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Water budget of a Ramsar site in Ecuador

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Abstract. Wetlands have been degrading and disappearing due to several anthropogenic impacts, such as pollution by discharge of domestic and industrial wastewater, agricultural runoff, land conversion, etc. The assessment and forecast of hydrological processes in wetlands, namely inflows and outflows, is essential for developing and implementing plans aimed at managing and protecting wetlands areas. We estimated the water budget of a Ramsar site, La Tembladera wetland, for a two-year period (2018–2019) by using the water balance method. The evapotranspiration was calculated using the Thornthwaite method and the runoff was estimated using the Curve Number method. The proposed water balance model showed that the major inflows to the wetland were the San Agustín and Bellavista canals, and Estero Pinto, about 92.9% (2018) and 90.5% (2019) of the total inflows. The runoff and wastewater flows represented the minor inflows. The runoff was 0.003% in 2018 and 0.004% in 2019, whereas the wastewater volume accounted for 0.05% of all inflows in both years. The actual evapotranspiration was the major outflow in both years, being 67.1% (2018) and 73.6% (2019) of the total outflows. On the other hand, the irrigation canal was the minor outflow, 32.9% in 2018 and 26.4% in 2019. Therefore, La Tembladera wetland hydrology is mostly linked to the canals system and climate conditions, precipitation and actual evapotranspiration. Our findings could be the basis for further research and developing plans in order to rationally manage and protect this wetland of international importance.

Keywords: water balance, wetland hydrology, wetland management, tropical wetland, La Tembladera

Authors' contributions: *P.J. Arias Ordonez* – conceptualization, methodology, investigation and writing – original draft preparation; *P.J. Arias Ordonez* and *C.V. Suasnavas Lagos* – formal analysis and writing – review and editing; *M.D. Kharlamova* – critical review; *W.R. Arias Ordonez* – data visualization.

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Водный баланс Рамсарского объекта в Эквадоре

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Аннотация. Водно-болотные угодья подвергаются деградации и исчезновению в результате антропогенного воздействия, такого как загрязнение бытовыми и промышленными сточными водами, загрязнение сельскохозяйственными стоками, преобразование земель и т. д. Оценка и прогноз гидрологических процессов водно-болотных угодий, а именно притоков и оттоков, необходимы для разработки и внедрения проектов, направленных на управление и охрану водно-болотных угодий. Был проведен расчет водного баланса водно-болотного угодья La Tembladera за двухлетный период (2018 и 2019 гг.) с использованием метода водного баланса. Эвапотранспирация была оценена по методу Thornthwaite, а ливневые стоки по методике «Число кривых стока». Предложенная модель водного баланса показала, что основные притоки в водно-болотное угодье приходятся на каналы San Agustín и Bellavista, а также на Estero Pinto, около 92,9 % (2018 г.) и 90,5 % (2019 г.) от общего объема притоков. Наименьшими притоками являлись ливневой сток и сточные воды. Ливневые стоки составили 0,003 % в 2018 г. и 0,004 % в 2019 г. Объем сточных вод составил 0,05 % от всех притоков в оба года. Выявлено, что фактическая эвапотранспирация является основным оттоком, составляя 67,1 % (2018 г.) и 73,6 % (2019 г.) от общего объема оттоков. Вместе с тем наименьший отток принадлежит каналу для орошения, он составил 32,9 % в 2018 г. и 26,4 % в 2019 г. Таким образом, гидрология водно-болотного угодья La Tembladera в основном связана с системой каналов и климатическими условиями, осадками и фактической эвапотранспирацией. Полученные результаты могут стать основой для дальнейших исследований и разработки проектов по рациональному природопользованию и охране данного объекта международного значения.

Ключевые слова: водный баланс, гидрология водно-болотных угодий, управление водно-болотными угодьями, тропическое водно-болотное угодье, La Tembladera

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Introduction

Wetlands play an important role in water quality enhancement, wildlife habitat, water retention during storms, shoreline protection, carbon storage, and providing cultural and recreational resources [1-4]. Unfortunately, wetland areas have been degrading and disappearing rapidly. They are often subjected to several anthropogenic impacts, such as direct discharge of domestic and industrial wastewater, agricultural runoff and sewage, land conversion, pollution, overgrazing, and future degradation is expected to continue [5-9].

