |
|---|---|---|
| January | 4.76 | 0 |
| February | 2.29 | 0 |
| March | 0.22 | 0 |
| April | 0.02 | 0 |
| May | 0.00 | 0 |
| June | 8.74 | 0 |
| July | 78.53 | 0.89 |
| August | 40.91 | 0.47 |
| September | 44.83 | 0.53 |
| October | 40.478 | 0.27 |
| November | 67.03 | 1.67 |
| December | 111.34 | 0.44 |

**Table 1.**
*Average monthly discharges and concentration data.*

the accumulated flows are around 2200 $m^3 s^{-1,}$ and in very wet years of a more than 4000 $m^3 s^{-1}$. If one considers a design flood with a return period (Tr) of 10,000 years, peak flows of 12,237.8 $m^3 s^{-1}$ and 12,867.4 $m^3 s^{-1}$ were obtained. When this design avenue passed through the spillway, a maximum discharge rate of 9048 $m^3 s^{-1}$ was obtained, reaching a maximum level of 2.3 m, which is less than the EMWL.

## 3. Method

To evaluate the impact of the operation of the PHLC in the lagoon and MaNas zones, a flash flood period for an average historical year from September 19th to October 6th, 2010 was analyzed. Two conditions were applied: without the dam using the hydrograph measured during the mentioned period, and with the dam using the turbine hydrograph plus the contributions of its own basin. **Figure 4** shows the two hydrographs considering these scenarios.

The operation of the PHLC in the lagoon and MaNas zones shows that the two hydrographs, with and without the dam are practically the same, so one can conclude that the alteration of the flow in flash floods due to the presence of the PHLC would be minimal, without any important consequence for the downstream areas. Another fundamental aspect to consider is the sedimentation sites and granulometric characteristics of the material. For that, Gracia-Sánchez et al. [27] applied physical models looking for a reliable representation of the reservoir entrance. Thus, sites with materials between 1.0 and 0.1 mm were identified for their possible extraction and, consequently, to refine or adjust the model results. With this information a numerical model was developed founding that only four sites required an adjustment (**Figure 5**), these sites are the mouths of Camichín (SEC1) and Palapares (SEC11), the Toluca Lagoon (SEC25), and the Mexcaltitlán lagoon (SEC85). However, even though the numerical model represents well the deposit of sediment at the entrance of the reservoir, there is no interpretation of the granulometric distribution that occurs in the deposit, particularly in the case of the PHLC, which is crucial to define the future transport downstream the curtain.

