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Spatial and Temporal Variations' of Habitat Suitability for Fish: A Case Study in Abras de Mantequilla Wetland, Ecuador

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1. Introduction

1.1 Wetlands and Tropical Floodplains

Wetlands are among the most productive environments in the world. They are crucial for the maintenance of biological biodiversity, providing water and primary production upon which numerous species of fauna and flora depend for survival (Halls, 1997; Ramsar, 2013). Tropical rivers associated with floodplain areas provide dynamic habitats for fish (Winemiller and Jepsen, 1998), and contribute to maintaining the biodiversity of the whole river ecosystem, provided that connectivity is maintained. Connectivity is a key issue in floodplains, since richness and diversity of species decrease with decreasing hydrological connectivity (Aarts et al., 2004). Tropical floodplains faced gradual drying due to anthropogenic activities such as dams and irrigation, causing impacts on fish communities. A reduction in the inundated areas of floodplains decreases the habitat availability for fish communities. Reduction in habitat areas in turn produces an increase in fish densities (per unit surface area), intensification in species interaction, and competition for resources (Winemiller and Jepsen, 1998). In South America, designation of aquatic protected areas has now started, and fish studies have been focused more frequently on local rather than on river basin scales (Barletta et al., 2010).

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1.2 Habitat Analysis and History

A series of Habitat Suitability Index (HSI) models was developed in the early 1980s to provide habitat information of several wildlife species in the United States (Schamberger et al., 1982), although initial habitat studies were started in the 1950s to determine suitable areas for salmon spawning (Jowett, 1997). Habitat suitability models are expressed with a numerical index on a 0.0–1.0 scale, with the assumption that there is a positive relationship between the index and the habitat carrying capacity of the selected species (Schamberger et al., 1982). Habitat suitability criteria can be expressed in different categories and formats (Bovee, 1982). A first category is based on expert opinions (professional, stakeholders) instead of data. A second category is based on data where organisms of the target species were collected. Thus they are known as "utilization or habitat use functions" because they represent the conditions that the target species faced at the time of observation or sampling. However, these criteria can be biased by the environmental conditions available at the observation time, since organisms could be forced to use suboptimal conditions when optimal conditions are not available. To correct this function bias and be less site specific, a third category "preference functions" can be created (Bovee, 1986; Bovee et al., 1998).

Habitat methods can be considered an expansion of hydraulic methods, where the evaluation of flow requirements is based on hydraulic conditions that aim to meet biological requirements. Hydraulic model outputs such as water depth and velocity are subsequently evaluated with habitat suitability criteria for a specific species or group of species. In use since 1970s, PHABSIM, a physical habitat model, is a component of the Instream Flow Incremental Methodology, a decision-support system designed to help managers in the evaluation of different water management alternatives (Bovee et al., 1998). This model was developed by the US Fish and Wildlife Service to analyze the relationships between flow and physical habitat (Milhous and Waddle, 2012; Spence and Hickley, 2000). The development of fish habitat models (CASIMIR) started in the early 1990s at the University of Stuttgart to investigate the impacts related to hydropower operations (Kerle et al., 2002; Schneider et al., 2010). Habitat models such as PHABSIM and CASIMIR use expert knowledge or statistical analysis of field data to describe biotic/abiotic relationships (Tuhtan and Wieprecht, 2012). Habitat suitability is then evaluated by the development and further application of membership functions, also called "preference functions". Habitat suitability models have been widely applied to fish in temperate areas (Brown et al., 2000; Costa et al., 2012; Kerle et al., 2002; Mouton et al., 2011; Muñoz-Mas et al., 2012; Schneider et al., 2010, 2012; Tuhtan and Wieprecht, 2012; Zorn et al., 2012).

In the Netherlands, a framework for habitat modeling based on an ecosystem approach started in the 1990s (Duel et al., 2003). This approach includes four steps: first, the spatial distribution of ecotopes is simulated. For this step hydro- and morphodynamics (stream velocity, depth, flood frequency), drivers that define the river ecotopes, are evaluated. Steps two and three assess the availability and suitability of these habitats for selected species. For habitat suitability, requirements (shelter, food, nutrients) and threats (pollutants, toxic chemicals, etc.) for target species are considered. These habitat requirements are usually derived from field observations, historical data, and statistical analysis of the environmental factors that belong to the habitats where the target species live. From this analysis, habitat suitability is determined by the environmental factors that limit its carrying capacity. A fourth step evaluates the connectivity of suitable habitats into ecological networks (Duel et al., 2003). HABITAT, a spatial tool for ecological assessment, has been applied in the Netherlands as a decision support system for implementation of the Birds, Habitats, and Water Framework Directive (Haasnoot, 2009a). Membership functions for several temperate fish species are available in the HABITAT toolbox (DELTARES, 2016), and fish studies related to spawning habitat availability have been developed (Wolfshaar et al., 2010). Nevertheless, in tropical systems, a few studies that identify habitat preferences and develop habitat suitability criteria for fish are available (Costa et al., 2013; Teresa and Casatti, 2013). These studies developed habitat suitability criteria in the form of "preference curves" for several fish species based on hydraulic features (depth, velocity) and substrate.

1.3 Habitat and Hydrology

The development of habitat suitability analysis has to be related to the fact that species are distributed according to their preferences for feeding and reproduction (Teresa and Casatti, 2013). Linking target species with their physical, chemical, and biotic conditions is the base of habitat assessment. Physical aspects include hydrology and geomorphology, and hydrological indicators can explain physical, chemical, and biological processes in wetlands (Funk et al., 2013). Thus hydrologic conditions are key drivers for the wetland's structure and function. Hydrology influences several abiotic factors that determine which biota will develop in the wetland. "Hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes" (Mitsch and Gosselink, 2007). Specific mesohabitat characteristics such as depth and velocity have been found to play a key role in explaining fish community structures (Arrington and Winemiller, 2006), with several studies considered as the main variables for fish habitat analysis (Freeman et al., 2001; Schneider et al., 2012; Teresa and Casatti, 2013; Wolfshaar et al., 2010).

1.4 Fish and Relations With Shallow Areas and Macrophytes

Several studies acknowledged the importance of littoral areas as habitats for fish communities (Arrington and Winemiller, 2006; Teixeira-de Mello et al., 2009), and the association of fish to macrophytes (Agostinho et al., 2007; Meerhoff et al., 2007a; Meschiatti et al., 2000). Shallow areas of Abras de Mantequilla wetland (Ecuador) are principally populated by small-sized fish from the Characidae family (Alvarez-Mieles et al., 2013). Characids are an important source of food for higher trophic levels (top fish predators that have a value for local communities) and important seed dispersers in neotropical floodplains. Previous studies in the wetland and associated basin, "Guayas River basin" reported the presence of this family (Florencio, 1993; INP, 2012; Laaz et al., 2009; Prado, 2009; Prado et al., 2012). Some species of this family are common in all the western basins of Ecuador (Gery, 1977; Glodek, 1978; Laaz et al., 2009; Loh et al., 2014), but others are endemic in the "Guayas basin" (Laaz and Torres, 2014; Roberts, 1973). However, information on the ecology or evolutionary history of most fish species in the region is very limited and even lacking (Aguirre et al., 2013). Littoral fish assemblages in Abras de Mantequilla wetland included both common and endemic species. At middle and low wetland areas endemic species such as *Phenacobrycon henni*, *Landonia latidens*, *Iotabrycon praecox*, and *Hyphessobrycon ecuadoriensis* have been collected, thus the importance of assessing the habitat conditions in this tropical wetland. Furthermore, the wetland provides a habitat for fish of commercial interest for local communities: *Aequidens rivulatus*, *Cichlasoma festae*, *Curimatorbis boulengeri*, *Brycon dentex*, and *Ichthyoelephas humeralis*. These species have been collected in the main channels of this wetland, and freely move in the pelagic areas, but they also utilize littoral vegetated areas to protect their eggs after spawning (Barnhill and Lopez, 1974; Florencio, 1993; Quevedo, 2008; Revelo, 2010).

1.5 Our Scope

In this chapter, the following key research questions are investigated:

- Are hydrological conditions an important factor shaping habitat analysis?
- Is there an optimal time period during the year that provides a higher extension of suitable areas?
- Are there specific regions in the wetland more suitable than others?

This study proposes a methodology to quantify the extension of suitable habitat areas for the fish communities of Abras de Mantequilla wetland based on hydrodynamic features. A measure related to the percentage of suitable habitat areas (PSA) is proposed as a tool to explore the temporal and spatial variability of the habitat through the year for different hydrological conditions. We suggest that by protecting the habitat of the fish communities, lower trophic community levels (e.g., macroinvertebrates and plankton) that also inhabit the wetland areas would be also protected.