Analyzing wetland water inflows and outflows components (i.e. water budget) is essential for understanding how wetlands respond to variations in flows and environmental conditions and how these changes influence the biota, nutrients concentration and distribution, organic matter, soil biochemistry, sediments and physicochemical parameters of the water [10–12]. This analysis allows to assess and forecast wetlands behavior in terms of quantity in order to develop and implement plans for managing and protecting wetlands [13] by the governments, decision-makers and ecologists.

Ecuador has 19 wetlands that belong to the Ramsar convention, they possess international status for protection and rational use of their resources [14]. La Tembladera wetland is one of these Ramsar sites since 2011 [15]. This unique ecosystem is located in the coast region of Ecuador and is mainly used for cattle grazing, short-cycle crops, pasture grasses and recreational activities [15; 16]. Besides, La Tembladera is the habitat for 43 plants species, 80 waterfowl birds, 14 fish species, 8 reptiles and 20 mammals. It harbors vulnerable and endangered species and 24 waterfowl endemic species [15]. However, this ecosystem is also facing pressure from anthropogenic activities, specifically, domestic wastewater discharge, agricultural runoff, discharge of urine and faeces produced by Brahman and Brownsuiz cattle, and water control structures (i.e. dams and canals) [16]. These factors influence the quality and quantity of the hydrologic variables as well as the ecological functioning of the wetland [17]. Despite the recognition of La Tembladera as a Ramsar site, studies aimed at the assessment of hydrologic variables are scarce. In general, hydrology research is a complex task due to the various processes involved [18; 19] and the lack of financial support for investigating and estimating all processes that control wetland hydrologic behavior. Low scientific productivity is a crucial issue that affects most of the developing countries in Latin America, including Ecuador because of the economy instability and other factors [20].

The empirical water balance method can be a feasible tool for assessing wetlands hydrologic balance because requires available input data, such as hydrometeorological data and parameters representing the soil and vegetation characteristics of aquatic ecosystems catchments. This method is simple and widely applied [6; 18; 21-23]. Thus, the present study proposes a water budget estimation during a two-year period in La Tembladera wetland by using the water balance method.

Materials and methods

Study site

La Tembladera wetland is a continental-type freshwater wetland located in the southwestern coast of Ecuador, canton Santa Rosa, province El Oro (3° 29' 26" S, 79° 59' 43" W; 12-18 m a.s.l) (Figure 1). The region has a tropical climate, which is characterized by a wet season (winter) and a dry season (summer). The average annual precipitation is 250-500 mm. The air temperature ranges between 24°C and 26°C [15].

The water body area occupies 1,471.19 ha, its permanent water area is 104 ha. The flooded area depends on the season, the water surface may reach 188 ha during the wet season, and the land surface 1,199 ha. The wetland monthly average water temperature is 25.82°C. During the wet season, the wetland annual average flow rate is 14.50 m^3/s, the monthly maximum is 61.0 m^3/s and the minimum 0.20 m^3/s. The flow rate is usually 0 m^3/s during the dry season [15].