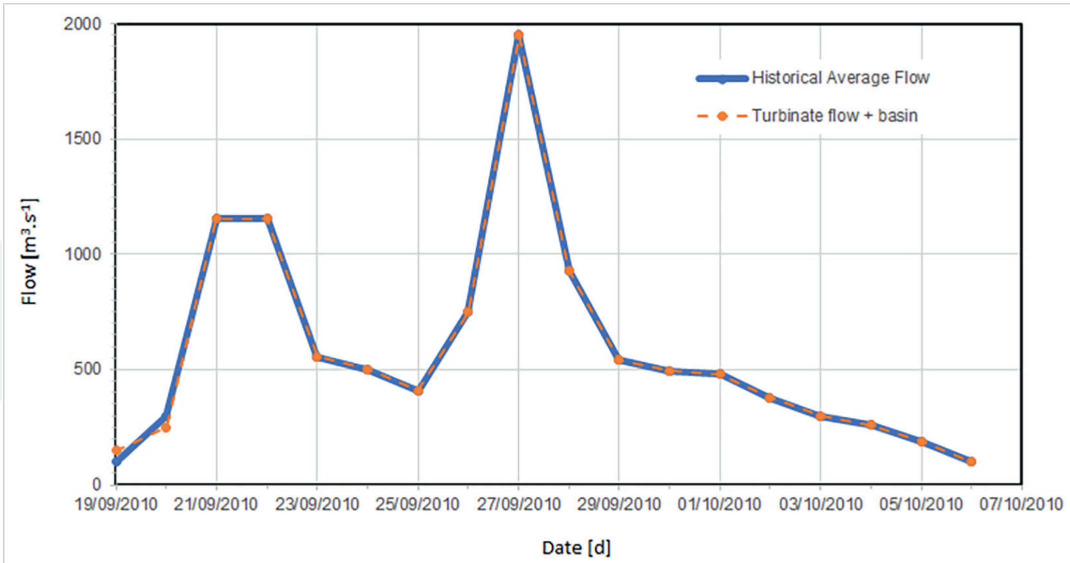


**Figure 4.**
*Hydrographs for the simulation scenarios in the flash flood season.*

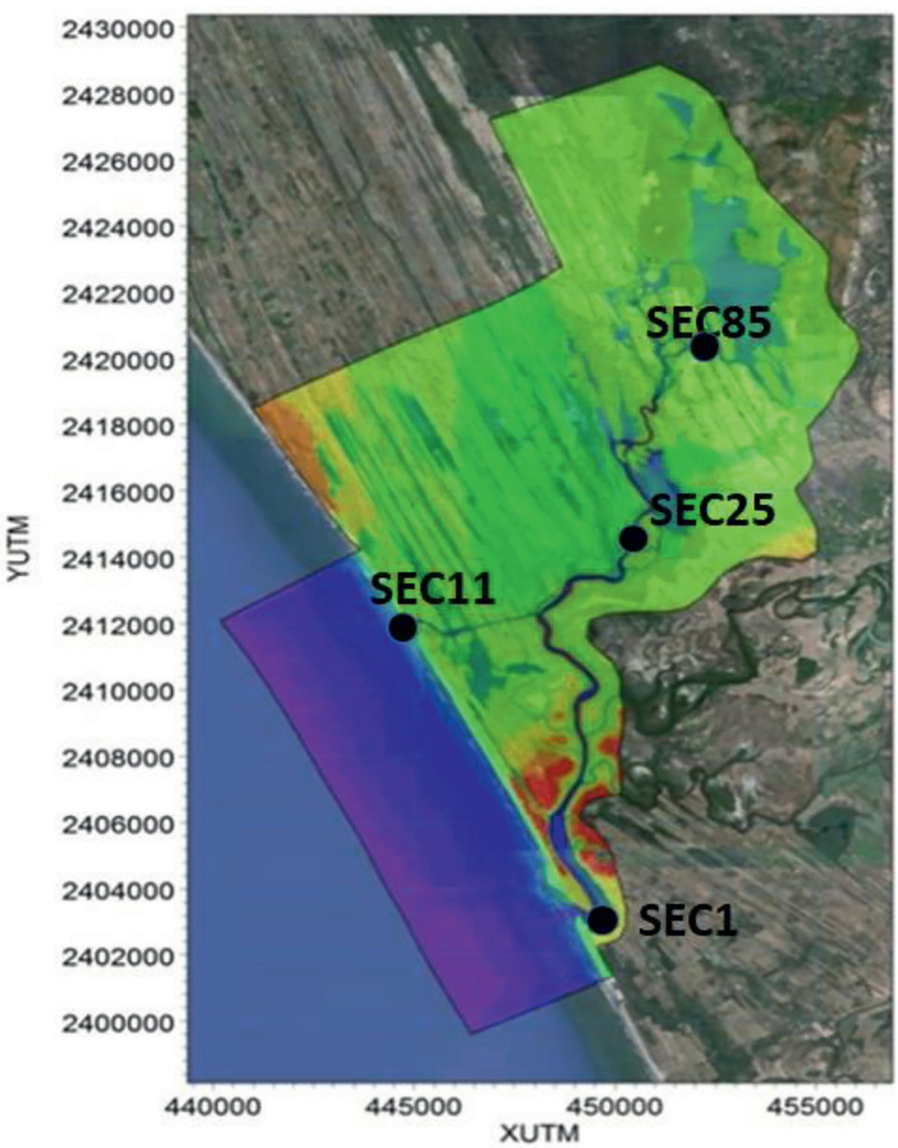


**Figure 5.**
*Flash flood analysis sites.*

## 4. Results and discussions

To understand the effect that the PHLC would have on the flow downstream, a simulation was carried out considering two scenarios: a historical condition and the PHLC for dry and rainy seasons.