2. Methodology

2.1 Study Area

The Abras de Mantequilla wetland is located at the center of the Guayas River basin in the coastal region of Ecuador (Fig. 6.1). The wetland was declared a RAMSAR site in 2000 due to the important role in conservation of bird fauna biodiversity, and especially because it supports three migratory species of birds (Ramsar, 2014). It is also an

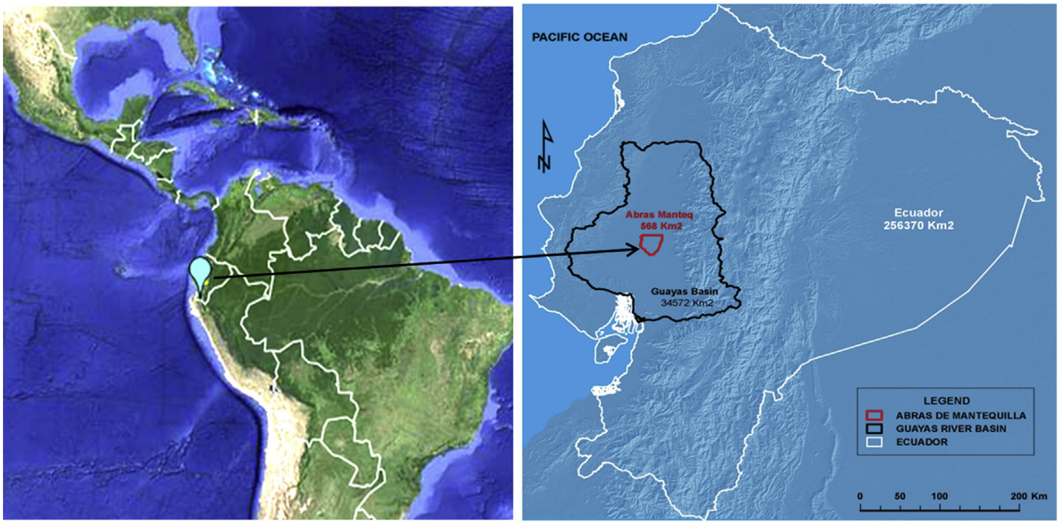


FIGURE 6.1 Study area: Abras de Mantequilla wetland location.

Important Bird and Biodiversity Area (IBA) with 127 bird species reported. The wetland was selected as the South America case study for the WETwin Project, a project funded by the European Commission (FP7) to enhance the role of the wetlands in integrated water resource management. The project included seven study areas in three continents: Europe, Africa, and South America. The main characteristic of these areas is that all of them are inland wetlands related to a river basin. The wetland, part of the Chojampe subbasin consists of branching water courses surrounded by elevations of 5−10 m (Quevedo, 2008). Due to land conversion to agriculture in the last few decades, original forest coverage around the wetland is less than 3%. Agriculture in the surrounding wetland area mainly consists of short-term crops (rice, maize). Current land uses around the wetland and hydropower projects in the upper catchment area are expected to be the main constraints for the future health of the wetland. Littoral areas of the wetland are covered by banks of macrophytes populated by small fish (Characidae family) (Fig. 6.2D). Collected species from this family include common ones such as *Astyanax festae*, and endemic species such as *L. latidens* and *H. ecuadoriensis* (Fig. 6.3). The wetland also provides a habitat for several fish species of commercial interest for local communities (Barnhill and Lopez, 1974; Florencio, 1993; Quevedo, 2008; Revelo, 2010).

Due to the proximity to Equator, there are only two climatic periods: the wet season (mid-December up to mid-May) and the dry season (July−November) (Fig. 6.4). Annual variability in precipitation is depicted in Fig. 6.5. The highest annual precipitation in Pichilingue station was observed in the 1997 and 1998 ‘El Niño event’ with yearly values of 4736 and 4790 mm. The lowest annual precipitation was observed in 1968,

FIGURE 6.2 Study area: sampling sites located in the upper (A) and middle (B) wetland areas. Fish sampling (C and D).

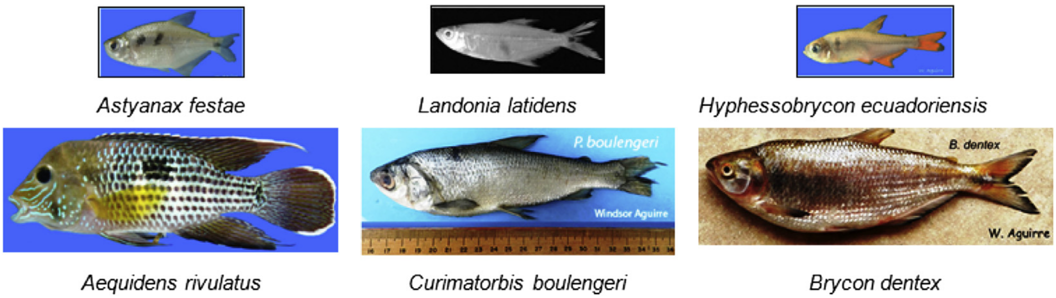


FIGURE 6.3 Some species of small littoral fish species of the Characidae family collected in Abras de Mantequilla wetland (*upper panel*). Species of commercial interest for local communities reported in the wetland (*low panel*). *Photos source Aguirre, W., 2014. The Freshwater Fishes of Western Ecuador. In: http://condor.depaul.edu/waguirre/fishwestec/intro.html.*

1975, and 2005, with values between 1066 and 1222 mm. The figure also highlights the years of the monitoring campaigns of the present study to relate them to historical rainfall variability.

The main inflow to the wetland is the Nuevo River that flows through the Estero Boquerón and contributes to 85% of total wetland inflow. During a strong rainy year like El Niño, inflow discharges from the Nuevo River to the wetland can reach maximum values up to 650 m^3/s, while during a dry year, maximum discharges are up to 260 m^3/s. The wetland also receives rainfall runoff from the Chojampe subbasin with a

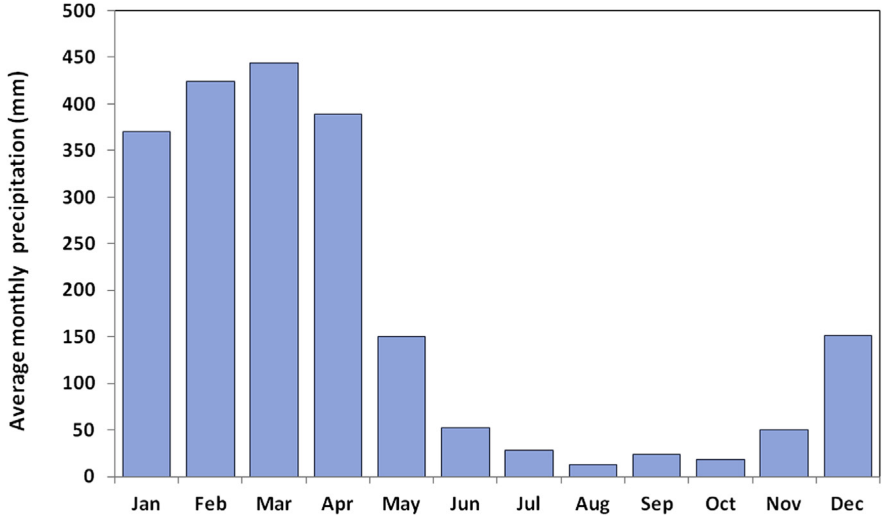


FIGURE 6.4 Average monthly precipitation in Quevedo-Vinces basin. Pichilingue station (1963–2012).

contribution of around 15% (Fig. 6.6). These contributions slightly fluctuate according to the type of year (dry or wet). During the dry season, the water level in the wetland decreases considerably, and water remains only in the deep central channels, reducing the inundated area to around 10% compared with the wet season.

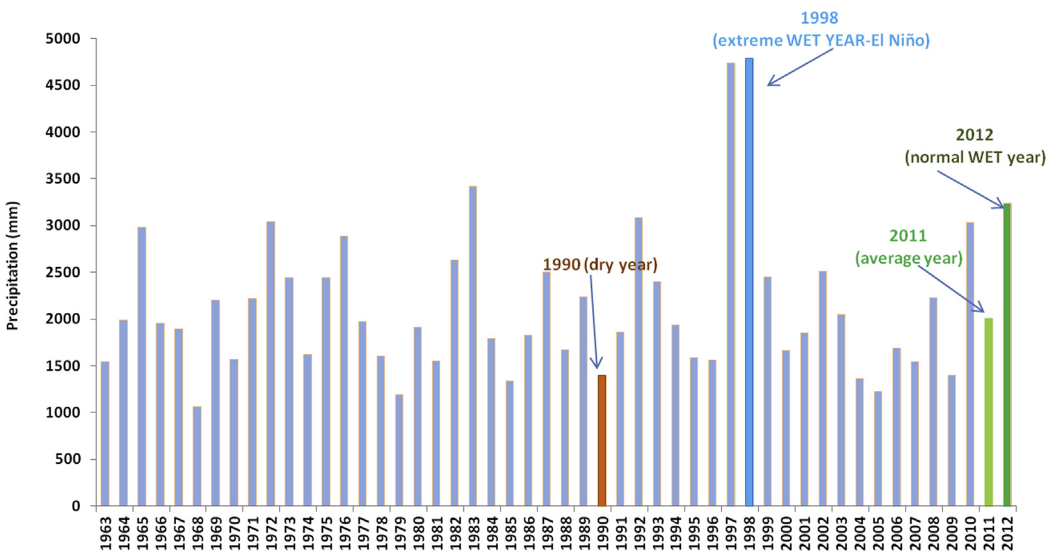


FIGURE 6.5 Annual precipitation in Quevedo-Vinces basin. Pichilingue station (1963–2012).