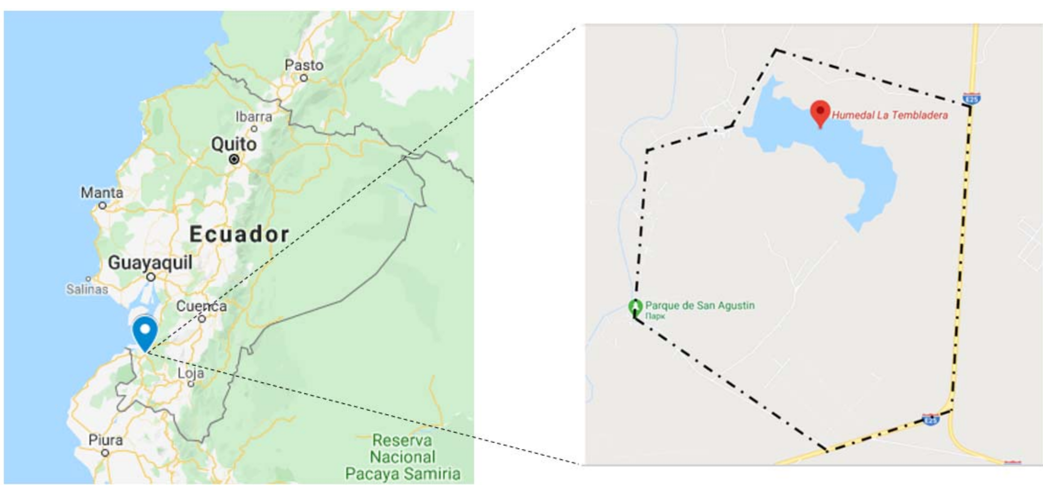

Figure 1. The location of La Tembladera wetland in Ecuador (*left*) and the wetland area boundaries (*right*)

La Tembladera wetland (Figure 2) belongs to the life zone Tropical Spiny Mountain (Monte Espinoso Tropical). For much of the year the wetland water table is near the land surface, hence the vegetation is adapted to moisture conditions, for instance, water lettuce (*Pistia stratiotes*), water hyacinth (*Eichhornia crassipes*), common cattail (*Typha latifolia*) and white lotus (*Nymphaea lotus*) [25].

Figure 2. North side of La Tembladera wetland in April 2019

Water budget

The water balance of wetlands depends on interactions among inflows and outflows, showing the changes in the surface-water volume for a given period time. Hence, the basic mass balance equation, is used to express the hydrologic processes in a wetland and it is often referred to as a water budget. The water balance was estimated for two years (2018 and 2019) using the general water mass balance equation [26]:

$$\Delta dV/\Delta t \;=\; P + Q_{in} + GW_i - ET - Q_o - GW_o$$

where $\Delta dV/\Delta t$ is the volume of water storage per unit of time; P the precipitation; Q_{in} the surface inflows from rivers, streams, marine sources, etc.; GW_i the groundwater inflows; ET the evapotranspiration; Q_o the surface outflows; and GW_o the groundwater outflows.

Concerning the surface inflows, La Tembladera wetland receives freshwater from the Santa Rosa and Arenillas rivers, which are connected with the wetland through a system of canals and gates: the Bellavista canal, San Agustín canal and the Estero Pinto [27]. Regarding the surface outflows, the wetland supplies water for agricultural purposes through several canals of irrigation, and the excess of water is drained through the Negrito and Huásimo canals [24]. The inflows data from the Bellavista canal, San Agustín canal, Estero Pinto, and the outflow data from one of the irrigation canals were taken from [24] and the average monthly values are presented in Table 1. The San Agustín and the irrigation canals have irregular flows due to the gates manipulation by the farmers [24]. The canals were considered as partially open. The outflows from the Negrito and Huásimo canals and all the irrigation canals were not included due to the lack of data.

Table 1. **Canals inflows and outflows**

Bellavista canal, m^3/month	San Agustín canal, m^3/month		Estero Pinto, m^3/month	Irrigation canal, m^3/month	
	Open	Partially open		Open	Partially open
9.6×10^6	61.57×10^6	3.6×10^6	1.06×10^5	34.27×10^6	3.1×10^6

Temperature and Precipitation (P)

Temperature and precipitation data from January 2018 to December 2019 were obtained from the National Institute for Meteorology and Hydrology of Ecuador (Instituto Nacional de Meteorología e Hidrología, INAMHI). These data were collected from La Cuca Meteorological station (6 km from La Tembladera wetland) and were used to estimate the potential evapotranspiration, actual evapotranspiration, runoff from rainfall and infiltration.

Estimation of potential evapotranspiration (PET)

The Thornthwaite method is a temperature-based method and was used for the PET calculation since depends on air temperature records that are, commonly, available data [28]:

1. To calculate Potential Evapotranspiration (*PET*), the Monthly Thornthwaite Heat Index (i) estimation is obtained using the following formula:

$$i = \left(\frac{t}{5}\right)^{1.514}$$

where t is mean monthly temperature.