### 4.1 PHLC functioning during the dry season

**Table 2** presents the discharges observed in the lagoon system without and with dam during the dry season in the sections identified along the river. The negative signs in the average discharge indicate that the direction of the flow is toward the sea.

When the average flow rate is 0 $m^3 s^{-1}$, it indicates that during the analyzed period, the volume of water that entered the system is the same as the one that left. If this is different from 0 with a positive sign, it indicates that, during the studied period, the volume of water that enters is greater than the one that leaves and, on the contrary, if the sign is negative, it indicates that more water leaves than the one that enters the system. In this way, it is observed that with the operation of the PHLC, when the discharge in the San Pedro river increases, the volume of water that leaves the system toward the sea increases (**Table 3**).

Also, it was observed that when the levels in the lagoon system increase due to the operation of the PHLC during the dry season, the difference in levels between the system and the sea is modified by: (a) in high tide conditions the gradient is lower; therefore, the flow of water from the sea to the system decreases, a situation that is reflected in the reduction of the discharges that enter through the sea toward the lagoons; and (b) low tide condition, the gradient is greater; therefore, the flow of water toward the sea increases as well as in the flows that leave the system. In particular, in the Camichín mouth (SEC25), there is a major exchange of water between the sea and the lagoon system, leaving the Palapares mouth with a reduced exchange (SEC11). This water exchange defines the maximum, average, and minimum water levels at each site with respect to the two established conditions (without and with the PHLC) as shown in **Table 4**.

As highlighted in **Table 4**, in the four sites, the water level impact due to the operation of the dam is not significant. This is confirmed in **Table 5**, which shows the maximum, average, and minimum variations reached for each site.

The water level variation associated with the operation of the PHLC during the dry season showed that at the Camichín mouth there are no differences, but in the Palapares mouth and in both lagoons (Mexcaltitán and Toluca), there is an increase in the average level of the order of 1 cm. Thus, the average water level for the four sites is 0.18 m, 0.14 m, 1.0 m, and 1.6 m, respectively. In addition to the discharge and water

| Discharge ($m^3 s^{-1}$) | SEC1 | | SEC11 | | SEC25 | | SEC85 | |
|---|---|---|---|---|---|---|---|---|
| | Without | With | Without | With | Without | With | Without | With |
| Maximum | 426.5 | 423.0 | 157.3 | 156.1 | 231.3 | 227.5 | 79.4 | 78.9 |
| Reflux | 423.0 | 425.4 | 115.4 | 116.5 | 199.6 | 205.1 | 65.1 | 69.8 |
| Average | −5.1 | −9.3 | 0.1 | −1.8 | −7.0 | −12.2 | −4.2 | −8.7 |

**Table 2.**
*Maximum (toward the system), reflux (toward the sea), and average discharges in the lagoon system, without and with dam during the dry season.*

| Discharges variation ($m^3 s^{-1}$) | SEC1 | SEC11 | SEC25 | SEC85 |
|---|---|---|---|---|
| Maximum flow | −3.5 | −1.2 | −3.8 | −0.5 |
| Reflux | 2.4 | 1.1 | 5.5 | 4.7 |
| Average | −4.2 | −1.9 | −5.2 | −4.5 |

**Table 3.**
*Discharges variation for the operation of the PHLC in the dry season.*

| Water level (m) | Tidal wave | SEC1 | | SEC11 | | SEC25 | | SEC85 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Without | With | Without | With | Without | With | Without | With |
| Maximum | 0.73 | 1.01 | 1.01 | 0.88 | 0.88 | 2.53 | 2.53 | 2.79 | 2.79 |
| Average | −0.01 | 0.17 | 0.17 | 0.13 | 0.14 | 1.03 | 1.04 | 1.57 | 1.58 |
| Minimum | −0.74 | −0.67 | −0.67 | −0.63 | −0.63 | −0.49 | −0.49 | −0.10 | −0.10 |

**Table 4.**
*Maximum, average, and minimum water levels without and with dam during the dry season.*

| Water level variation (m) | Camichín Mouth | Palapares Mouth | Toluca lagoon | Mexcaltitán lagoon |
|---|---|---|---|---|
| Maximum | 0.00 | 0.00 | 0.00 | 0.00 |
| Average | 0.00 | 0.01 | 0.01 | 0.01 |
| Minimum | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 5.**
*Variation of levels due to the operation of the P. H. Las Cruces (PHLC) during the flash flood season.*

levels data, other aspects to be considered in the operation of the lagoon system are velocity and salinity.