2.2 Modeling the Hydrodynamics of the Wetland

The 2D model of the wetland was built in Delft3D-FLOW software, based on a 1:10,000 topography. The model was built considering the wetland extension and the location of the discharges. According to this topography, the wetland area recorded levels between 6 and 34 masl. The boundary conditions for Nuevo River (inflow to the wetland) were estimated based on an HEC-RAS model (Arias-Hidalgo, 2012) and correlations with an upstream gauging station (Quevedo en Quevedo station), while the boundary conditions for Nuevo River (outflow of the wetland) were estimated based on the total discharge flowing outside the wetland system and a rating curve. The boundary conditions for the four tributaries of Chojampe subbasin were determined using HEC-HMS, a rainfall runoff model built for this purpose. The grid was set up with a cell size of 75 × 75 m, with a total of 7163 cells (Galecio, 2013). The total modeled wetland area was 4029 ha (40.3 km^2) (Fig. 6.6).

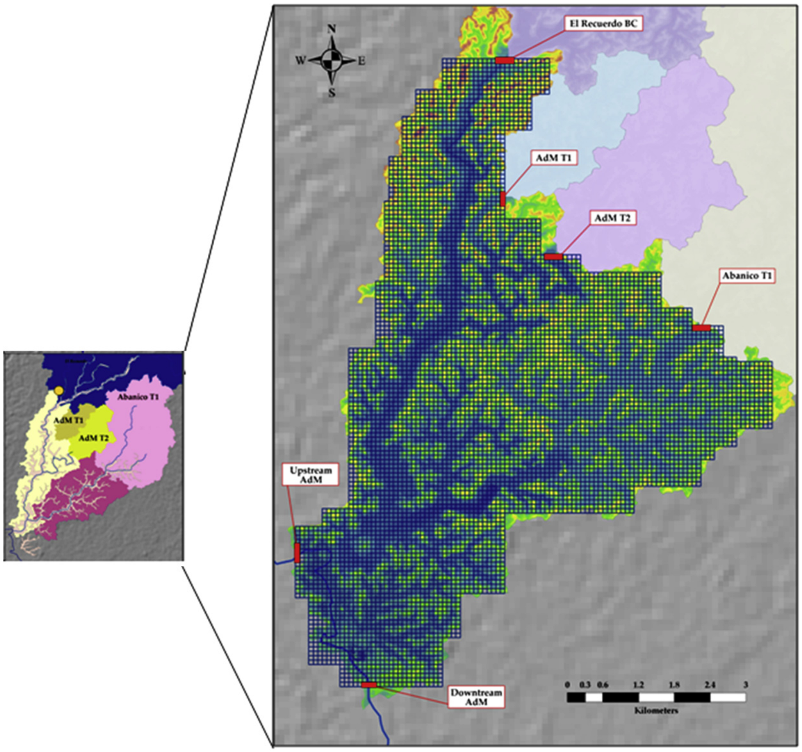


FIGURE 6.6 Abras de Mantequilla wetland (AdM)—main inflows and hydrodynamic model schematization. *Left*: "El Recuerdo" (*yellow dot*) collects the runoff of the five contributing microbasins from the Upper Chojampe subbasin. Abras de Mantequilla wetland area (*light yellow*). *Right*: Hydrodynamic model schematization—Abras de Mantequilla wetland grid (from Delft3D-FLOW). Boundary conditions (*red lines*). Low boundary condition (upstream AdM) represents the main inflow to the wetland "The Nuevo River-Estero Boquerón." Upper boundary conditions (El Recuerdo, AdMT1, AdMT2, and Abanico T1) collect the runoff from the Chojampe subbasin. *Source: Galecio, E., 2013. Hydrodynamic and Ecohydrological modeling in a tropical wetland: The Abras de Mantequilla wetland (Ecuador). UNESCO-IHE.*

Results from the hydrodynamic model show that the wetland is flooded up to 27 km^2 (Fig. 6.7). The natural variability of the wetland inundation area is depicted in Figs. 6.8 and 6.9. Monthly averages of inundated areas determine that historically the wetland experiences flooding from 5 to 23 km^2. A high variability between the different simulations is evident during the wet season. On the other hand, during the dry season, the inundation areas do not differ among the simulations, reaching all a value of 5 km^2 (Fig. 6.9). Nevertheless, the exception is the maximum historical condition since this time series includes the complete set of extreme wet conditions for a long historical period (1962–2010). As an example to illustrate both spatial and temporal variation in inundation patterns, water depth maps from 2012 are presented in Fig. 6.10.

2.3 The Habitat Suitability Index

The aim to develop a habitat index (HI) is to indicate how suitable an area is for a determined species or group of species. Nevertheless, it has a number of assumptions, for example, it is not clear if an index will certainly indicate the presence or absence of either these species or the quantity of the species. On the other hand, to be able to determine a species habitat it is important to know in which period a species distributes and if this period is logical. Thus by exploring the space–time variability of an index the presence of these species could be estimated. The hydrological behavior of the wetland explained in the previous section provides the base for our habitat suitability approach, given that the hydrology shapes our habitat. The following section of the methodology describes the multiple tests performed to determine the level of relationship between water depth, velocity, and habitat for the fish community in this tropical wetland:

1. Calculation of the habitat index (HI) was based on a general rule based on literature of the natural behavior of fish in the study area. Some key aspects explored include seasonal behavior, spawning, food availability, and inundation area fluctuations. Field information and expert knowledge were used to validate this information. In situ measurements of water depth and velocity were compared with literature values to understand the distribution and habitat preferences of the overall fish community. As a result, response curves (knowledge rules) for these two variables were derived (Fig. 6.11).
2. A dynamic HABITAT modeling tool was built with the MATLAB toolbox (Fig. 6.12).
3. Habitat suitability was evaluated by relating in situ measurements of water depth and flow velocity from sampling years 2011 and 2012 with the results of the 2D hydrodynamic model (Delft3D-FLOW). Furthermore, extreme conditions (dry and wet years) and minimum and maximum historical conditions were also modeled to account for natural variability.
4. Output maps of water depth and velocity from the 2D hydrodynamic model (Delft3D-FLOW) were used as an input for the dynamic HABITAT model.

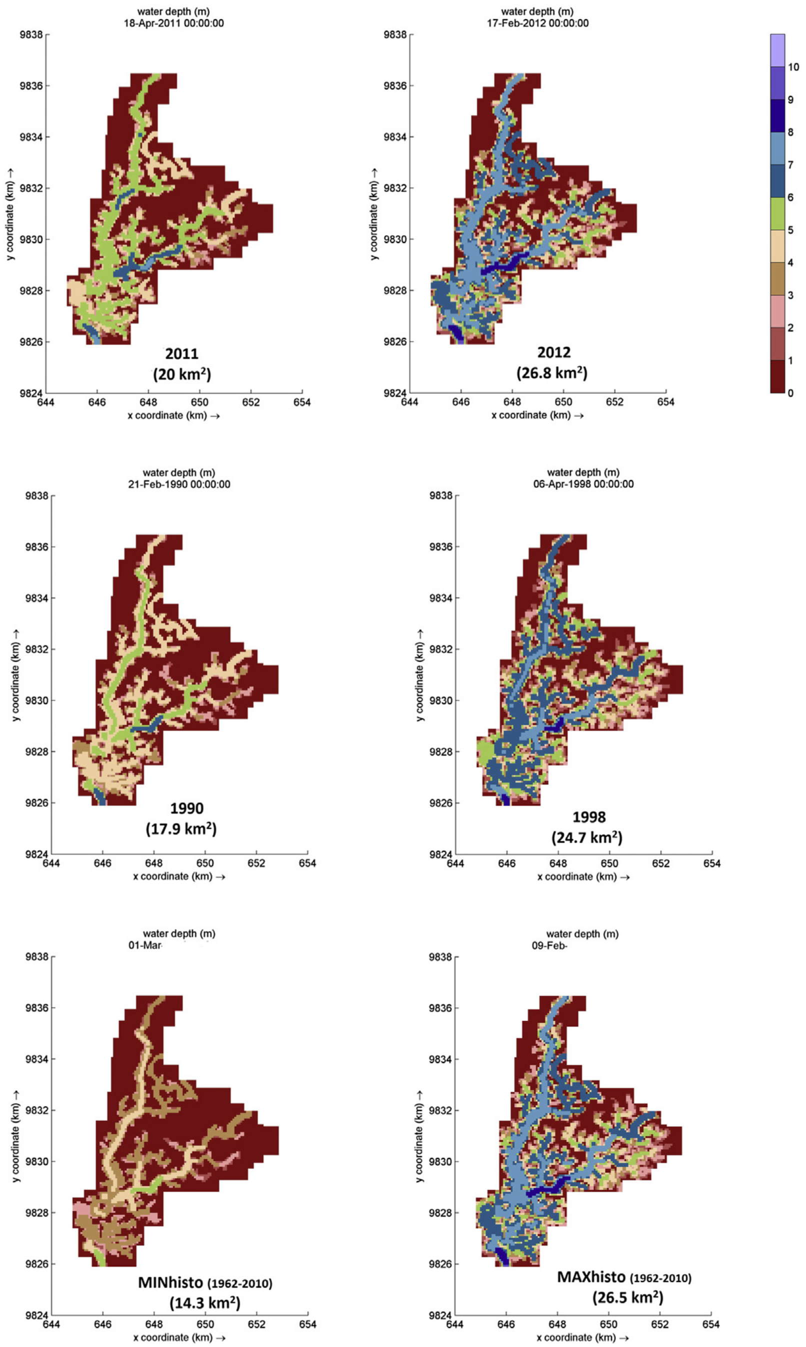


FIGURE 6.7 Maximum wetland inundated areas (km^2) from Delft3D-FLOW simulations for: 2011 and 2012 (sampling years); 1990 (dry year); 1998 (wet year); and minimum and maximum historical conditions (period 1962–2010). Scale bar indicates the water depth range (m).