2. Annual Heat Index (I) was calculated as the sum of the Monthly Heat Indices (i):

$$I = \sum_{i=1}^{12} i.$$

3. Potential Evapotranspiration (*PET*) estimation was obtained for each month applying the equation:

$$PET_{(non\ corrected)} = 16\left(\frac{10 \times t}{I}\right)^{\alpha}$$

where *PET non corrected* is the monthly potential evapotranspiration, considering a month is 30 days long and there are 12 theoretical sunshine hours per day, mm/month; t is the average monthly air temperature, °C; I the Annual Heat Index; α the cubic function of I and was calculated with the following equation:

$$\alpha = (675 \cdot 10^{-9} \cdot I^3) - (771 \cdot 10^{-7} \cdot I^2) + (1792 \cdot 10^{-5} \cdot I) + 0.49239.$$

The α value ranges from 0 to 4.25 and the Annual Heat Index I varies from 0 to 160.

4. Finally, the average monthly potential evapotranspiration was corrected using the formula:

$$PET_{(corrected)} = PET_{(non\ corrected)} \times \frac{N}{12} \times \frac{d}{30}$$

where N is the theoretical sunshine hours for each month and d the number of days for each month.

Estimation of actual evapotranspiration (AET)

The Thornthwaite method [29] was used to determine the AET. Monthly temperature, monthly precipitation and water holding capacity of the soil were required. Since La Tembladera wetland is characterized by sandy clay loam soils [30], then the water holding capacity of 160 mm was considered [24]. Furthermore, the following parameters were calculated:

- Soil water storage (R), whose calculation begins with the first humid month and the previous month receives null reserve (0). The soil storage for the next months was estimated using the equation [31]:

$$R_i = R_{i-1} + (P - PET)$$

where R_i is the soil storage of the current month and R_{i-1} is the soil storage of the previous month. If the result is more than 160 mm, then R_i = 160 mm and the rest is transferred to the water surplus. If R_i varies between 0 and 160 mm, it takes that result; and if the result is less than 0, R_i = 0 and the result goes to water deficit.

- Change in soil water storage (ΔR) for each month was calculated according to:

$$\Delta R = R_i - R_{i-1}.$$

Finally, the *AET* was established for each month considering the following: The estimation began with the first month of the hydrological year, i.e. the first month in which $P > ETP$. This is after the period in which $ETP > P$. When $P > ETP$, then $AET = ETP$, indicating that there is no water deficiency and if $P < ETP$, then $AET = P + \Delta R$, demonstrating thus water deficiency.

Runoff from rainfall

The Curve Number method (CN), developed by the Soil Conservation Service (*SCS*), U.S. Department of Agriculture, was used to estimate the volume of runoff [32]. This method is commonly applied [19; 33–35] because it's easy to understand and considers all the important factors, which influence runoff volume: soil type, land use, hydrologic condition, and antecedent moisture condition [36].

The *SCS* runoff equation is:

$$Q = \frac{(P + Ia)^2}{(P - Ia) + S} \qquad (1)$$

where Q is the runoff (mm), P is the rainfall (mm), S the potential maximum retention after runoff begins (mm) and Ia the initial abstraction (mm). Ia is determined by the following formula:

$$Ia = 0{,}2 \times S. \quad (2)$$

By removing Ia as an independent parameter, this approximation allows use of a combination of S and P to produce a unique runoff amount. Substituting equation 2 into equation 1 gives:

$$Q = \frac{(0{,}2 + S)^2}{P + 0{,}8S}.$$

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10.$$

The hydrologic soil group and land cover type of the study area were determined in order to calculate the CN. According to [30; 37] La Tembladera wetland soils belong to the group C, sandy clay loam, and the mainly land cover types in the area are pasture, grassland, row crops, woods and urban area. The appropriate CN value was estimated using the corresponding tables [32] and weighted CN value of the whole catchment was computed manually using the equation:

$$CN_w = \sum CN_i \times A_i / A$$

where CN_w is the weighted curve number; CN_i the curve number from 1 to any number N; A_i the area with curve number CN_i; and A the total area of the watershed (km^2).