Reviewing velocities for the four sites, one can find that the main changes were observed in both mouths of Camichín and Palapares. In the first, the average flow velocity for both scenarios (without and with a dam) is around 0.933 m $s^{-1}$. However, the maximum velocity was 2.097 m $s^{-1}$ for current conditions and 2.099 m $s^{-1}$ for the project conditions, so there would be an increase of the order of 0.002 m $s^{-1}$, which is not significant. At the Palapares mouth, an average velocity of 0.840 m $s^{-1}$ for the current condition, and 0.842 m $s^{-1}$ for the project condition were observed, which shows an increase of the order of 0.002 m $s^{-1}$, which is also not significant. The maximum velocity registered was 1.807 m $s^{-1}$ for the current conditions and 1.808 m $s^{-1}$ with a dam; thus, there is an increment due to the operation of the project of 0.001 m $s^{-1}$.

In 2016, the Institute of Marine Sciences and Limnology (ICMyL) of the UNAM established an initial salinity of the system and concluded that there is an important change from almost 0 in the river to close to 30 PSU in the lagoons, and then a gradual increase from the lagoon to the sea, as shown in **Figure 6**. Salinity is measured in practical salinity units (PSU) or ppt (parts per thousand).

To estimate the salinity of the system under PHLC operation, simulations were carried out considering that the San Pedro river has fresh water, while the lagoon