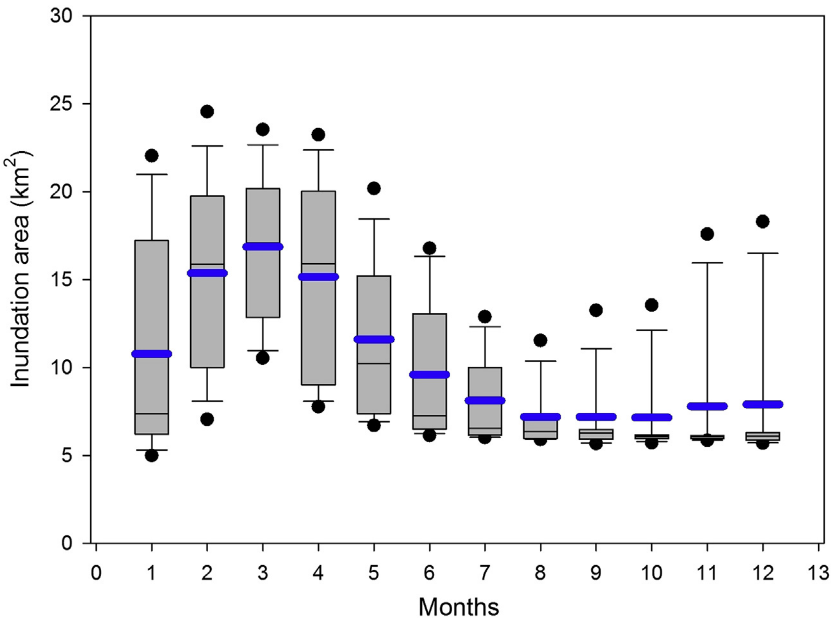


FIGURE 6.8 Boxplot for the wetland inundation area (km^2) calculated from Delft3D-FLOW simulations results: 1990 (dry year); 1998 (wet year); 2011 and 2012 (sampling years); and minimum and maximum historical conditions (period 1962–2010). Each month is built with the daily values of each simulation. *Blue line* (mean), *upper and lower dots* (5th and 95th percentiles).

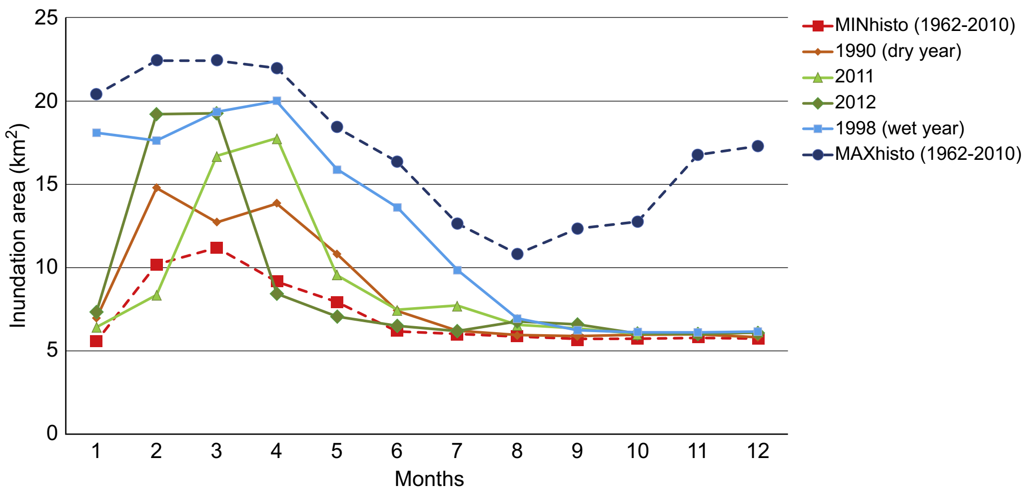


FIGURE 6.9 Monthly average of wetland inundation area (km^2). Built from Delft3D-FLOW simulation results.

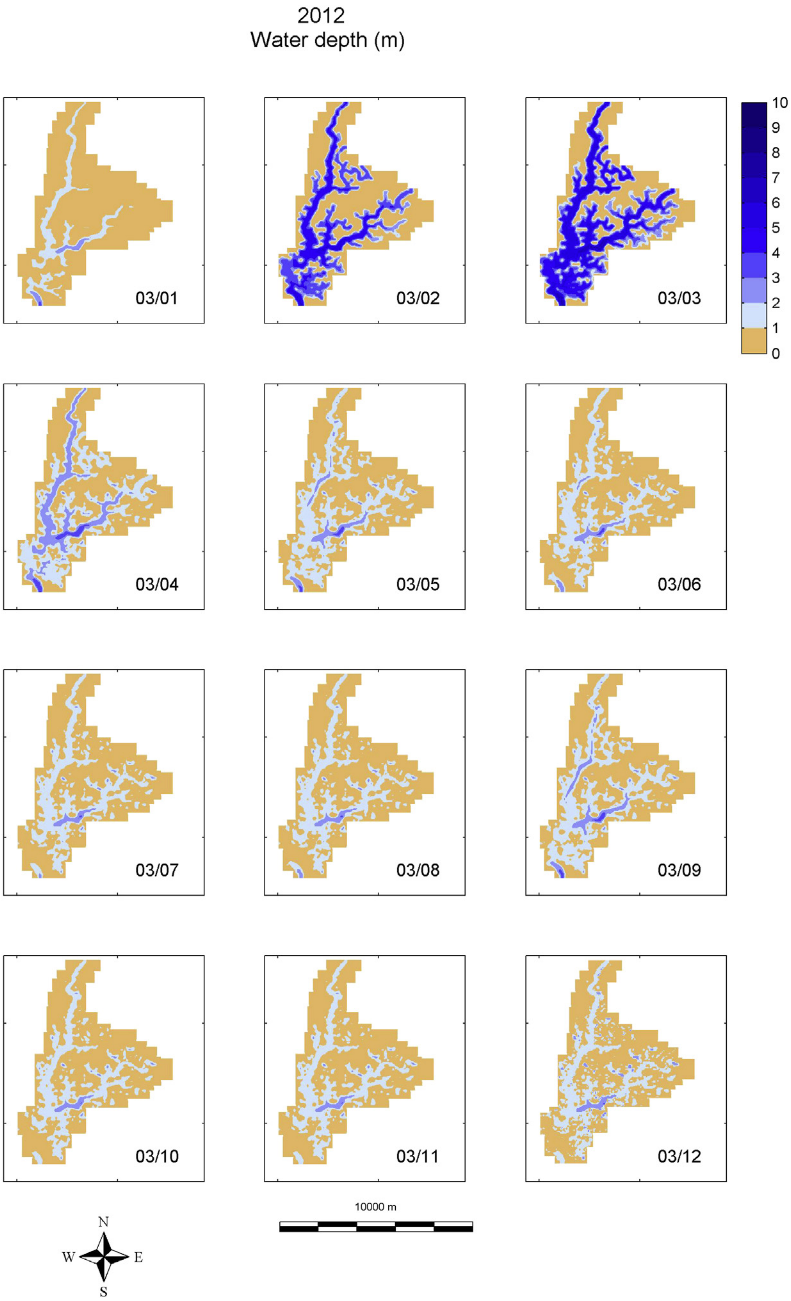
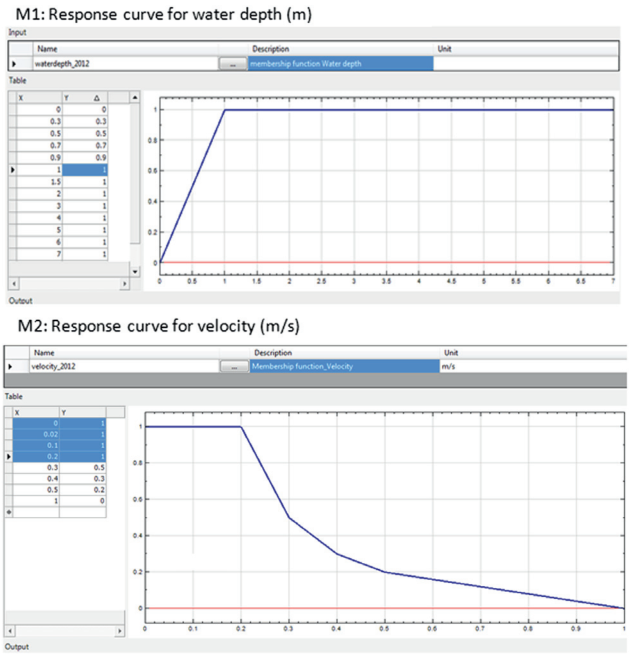


FIGURE 6.10 Water depth (m) maps (January–December 2012) from DELFT- FLOW. Output maps extracted the same day every month. Scale bar indicates the water depth range (m). Months display: top left (January), low right (December).