Infiltration

The infiltration was determined considering precipitation (P), actual evapotranspiration (AET) and runoff (R) [22]:

$$Q_{IN} = P - (AET + R).$$

Domestic wastewater flow

The average domestic wastewater flow was calculated using the equation [38]:

$$Qdw = \frac{Pop \times L \times R}{1}$$

where Pop is the population, L is the per capita water consumption (L/inhab*day) and R the sewage flow/water flow return coefficient. Typical return coefficient values range between 60 and 100%, a value of 80% (R = 0.8) is usually adopted. The water consumption data was provided by The National Water Secretariat of Ecuador (Secretaría Nacional del Agua, SENAGUA) [39].

Microsoft Excel for Windows 10 was used for statistical data processing and graphing.

Results and discussion

Meteorological conditions

The average annual air temperature during the two-year period was 24.7 and 25.2 °C, respectively (Figure 3). The total precipitation was 430.5 mm and 587.7 mm, respectively. The second year was warmer and wetter than the previous year. Most of the precipitation fell during the wet season (222.6 mm in 2018 and 549.8 mm in 2019) and the summer was the driest period (207.9 mm in 2018 and 37.9 mm in 2019) (Figure 3). The distribution of precipitation displays the dry–wet annual cycle typical of the region, showing abrupt low precipitation at the end of the wet season during 2018 and high precipitation at the beginning of the dry season (Figure 3, *a*).

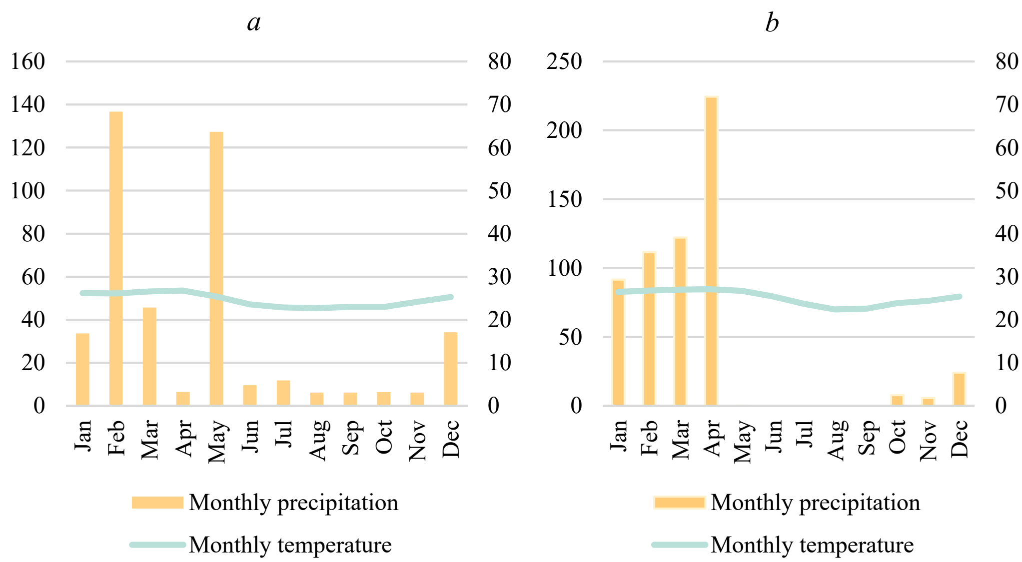

Figure 3. Precipitation (mm/month) and temperature (°C) at La Tembladera wetland region during the two-year period: 2018 (*a*) – 2019 (*b*)

Potential and actual evapotranspiration

The total *PET* estimated was of 1339.3 mm and 1417.5 mm in 2018 and 2019, respectively. During 2018, the highest and lowest *PET* occurred in March (143.3 mm) and August (87.2 mm), respectively (Figure 4, *a*). During 2019 (Figure 4, *b*), the highest and lowest *PET* occurred in March (149.9 mm) and September (80.6 mm).