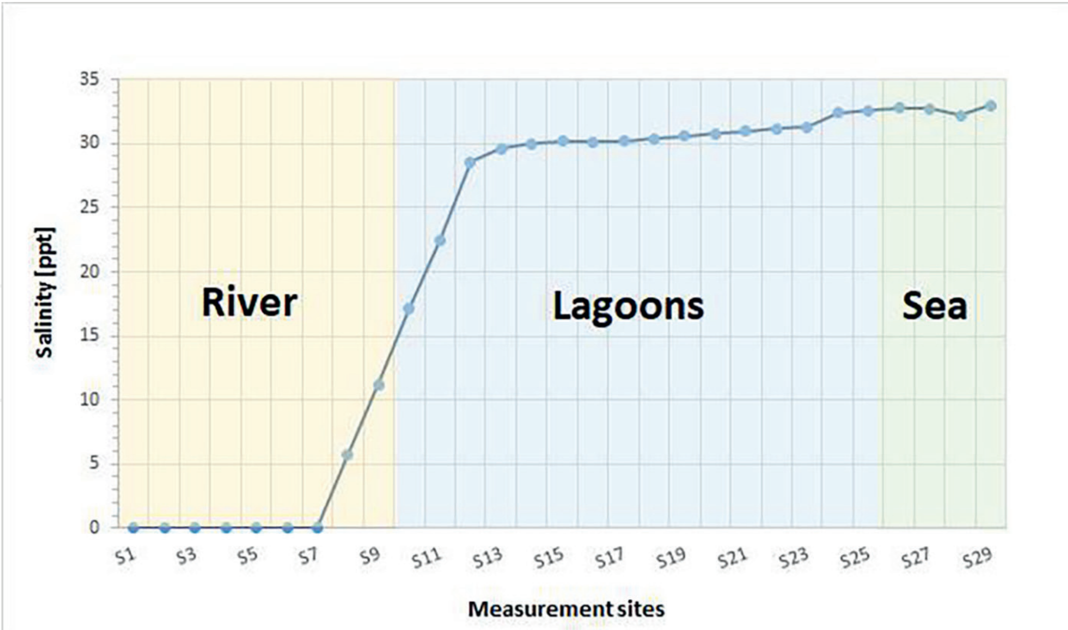


**Figure 6.**
*Salinity measured in the system in May 2014.*

system presents high salinity concentrations (29–32 ppt), and close to the sea the salinity is 33 ppt. Thus, for the dry season, the average salinity of 32.9 ppt was obtained in the mouths of Camichín and Palapares, as well as in the lagoons of Toluca and Mexcaltitán in current conditions, and with the dam, the salinity decreased by only 0.1 ppt. The latter is due to the PHLC operation, where it is expected a greater contribution of freshwater coming from the San Pedro river; thus, the salinity concentration decreases mainly in the Mexcaltitán and Toluca Lagoons, with average values of 11 and 3 ppt, respectively. Similarly, in the mouths of Camichín and Palapares, the salinity decreases on average by 0.1 and 0.8 ppt, respectively.

### 4.2 Lagoon behavior in the dry season and its relationship with the tides

The water level behavior within the lagoon system is mainly determined by the tidal condition and its influence reaches the Mexcaltitán lagoon, at a distance of around 25 km from the Camichín mouth. With the operation of the PHLC during the dry season, there is an increase in the level of the lagoon system, in the Mexcaltitán lagoon, the average increment is around 0.06 m, while in the Toluca lagoon is around 0.02 m. Thus, when comparing and calculating the maximum amplitude of the water levels in the sea and in each of the lagoons, it was found that in the sea the amplitude is 1.85 m, while in the Toluca lagoon is 0.95 m without and with the dam, and in the Mexcaltitán lagoon is 0.3 m under current conditions with an increment of 0.33 m with the dam. As one can observe, the amplitude of the water levels in the Toluca lagoon does not have a significant impact due to the operation of the hydroelectric project. However, in the Mexcaltitán lagoon, the amplitude of the water levels increases by around 3 cm due to the contributions of the San Pedro river during the dry season. Thus, in the Toluca lagoon, the percentage of tidal damping is around 48% for both scenarios, while in the Mexcaltitán lagoon, it is around 84% under current conditions and around 82% under hydroelectric project conditions.

In addition, velocities values do not present significant differences in the dry season considering the PHLC operation as increments of just 0.01 and 0.02 m $s^{-1}$ were observed. Therefore, the sediment transport conditions are not substantially modified in the lagoon system. This was confirmed since the velocities are determined by the tide condition, when the maximums are reached, close to the high and low tides, the system has the capacity to put the sediment in suspension.

As the largest discharges in the entire system were at the mouth of Camichín, it is the site where the main exchange of fresh water with the sea occurred. The maximum flow entering the system under current conditions was calculated at around 427 $m^3$ $s^{-1}$, whereas the one leaving the system was 423 $m^3$ $s^{-1}$. With the operation of the hydroelectric project, a reduction of the maximum flow that enters the system through the sea of the order of 4 $m^3$ $s^{-1}$ was observed; however, the flow that leaves increased by the order of 2 $m^3$ $s^{-1}$. On the contrary, at the mouth of Palapares, under current conditions, the maximum flow that entered the system through the sea was 157 $m^3$ $s^{-1}$ and the one leaving was 115 $m^3$ $s^{-1}$. With the operation of the project, there was a decrease in the flow that enters of around 1 $m^3$ $s^{-1}$, while the flow that leaves increased in the order of 1 $m^3$ $s^{-1}$.

### 4.3 PHLC operation during the rainy season

Applying numerical modeling during the period of flash floods, the PHLC operation does not have significant modifications in the hydrodynamics and salinity of the lagoon system. Thus, the water level behavior in the Mexcaltitán and Toluca lagoons, in both conditions (without and with the project), is mainly determined by the contributions of the San Pedro river. Unlike the mouths of Camichín and Palapares, where their behavior is mainly determined by the influence of the tide, with an increase in its average level due to the contributions of the river. In general, the water level in the lagoon system for the flash flood season, is above the mean sea level, of the order of 18 cm at the Camichín mouth, 14 cm at the Palapares mouth, and 1 and 1.6 m at the Toluca and Mexcaltitán lagoons, respectively. Thus, if the project comes into operation, it would be expected an average increase in the water level of the order of 1 cm in the Camichín and Palapares mouths. Whereas, the maximum water levels in the Mexcaltitán and Toluca would reach around 2.8 and 2.5 m, respectively.