M1 $(WD_{i,j})$

where:

WD: water depth (m)

i = position in x

j = position in y

$(0 \le WD_{i,j} \le 1) \rightarrow \text{M1}=WD_{i,j}$

$(1 \le WD_{i,j} \le 7) \rightarrow \text{M1}=1$

M2 $(vel_{i,j})$

where:

vel: velocity (m/s)

i = position in x

j = position in y

$(0 \le vel_{i,j} \le 0.2) \rightarrow \text{M2} = 1(vel_{i,j})$

$(0.2 \le vel_{i,j} \le 0.3) \rightarrow \text{M2} = 1\text{-}\left[(0.5/0.1)(vel_{i,j} - 0.2)\right]$

$(0.3 \le vel_{i,j} \le 1) \rightarrow \text{M2} = 0.5\text{-}\left[(0.5/0.7)(vel_{i,j} - 0.3)\right]$

FIGURE 6.11 Response curves for water depth (M1) and velocity (M2). The *x* axis presents the variable values: water depth (m), velocity (m/s); the *y* axis presents the habitat index score.

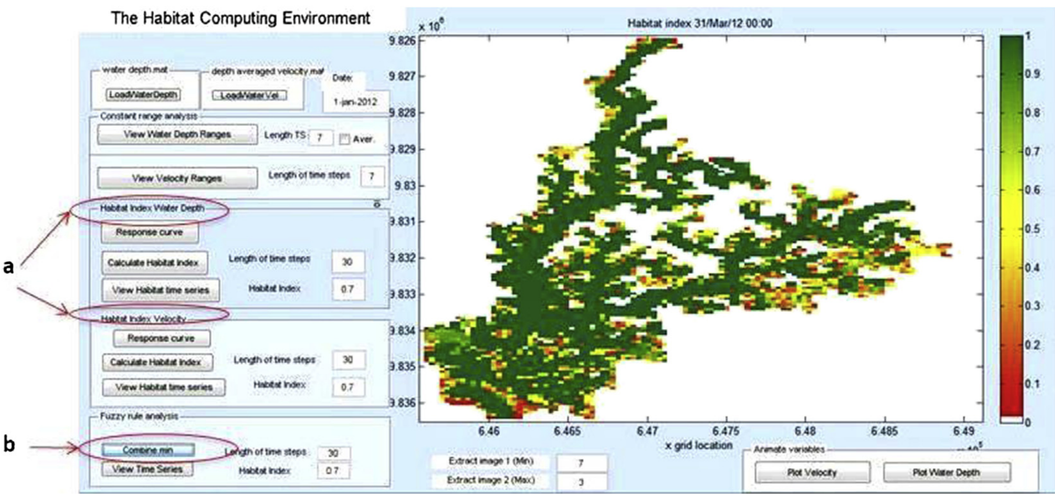


FIGURE 6.12 The dynamic habitat computing tool. (a) Constant range analysis, (b) variable habitat index (VHI), (C) combined habitat index (Comb-HI). Color bar indicates the habitat index scale (0: not suitable; −1: most suitable).

5. The wetland was divided into five areas considering the influence of the boundary conditions and residence times. This division criterion evaluated the response of each area according to the influence of each boundary on the two hydrodynamic variables (water depth and velocity) (Fig. 6.13).
6. The overall habitat analysis was performed for the total wetland area and for each area independently.

2.4 Habitat Suitability Index Formulation

HSI formulation was developed using the following steps:

1. A response curve for water depth and velocity was developed (Fig. 6.11).
2. An HI was calculated independently for water depth (HI-WD) and for velocity (HI-Vel) for each cell of the grid (Fig. 6.12). Delft3D-FLOW output maps of water depth and velocity were combined with their corresponding response curves (Fig. 6.11). Cells with an index >0.7 were given a value of 1 and considered for further calculation of the HSI:

   Selection of the cells with $HI\_WD > 0.7$:

$$HI\_WD > 0.7 = 1$$

$$HI\_WD < 0.7 = 0.$$

   Selection of the cells with $HI\_vel > 0.7$:

$$HI\_vel > 0.7 = 1$$

$$HI\_vel < 0.7 = 0.$$

3. A Combined Habitat Index (HSI) was calculated for each cell of the grid (Fig. 6.6). In this step, the HABITAT model selected the minimum of both HI (HI-WD and HI-Vel) (Fig. 6.12). Thus, total habitat suitability is the minimum of the results of both rules (Eq. 6.1). The results of the HSI were expressed in terms of percentages

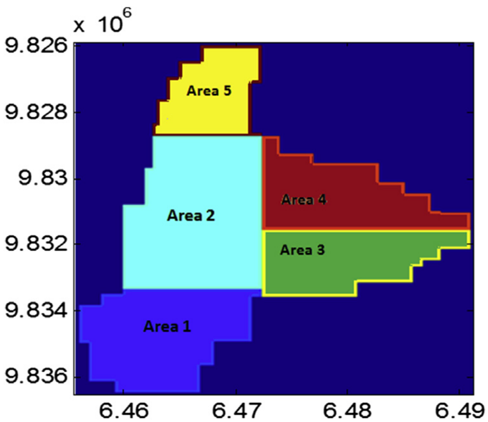


FIGURE 6.13 Wetland areas delimitation.

of suitable areas (PSA) with HSI >0.7. PSA was calculated for each time step. (Eq. 6.2):

$$HSI = \mathrm{Min}(HI\_WD, HI\_vel) \tag{6.1}$$

$$PSA = \frac{\sum_{k=1}^{n} HSI \geq 0.7}{N} \times 100 \tag{6.2}$$

Where:

HSI = Habitat Suitability Index
n = each cell
N = total number of cells

Furthermore, in order to have a large scale and overall HSI for each of the five areas, a second approach was applied. In this second approach, the cell values of water depth and velocity of each area were averaged before the calculation of *HI_WD* and *HI_vel*. Subsequently, the HSI was calculated in the same way as the previous approach by selecting the minimum of both. Results of this second approach were expressed in HSI (with a scale from 0 to 1), both temporally and spatially. All the calculations for approaches 1 and 2 were performed for the total wetland area, and also for each of the five areas independently.

3. Results

Two different approaches were evaluated to explain the habitat conditions of this tropical wetland. Results of the first approach are expressed in terms of PSA with an HSI above 0.7 (Sections 3.1–3.3). A second approach evaluated the wetland in terms of HSI scores (Sections 3.4–3.6).

3.1 Natural Variability of Suitable Areas

Our analysis started by evaluating the temporal distribution of the PSA with an HSI above 0.7 (first approach). Different hydrological years were simulated to understand the natural variability. Results described a high variation in terms of suitable areas depending on the hydrological conditions simulated. During a dry year, the percentage of suitable areas was up to 40% of the total wetland area, increasing to around 70% during wet years and historical maximum condition. Sampling years 2011 and 2012 were between both extreme conditions, with 2012 presenting higher percentages of suitable areas (up to 60%) compared to 2011 (up to 50%). Minimum (MINhisto) and maximum (MAXhisto) temporal distributions provided with the limits to understand the historical thresholds that the wetland has experienced during the period 1962-2010. The simulation of the minimum time series shows that historically the wetland had always provided at least a 25% of suitable area even in this extreme condition. For all conditions, higher percentages of suitable areas occurred during the wet season (January–May) (Fig. 6.14).

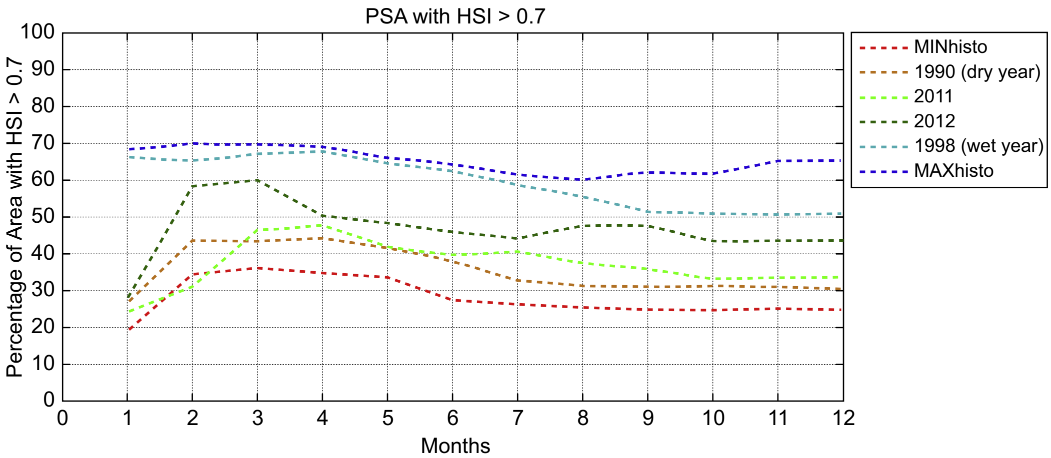


FIGURE 6.14 Temporal distribution of the percentage of suitable wetland area (PSA) with Habitat Suitability Index (HSI) >0.7 for sampling years (2011 and 2012), compared with extreme dry and wet years (1990 and1998), and minimum and maximum historical conditions (period 1962–2010). Months: January (1) to December (12).

3.2 Contribution of Each Wetland Area to the Total Wetland Suitable Area

Fig. 6.15 illustrates the contribution of each of the five areas to the total wetland area with an HSI > 0.7. From the results, it can be seen that areas 1 and 2 have a higher contribution, while the rest of the areas contribute less. The proportion of this contribution is maintained throughout the years analyzed. The timing at which the maximum of suitable areas occurred during the wet season differed between the years. Thus in 2011 it occurred during March and April, and in 2012 during February and March.