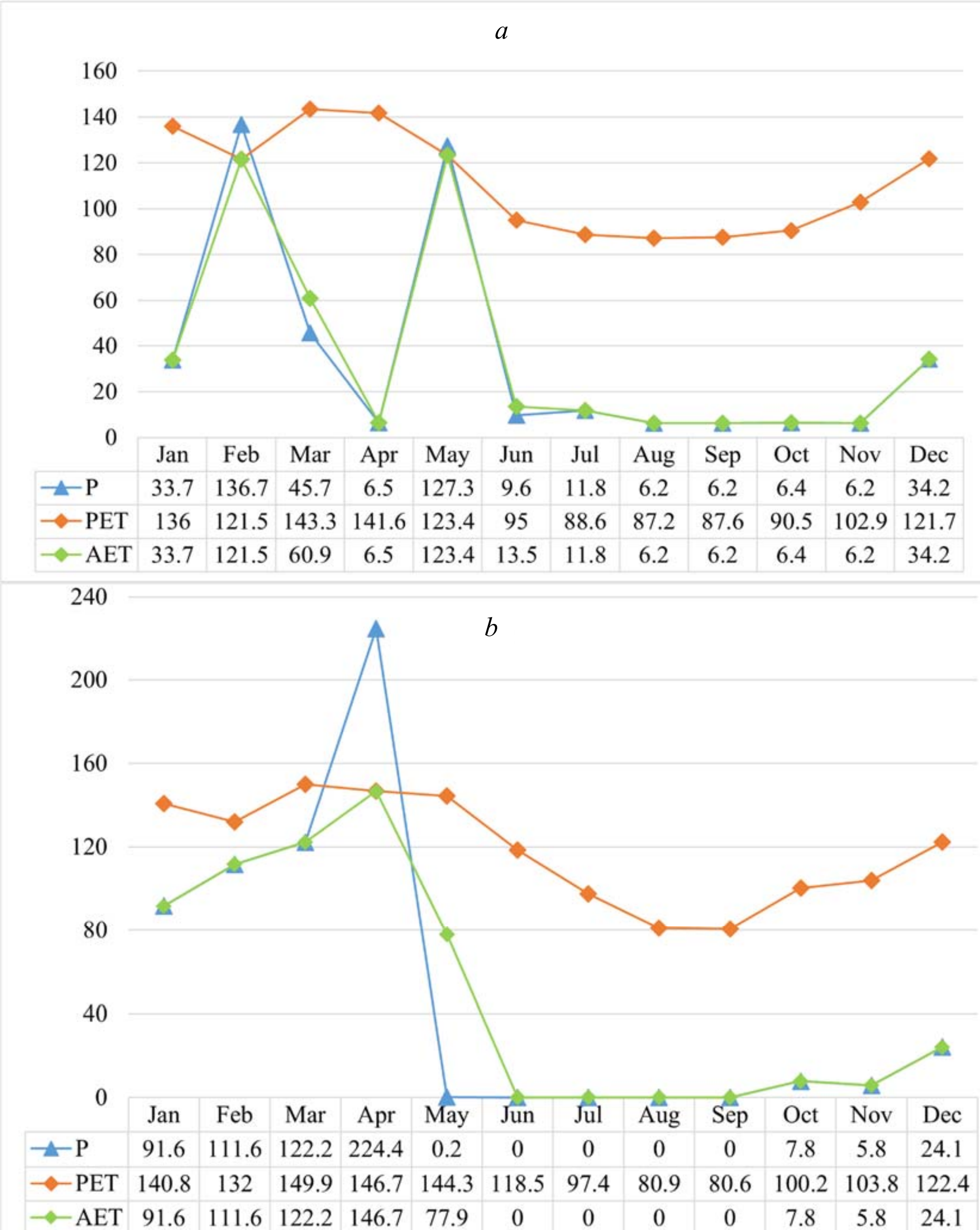

Figure 4. Monthly precipitation *P* (mm), potential evapotranspiration *PET* and actual evapotranspiration *AET* (mm) at La Tembladera wetland during the study period: 2018 (*a*) – 2019 (*b*)