Regarding the flow velocity, this increase considerably throughout the lagoon system in the rainy season. In the dry season, the velocities analyzed never were above 1 m $s^{-1}$, while in the flood season, the speeds were close to 2 m $s^{-1}$ at the mouths of Camichín and Palapares. On the contrary, the simulation with the operation of the PHLC showed that the speed does not present significant differences with respect to the current conditions calculating increments between 0.001 and 0.002 m $s^{-1}$.

Looking at the discharge values during the rainy season, and for most of the simulation time, the discharge moves out through the mouths toward the sea and exceeds 1000 $m^3$ $s^{-1}$, which corresponds to the peak of the flood. With the operation of the project, there is an average increment in the system discharges of 1 $m^3$ $s^{-1}$. In this way, it is considered that during flash floods, practically a constant gradient of the lagoon system toward the sea is established.

Undoubtedly, the greatest change observed in the rainy season is in the salinity concentration of the entire system. This is due to the contribution of freshwater from the San Pedro river at that time that reaches 0 PSU in a short period (2 days) and this behavior is not modified with the operation of the PHLC.

Also, the natural conditions of flooding analysis were assessed (without ribs), and the results showed that there is no significant change because the disturbance in the average annual maximum discharge is not representative. In fact, it is expected a possible attenuation of floods during the rainy season, which is more related to the existence of the reservoir than to its operating policy. This is because, unlike the minimum annual discharges, which are very low in the EH San Pedro, any change in the operation of the reservoir would alter the flooding conditions. This means that only by reducing the operating volume to the desired minimum, the minimum average annual discharge frequency curves (ecological expenditure) could be preserved. Thus, the most important aspect is to establish operating policies that can meet the generation needs and that these policies are viable for the San Pedro river ecosystem conservation. Another determining factor observed was that flood volumes and times are related to sediment dynamics. Thus, larger floods stir up sediment deposition, while shorter flood times alter the rate of sediment deposition.

### 4.4 Coastal wetlands reduction

The coastal marshes of the San Pedro river own a complex hydrological connectivity due to the existing interaction between freshwater and marine water, which affects largely the spatial distribution of salinity and vegetation in this region. The greatest changes observed in the Río San Pedro-MaNas ecosystem occurred in the alteration of the land cover and use, generating modifications of the hydrology and the local landscape, as well as altering the flood patterns responsible for the functional dynamics of the system, the maintenance, productivity and services that these ecosystems naturally provide to societies. Currently, the construction of any infrastructure can be seen as disastrous as it would profoundly modify the physiography of the entire basin, but at the same time dams, reservoirs and canals are an aid that would help to distribute hydrological resources in a constant manner and control possible flood events. Although the presence of a dam in the middle basin of the San Pedro-Mezquital river would generate initial changes, after the adjustment period, the system would be expected to work supportive of the MaNas conservation by reinforcing the marine influence in the area. This, in turn, would lead to a re-elaboration of the sediments of the coast, which may favor an effective wave that transports sand to the most deprived areas.

The fine sediment constitutes one of the most important aspects in the continuity of the sediment as it plays a determining role in the zone of the lagoons and mangroves for its sustainability. So far, what can be obtained from the work carried out is that the fine sediment will not be significantly retained in the PHLC reservoir. Rather it will re-distribute over time, that is, it will continue passing the same fine sediment but distributed differently over time. In fact, the first results indicate that the amount of fine sediment that would pass through the PHLC reservoir is not significant with respect to the total that reaches the mangrove area since the contribution of fine sediment from the San Pedro river is $0.28 \times 10^6$ $m^3$, while the amount contributed downstream of the EH San Pedro is $1.62 \times 10^6$ $m^3$ and this reaches $2.19 \times 10^6$ $m^3$ at the outlet to the sea. Therefore, it can be stated that in the hypothetical case, if all the fine material is retained in the PHLC reservoir, only 10% of the material that reaches the sea would be modified, but the reservoir, as mentioned, cannot retain this type of sediment, even if the dam acts as a blocking of the transported sediments to avoid that a lack of sediments downstream could become critical, maintaining the floodplain ecosystem. Auel et al. [28] indicated that it is possible to achieve sediment management to maintain the sediments downstream. Some techniques used for this purpose are flushing, sluicing, and bypassing [29, 30]. However, in the simulations carried out by [27], the main deposit of the thick material occurs in the tail of the vessel, for which its extraction must be done through a mechanical mechanism. In theory, the sediment can be moved to the curtain by emptying the reservoir several times, since it is a cannoned channel, that is, it is narrow and the water can reach high speeds for sediment transport. Therefore, if the coarse sediment is really needed downstream of the curtain, an option would be to use some mechanical methods such as dredging and transporting the material to the sites where the coarse sediment is needed.