3.3 Independent Analysis of PSA per Area

Each of the five wetland areas was also analyzed independently in terms of PSA. For this analysis each area was compared to its own total area. Fig. 6.16 illustrates the temporal behavior of each area for sampling years 2011 and 2012. From the analysis, it is shown that areas 1 and 2 are the ones with a higher percentage of suitable areas HSI > 0.7, with percentages up to 70% and 50% in 2011, and 80% and 65% in 2012, respectively. Wetland area 3 showed an intermediate behavior during both years, with percentages around 45% in 2011 and 60% in 2012. Lower percentages were observed for areas 4 and 5. Area 4 showed values around 30% in 2011 and up to 40% in 2012, showing a clear separation from area 5 in 2012, while in 2011 both areas followed a similar pattern.

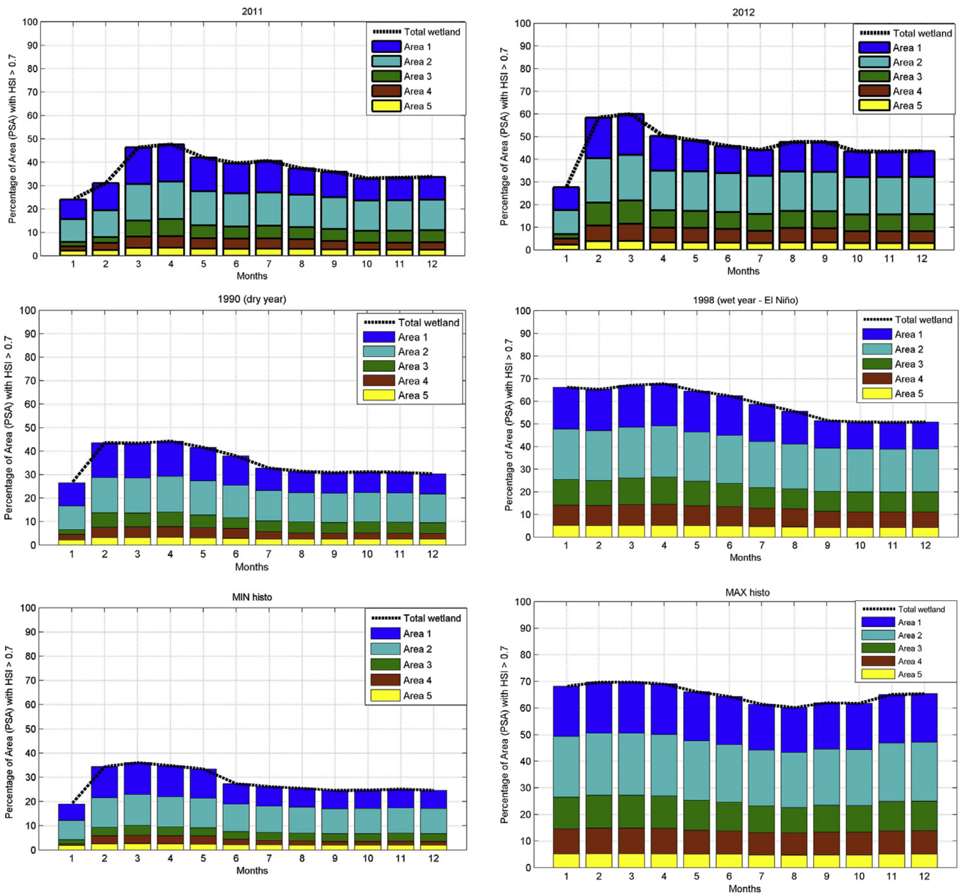


FIGURE 6.15 Contribution of each wetland area to the total wetland area with Habitat Suitability Index (HSI) > 0.7. For sampling years (2011 and 2012) (*upper panel*), dry and wet (1990 and1998) (*middle panel*), and minimum and maximum historical conditions (1962–2010) (*lower panel*). The sum of the five areas is equal to the total wetland area (*dashed black line*). Months: January (1) to December (12).

3.4 Natural Variability of the HSI

The second approach of this chapter analyzes the wetland in terms of HSI scores. As well as in the first approach, different hydrological years were simulated to understand the natural variability of the index. The dry year maintained an HSI score of 1 from February to May, decreasing to 0.5 from July on. On the other hand, a wet year (El Niño) maintained an HSI of 1 for a longer period, decreasing slightly to 0.8 from September on. Sampling years 2011 and 2012 reached the maximum score in the months of

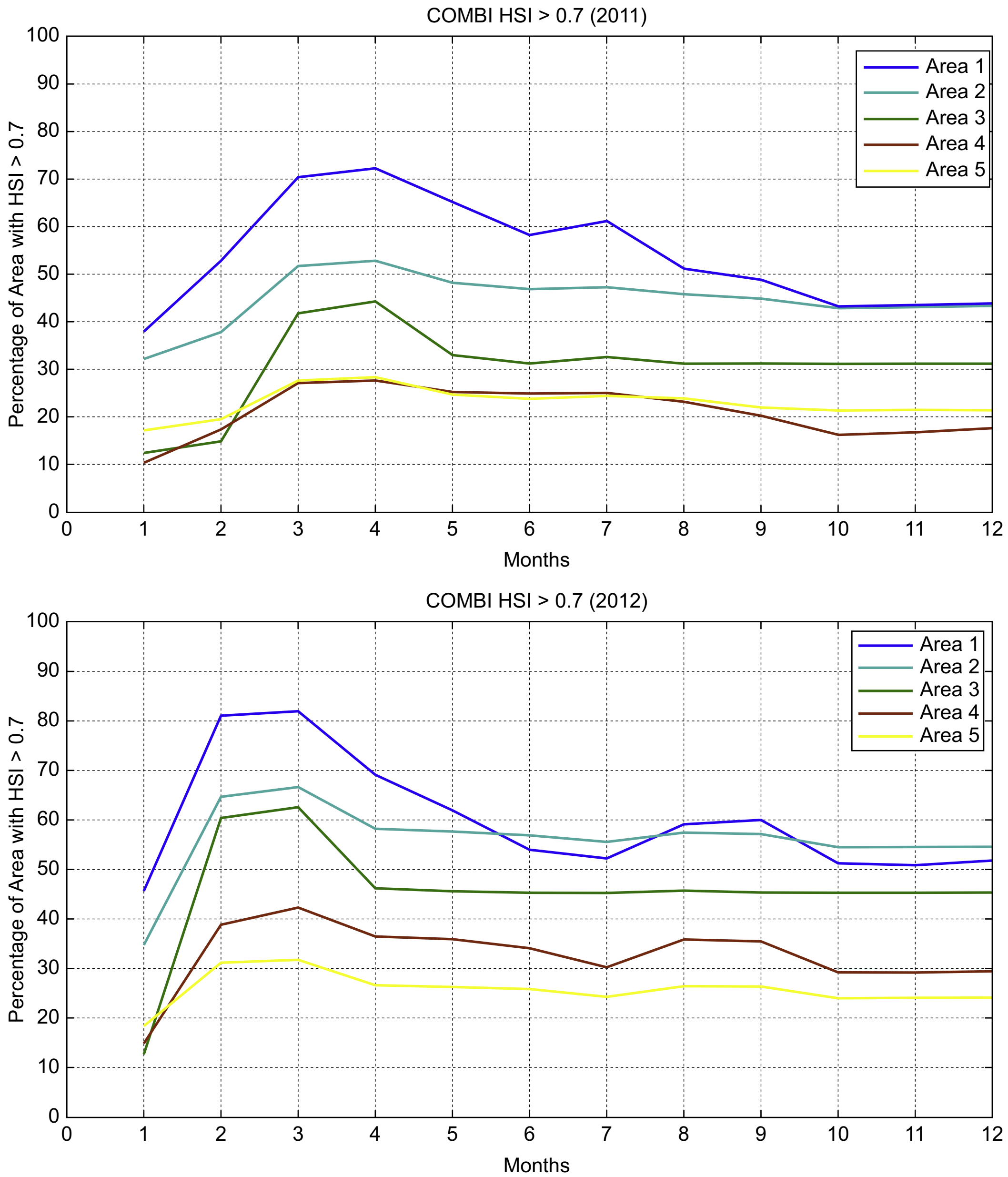


FIGURE 6.16 Percentage of suitable area (PSA) with a Habitat Suitability Index (HSI) >0.7 for each wetland area. Sampling years 2011 and 2012. Months: January (1) to December (12).

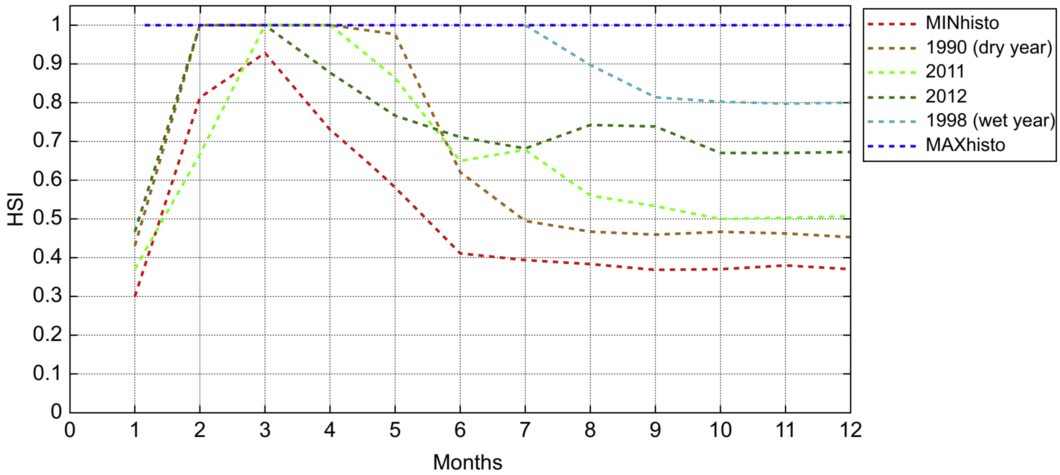


FIGURE 6.17 Temporal distribution of the Habitat Suitability Index (HSI) for sampling years (2011 and 2012), dry year (1990), wet year (1998), and minimum and maximum historical conditions (period 1962–2010). Months: January (1) to December (12).