The calculated *AET* was 430.5 mm and 587.7 mm for each year or 100% of measured precipitation in both years. That is, the actual evapotranspiration equals precipitation, evidencing dry conditions. This is in line with the bioclimate map of the Ministry of Environment, Water and Ecological Transition of Ecuador [40] that determined the bioclimate of La Tembladera wetland region as xeric. Since the actual evapotranspiration is based on the precipitation rate, the low precipitation values during the dry season thus influenced the obtained results. In 2018, the months of the lowest *AET* were August, September, October and November (less than 6.4 mm for each month), whereas the month of the highest *AET* was May with 123.4 mm (Figure 4, *a*). During 2019, June, July, August and September are characterized by an *AET* of 0 mm, while the month of the highest *AET* was April with 146.7 mm (Figure 4, *b*). However, for better understanding the moisture factor or whether a climate is moist or dry, it should be analyzed whether precipitation is greater or less than the evapotranspiration [28]. The Figure 4 reveals that most of the months during the two years of study are under conditions $PET > AET$, showing water deficit or demand regardless of the season, specially in 2019. During this year the water deficit was found to be major during the dry season compared to the wet season. The area of the graphic (Figure 4), where the precipitation is above the *PET*, demonstrates storage in reserve plus excess and this is observed only during February and April in 2018 and 2019, respectively. The area under the conditions $AET > P$ (i.e. soil moisture utilization) is not significant and it is observed only in the beginning of the dry season in 2019. Based on the AET analysis it can be suggested that the region is subjected to water deficit. These results are essential when developing sustainable water management practices since La Tembladera wetland is an important ecosystem for crop production, pasture grasses and the habitat of unique flora and fauna.

Wastewater

According to SENAGUA, one inhabitant consumed in average 259.05 liters of water per day in 2018 and 252.58 liters of water per day in 2019. Along the western zone of the wetland are situated four coastal communes (San José, La Florida, Las Crucitas, San Agustín) with an approximately population of 635 people [36] and considering a return coefficient of 80%, the volume of domestic discharge into the wetland was about 131.6 m^3 per day (48,033 m^3 per year) in 2018 and 128.3 m^3 per day (46,833 m^3 per year) in 2019.

Water balance model

The conceptual water balance model of La Tembladera is shown in Figure 5. During the wet season the inflows were precipitation (*P*), San Agustin canal (Q_{SA}), Bellavista canal (Q_B), Estero Pinto (Q_{EP}) and runoff from rainfall (Q_R). We have also considered the wastewater flow (Q_{WW}) from the coastal communes along the wetland as an inflow into La Tembladera. The lack of a sewerage system among these communes leads population to discharge the wastewater into the wetland [16]. The outflows were evapotranspiration (*AET*), the canal for irrigation (Q_{IR}) and infiltration (Q_{IN}). During the dry season the water balance model is almost the same except for the Bellavista canal that is closed during this season. The proposed water budget for La Tembladera wetland for the two-year study is presented in Table 2.