The operation of the PHLC in the lagoon and MaNas zones shows that flash floods would be minimal, without any important consequence for the downstream areas. Even looking at the velocity results, the operation of the PHLC would not significantly modify the exchange conditions and water contributions to the lagoon system during a flash flood event. However, it is important to mention that with the operation of the PHLC, discharges on the San Pedro river would increase the volume of water that leaves the system toward the sea. Another important result of the operation of the PHLC is that the concentration of salinity would decrease due to the increase in the contributions of freshwater (constant flow) from the San Pedro river during the dry season.

It is during the dry season, when the water levels in the lagoon system increase as a result of the PHLC operation, the difference in levels between the lagoon system and the sea is modified according to:

- In high tide conditions, the gradient is lower; therefore, the flow of seawater into the system decreases. This situation is reflected in the reduction of the flow that enters through the sea toward the lagoons.

- In low tide conditions, the gradient is greater; therefore, the flow of freshwater toward the sea increases, and it is reflected in the increase in the flow that leaves the system.

Twilley and Brinson [31] observed that rising sea level is the main force affecting coastal wetlands, basically because there is no possible migration inshore of them. Migration takes place when the reduction of freshwater flow upstream accelerates salinity intrusion inland but also if the landscape has the possibility to allow mangroves to colonize inland marsh habitats. However, this kind of mangrove migration is almost impractical because of urbanization, tourism, agriculture, and aquaculture development in the zone. Thus, there is a significant reduction of land for this kind of refuge area in many coastal zones, such as the MaNas case.

## 5. Conclusions

The main problem with the construction of the dam on the San Pedro-Mezquital river would be the effect of a controlled flow that reaches the wetlands of the alluvial plains, affecting the estuarine and coastal ecology. However, it was observed that the behavior of the flood is the same; thus, the PHLC project does not change the flood conditions of the plain.

Also, the fine material will not represent any continuity problem and will only travel downstream, with a somewhat different distribution in time than what currently occurs, but it will be able to reach the mangrove area without any problem. Opposite to the coarse material that will effectively be retained in the reservoir and, specifically, at the reservoir entrance 60 km from the curtain. However, the amounts of sediment that are calculated in the range from 1.0 to 0.1 mm are of the order of 100,000 $m^3$ per year on average and this is only a small part of all the sediment that will be stored at the reservoir entrance.

Finally, an ecological cost should be assessed considering the contributions of the base flow (underground) since this can substantially alter the ecosystem. Especially, during the dry season, when it would be a higher discharge for these ecosystems. However, the ecosystems from these regions have already evolved to adapt to the dry season, which is necessary for their survival. Thus, the most probable loss of these marshlands is associated mainly with human activities rather than the hydrological behavior of the system.

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## Acronyms and abbreviations

| | |
|---|---|
| CFE | Federal Electricity Commission |
| DR | irrigation districts |
| EH | hydrometric stations |
| EMWL | extraordinary maximum water level |
| ET | evapotranspiration |
| ICMyL | Institute of Marine Sciences and Limnology |
| LIDAR | light detection and ranging |
| MaNas | Marismas Nacionales |
| OMWL | ordinary maximum water level |
| PHLC | Las Cruces Hydroelectric Project |
| ppt | parts per thousand |
| PSU | practical salinity unit |
| SEC | bathymetry sections |
| U.S. EPA | U.S. Environmental Protection Agency |

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