March–April and February–March, respectively. The year 2011 followed a similar trend of a dry year, with values around 0.5 during the dry season. Extreme scenarios indicated that during maximum conditions the wetland can maintained an HSI of 1 during the whole year. The time series of the minimum historical condition illustrated that in the most unfavorable conditions, the HSI score in the wetland was around 0.4 (Fig. 6.17).

3.5 Independent Analysis of the HSI per Area

The five wetland areas were also analyzed independently in terms of HSI scores. Fig. 6.18 illustrates the temporal behavior of the HSI in each area for the different hydrological conditions. From this analysis, areas 1 and 2 were the ones with higher HSI scores; area 3 exhibited intermediate scores; while areas 4 and 5 had the lowest scores, for all the simulated conditions. During a dry year, a clear separation between the areas was observed along the whole simulation period, while during a wet year this separation was only evident during the dry season period. The maximum historical condition displayed a constant highest score of 1 during the whole simulation, with the exception of areas 4 and 5 that slightly decreased to 0.9 during August. It was interesting to see that higher scores for areas 1 and 2 were also reached during the minimum historical simulation. Overall and from a temporal perspective, all wetland areas reached higher scores of HSI during the wet season period.

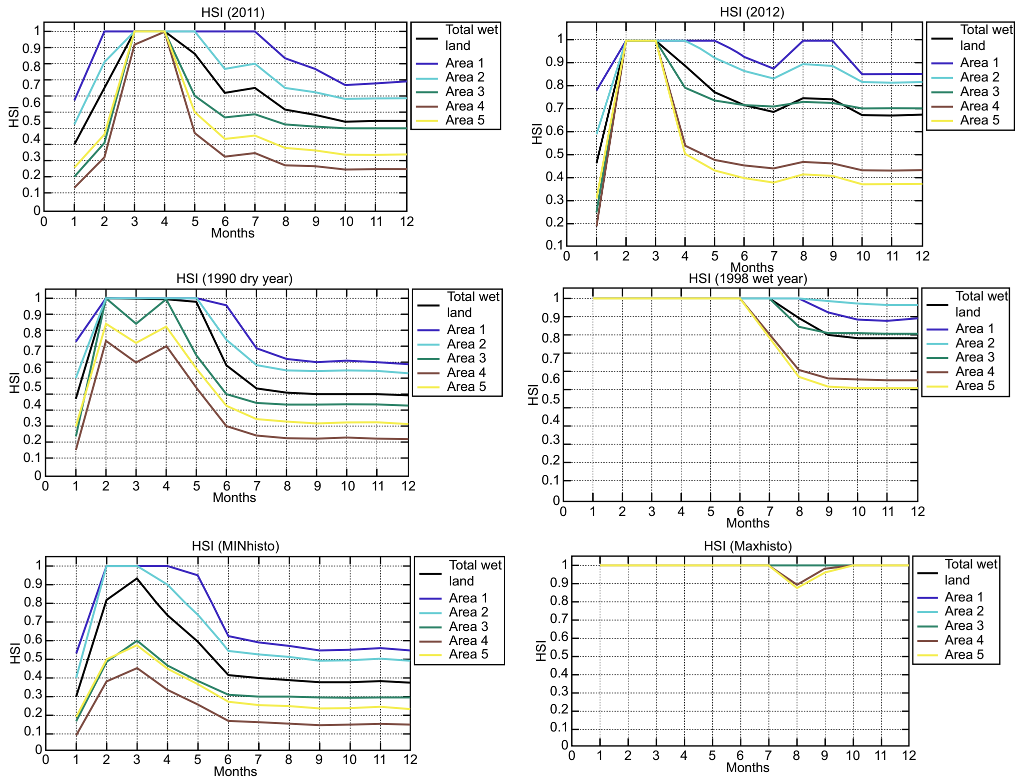


FIGURE 6.18 Temporal distribution of Habitat Suitability Index (HSI) for each wetland area (*colored lines*) and total wetland area (*dashed black line*) for sampling years (2011 and 2012), dry year (1990), wet year (1998), and minimum and maximum historical conditions (period 1962–2010). Months: January (1) to December (12).

3.6 Spatial and Temporal Variation of the HSI

Fig. 6.19 displays the spatial and temporal variation of the habitat suitability index (HSI) for the different hydrological conditions. During the first 6 months of a wet year (El Niño year 1998), all areas reached an HSI of 1, and were >0.6 even during the dry season. The maximum historical simulation showed a constant HSI above 0.9 during the whole year for all the areas. Overall, spatial HSI results for simulations were 1990, 2011, 2012, and minimum historical described areas 1 and 2 as the ones with higher HSI scores (even during the dry season [>0.6]), while areas 4 and 5 were the ones with the lowest HSI scores (HSI values <0.5 during the dry season). Area 3 presented intermediate HSI values. Thus results suggest that wetland areas 1 and 2 are the ones that provide better conditions for fish. Since wetland areas 4 and 5 showed lower HSI scores, these areas may require special attention in terms of management. Temporal behavior of the HSI (for all simulations) defined the wet season period (February–April) as the key period providing suitable habitat conditions for the entire fish community of Abras de Mantequilla wetland.

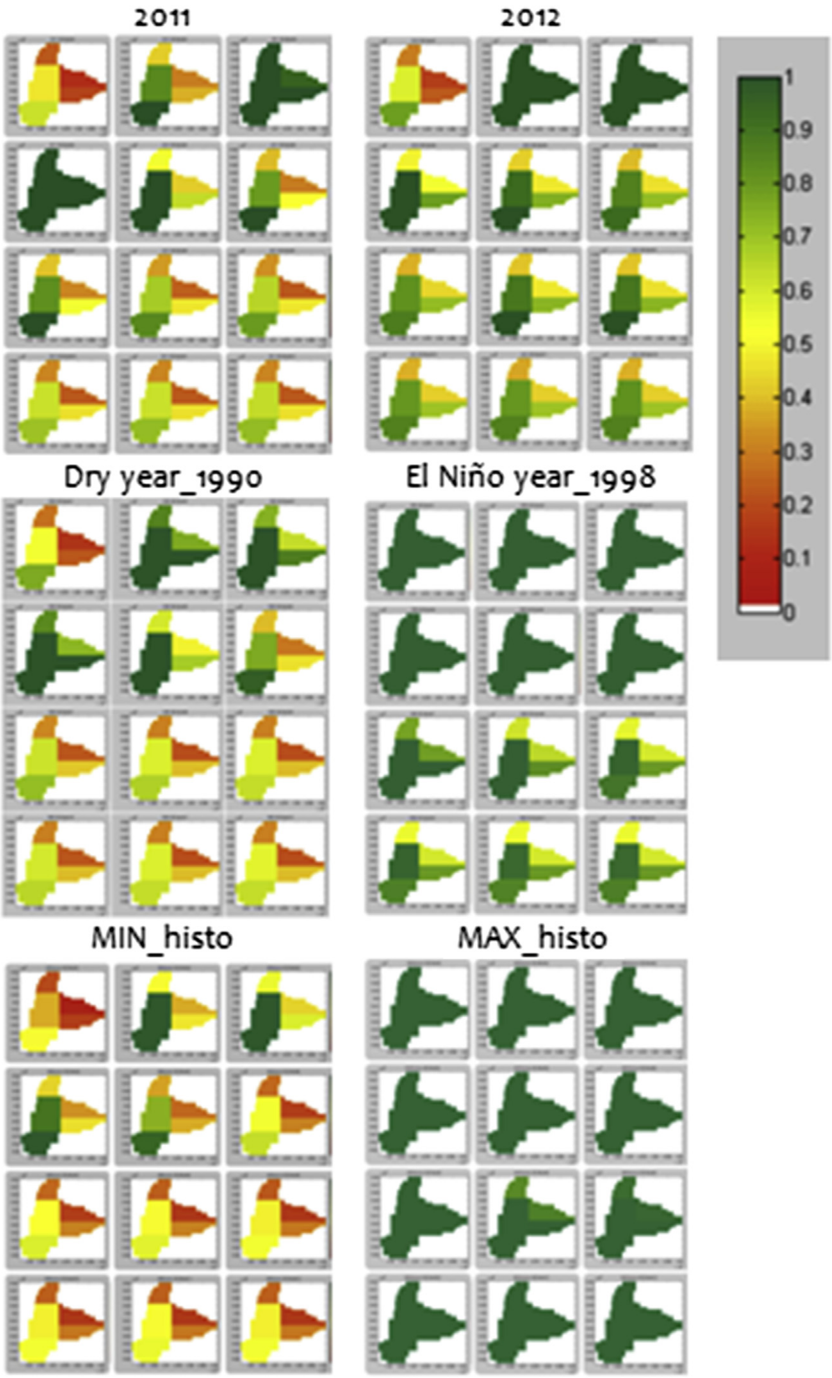


FIGURE 6.19 Spatial and temporal distribution of Habitat Suitability Index (HSI), for sampling years (2011 and 2012), dry year (1990), wet year (1998), and minimum and maximum historical conditions (period 1962–2010). Months display follows the same sequence as Figure 6.10: top left (January), low right (December). *Color bar* indicates the habitat index scale from 0 (not suitable in *red*) to 1 (most suitable in *dark green*).