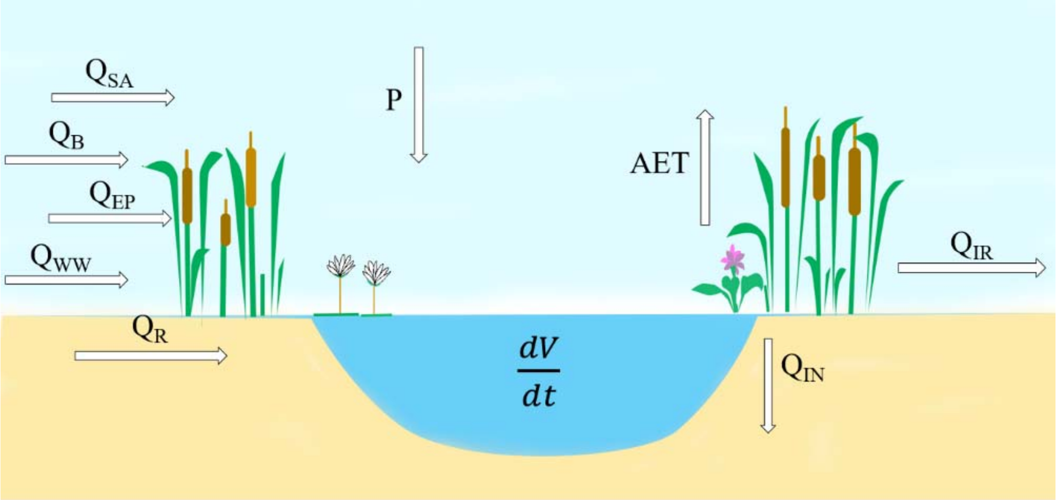

Figure 5. Conceptual water balance model of La Tembladera wetland, Ecuador

Table 2. Water budget (in m^3) of La Tembladera wetland

Year	*P*	Q_R	$Q_{(SA+B+EP)}$	Q_{WW}	*AET*	Q_{IR}	Q_{IN}
2018	6.33×10^6	2.2×10^3	83.15×10^6	48×10^3	6.33×10^6	3.1×10^6	-2.2×10^3
2019	8.64×10^6	4×10^3	83.15×10^6	46.8×10^3	8.64×10^6	3.1×10^6	-4×10^3

The estimated runoff was 2,244.51 m^3 (224.45 mm) representing 0.04% of the precipitation in 2018 and 4,003.77 m^3 (400.37 mm) or 0.05% of the precipitation in 2019.

The water budget revealed that the change in storage was 80.1×10^6 m^3 per year. The San Agustín and Bellavista canals, and the Estero Pinto were the major inflows to La Tembladera wetland, representing 92.9% and 90.5% of the total inflows in 2018 and 2019, respectively. The precipitation was in second place with 7% (2018) and 9.4% (2019) of the total inflows. The runoff and wastewater were the minor inflows. The runoff was 0.003% in 2018 and 0.004% in 2019. The wastewater volume was 0.05% of the total inflows in both years. These findings highlighted that the flows from the Arenillas and Santa Rosa rivers, and the Estero Pinto, influence the most the change in water levels, nutrients concentration and distribution as well as organic matter, pollutants and biota distribution, which in turn affect the trophic status of La Tembladera wetland.

The AET represented the major wetland outflows, 67.1% in 2018 and 73.6% in 2019. The canal for irrigation constituted 32.8% (2018) and 26.4% (2019) of the total outflows. The infiltration in 2018 was -2.2×10^3 m^3 and in 2019 was -4×10^3 m^3. This may mean that the ground of this area exudes water, or the opposite of infiltration occurs, therefore, it can be assumed that the infiltration in the wetland area is minor or zero. It is important to mention that the expression used for estimating infiltration considers precipitation, runoff and AET. Nevertheless, factors such as soil characteristics, chemical properties of the water and soil, and hydraulic conductivity of soil are omitted; consequently, this may have led to obtain less accurate infiltration values.

These results prove that the water budget of La Tembladera wetland is primarily driven by the canals systems, while the meteorological components (precipitation and evapotranspiration) play an important, but minor role.

Conclusion

This paper proposes a water budget model for La Tembladera wetland under tropical dry climatic conditions. Our findings of two-year study demonstrate that the empirical water balance method is a useful, simple and economic tool for assessing hydrological dynamics. The main outcomes can be summarized:

- The major inflows to the water budget of La Tembladera were the San Agustín and Bellavista canals, and Estero Pinto, about 92.9% (2018) and 90.5% (2019) of the total inflows. The runoff and wastewater flows represented the minor inflows. The runoff was 0.003% in 2018 and 0.004% in 2019, whereas the wastewater volume was 0.05% of the total inflows in both years.
- The AET was the major outflow in both years, being 67.1% (2018) and 73.6% (2019) of the total outflows. On the other hand, the irrigation canal was the minor outflow of the water budget, 32.9% (2018) and 26.4% (2019).
- The negative results of infiltration suggest that this component did not play an essential role in the water budget of La Tembladera.

Thus, it can be concluded that La Tembladera wetland hydrology is mostly linked to the canals system operations and climate conditions, namely precipitation and actual evapotranspiration. This study was limited by the lack of some data. Further hydrological long-term studies and data collection are therefore needed to assess and forecast more precisive water budget of La Tembladera wetland. Despite this, our work could be the basis for developing plans. This is a decisive issue because this Ramsar site is not only the habitat for many species of flora and fauna or a natural water filter, but also a key ecosystem for agricultural purposes since agriculture is the principal economic activity for the local population in the Ecuadorian coast region.

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