4. Discussion

This study described a methodology to evaluate the temporal and spatial distribution of habitat suitable areas for the overall fish community of Abras de Mantequilla wetland. Regarding response curves development, in the present study these curves were developed with the aim of including the overall fish assemblage (both littoral and pelagic/limnetic). The criterion for the development of these rules was based on field sampling and literature for the littoral fish community, while for the pelagic community, literature was the main source. Both communities utilize shallow littoral areas, the first as habitat during their entire life period and the second mainly to protect their eggs after spawning. Thus a general criterion above 1 m for water depth was assumed as optimal combined with velocities not higher than 0.2 m/s. Small littoral fish from the Characidae family were collected during both sampling campaigns in shallow littoral areas up to 1.5 m, combined with velocities not higher than 0.2 m/s. These hydrodynamic values are in agreement with the findings of other studies of neotropical Characids about their habitat, distribution, and feeding ecology (Casatti et al., 2003; Ferreira et al., 2012; Maldonado-Ocampo et al., 2012; Teresa and Casatti, 2013) and suggest both variables as good predictors of community structure and species abundance (Teresa and Casatti, 2013).

During fish sampling, another important characteristic observed in the littoral areas of Abras de Mantequilla wetland was the presence of associations of aquatic macrophytes. Floating macrophytes from the species *Eichornia crassipes* (Pontederiaceae), commonly known as "water hyacinth" represented around 80% of the total macrophyte biomass in Abras de Mantequilla wetland. *Salvinia auriculata*, *Pistia stratiotes*, *Ludwigia peploides*, *Lemna aequinoctialis*, *Paspalum repens*, and *Panicum frondescens* represented the other 20%. Thus our sampling results confirm the findings of other authors (Agostinho et al., 2007; Meerhoff et al., 2007a; Meschiatti et al., 2000) who recognized the association of small size species from the Characidae family to macrophyte banks that colonize littoral shallow areas, and their essential role as shelter and food provider. Since juvenile and adults stages of small size species and eventually also juveniles of larger species are typical in macrophyte banks present in lentic shallow habitats (Meschiatti et al., 2000), their shelter role to protect small fish from higher predators is important. Shallow areas are also important for the pelagic community. Thus pelagic species such as *A. rivulatus* (vieja azul) and *C. festae* (vieja roja), both typical of the wetland area, utilize also the littoral areas mainly during and after spawning. These species present high parental care after spawning because apparently they produce a low number of eggs (Barnhill and Lopez, 1974). Thus the general criteria in defining water depth as optimal from 1 m on, also consider this fact.

Regarding the influence of both hydrodynamic variables, results of the HI for water depth (HI-WD) and velocity (HI-Vel) showed that HI-WD was the main variable driving the HSI results because velocities were quite homogeneous in the entire wetland area.

Our findings revealed a high natural variability of the of the percentage of suitable areas (PSA) according to the different hydrological conditions simulated. Thus, from the historical perspective the results showed that the wetland can provide a range between 25% and 70% of suitable areas (given the response curves implemented for this study). These limits can be used as minimum and maximum thresholds for management purposes. Regarding temporal behavior, results describe the wet season period (January—May) as the one with a higher PSA for all simulations. Nevertheless, during extreme wet conditions, a higher PSA was also observed during what is considered normally the months of the dry season period.

Spatial analysis described areas 1 and 2 as those that provided more suitable habitat conditions and contributed higher percentages to total wetland habitat suitability. These areas are the ones that fulfill best the conditions described in the response curves. Local physical characteristics of these areas, as topography and proximity of the main inflow (Nuevo River), appeared to be the main drivers of our results. This is in agreement with the higher catch per effort for fishing activities reported in San Juan de Abajo (Florencio, 1993). This location belongs to area 1 of our study (low wetland area). On the other hand, areas 4 and 5 related to the Upper Chojampe inflows were the ones with a lower percentage of suitable areas. In these areas, the main source of water is related to runoff, and not to river inflow. Thus these areas will require specific management measures in the future to maintain their inflow contribution.

When the wetland was evaluated in terms of HSI scores, a similar pattern was observed for both spatial and temporal results. Thus higher HSI scores were obtained for areas 1 and 2 despite the hydrological condition simulated, and in general the months corresponding to the wet season period were the ones exhibiting higher scores for all simulations. From the historical perspective, and considering the whole wetland area, HSI scores were not lower than 0.4, even in the most unfavorable conditions (minimum historical).

This temporal availability of suitable areas definitely plays an important ecological role in the basin, since the majority of the fish of the Vinces River and associated floodplains present one reproductive cycle per year. At the end of the dry season, several fish species have a mature state ready for spawning. These species usually have high fecundity (high number of eggs to assure an adequate repopulation). However, there are also species such as *Aequidens rivulatus* (vieja azul) and *Cichlasoma festae* (vieja roja) that spawn during the transition periods between the wet and dry seasons, and others such as *Brycon dentex* that have been reported in mature stages also during the dry season (Barnhill and Lopez, 1974). Thus both seasons are important but for different species, therefore the importance of maintaining the natural timing of the inflows. A study on the biological aspects of the fish community in the basin revealed that 70% of the specimens sampled during the months of January to March reported an advanced stage of sexual maturity (stages III—V) (Revelo, 2010), and the rest of the specimens were already in stages of postspawning (I and II). When the analysis was more specific per species, the timing of mature stages differed slightly between the months of the wet season. For instance, *B. dentex* (dama) reported a higher number of specimens with an advanced mature stage in January (III, IV, and V), while in February and March immature stages were more frequent, indicating that spawning probably occurred between January and February. *Ichthyoelephas humeralis* (bocachico) reported specimens in advanced mature stages (III and IV) during January and February. Other species of less commercial interest such as *Hoplias microlepis* (guanchiche) reported mature stages during the first 3 months of the year (January–March), and immatures during April. *A. rivulatus* (vieja azul) reported specimens in advanced maturity stage (III, IV, and V) during January and February, and immature stages in April and May. Also a smaller percentage of immatures was reported during October and November, possibly explaining that this species has two reproductive cycles per year. *Curimatorbis boulengueri* (dica) reported advanced mature stages during February, and immature stages during March and April (Revelo, 2010). The last one is confirmed by the sampling performed during the present research where small immature specimens of *C. boulengueri* were collected during March 2012. All these findings provided evidence that the wet season and associated high flows represent an important period for the development and increase of the fish population in the study area, which is consistent with findings of other tropical systems that acknowledge the importance of high flows and floods in supporting the gonadal maturation of fish (McClain et al., 2014).

Fishing activities in the wetland occurred during 10 months of the year, but start usually at the end of the wet season (Florencio, 1993). Local farmers from ‘El Recuerdo’ village have also reported the catching of bigger size fish during the dry season (T. Estrella, pers. comm., 2016). They mentioned that they wait until the sizes are big enough to catch them to allow the fish population to grow. In this regard, there is also a regulation in Los Rios Province that establishes a ban (“veda”) for fishing activities from January 10 to March 10 (Revelo, 2010).

A parallel study on biotic communities structure (Alvarez-Mieles et al., 2018) determined that although the different areas of the wetland shared similar fish species from the Characidae family, there were species that seem to typify middle areas where higher residence times take place. Other species typify the lower area, which is more influenced by the river inflow, while other species characterize the river inflow. These findings at species level can provide the basis for future research on the construction of new rules and habitat assessment at a lower taxonomic level for the fish community in this tropical wetland.

5. Conclusions

The present study is the first attempt at providing an assessment of the temporal and spatial variation of suitable habitat areas for the fish community in Abras de Mantequilla wetland. Our results evaluated how hydrodynamic variables can facilitate the definition of suitable habitat areas in this wetland, in terms of both PSA and HSI scores. In this study, wetland areas with HSI >0.7 were described as optimal habitat for this fish community. However, areas with an HSI <0.7 cannot be considered necessarily as uninhabitable.

One of the limitations of our approach is that the rules were developed for the whole fish community, rather than for specific species. For this, more extensive sampling in the area is required to measure the habitat preference of different species. However, our methodology can provide an initial base for future habitat assessments of specific fish communities in the area.

The combination of hydrodynamic variables proved to be useful for an initial habitat assessment of the fish communities in this wetland. However, we acknowledged that other physical, chemical, and biotic variables play an important role in defining the habitat preferences and therefore should be gradually included for an integrated ecological habitat assessment. In this regard, the habitat tool developed for this study is quite flexible for adding more variables and their corresponding rules.

The high flow phase of the wet season was recognized as the period with a higher percentage of suitable areas and HSI scores for all the simulated conditions. Spatial zonation defined the areas close to the main inflow as the ones providing better habitat conditions, and areas related to the Chojampe subbasin as the ones that will require special attention in terms of management measures.

Based on the results of this study, it is recommended to maintain the timing and magnitude of the natural flows especially during periods with a higher percentage of suitable areas (high flows of the wet season), since this period is crucial to foment the spawning and development of the fish community in this wetland.

Acknowledgments

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