HYDROLOGICAL CONTROLS OF RIVERINE ECOSYSTEMS OF THE NAPO RIVER (AMAZON BASIN): IMPLICATIONS FOR THE MANAGEMENT AND CONSERVATION OF BIODIVERSITY

By

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ABSTRACT

HYDROLOGICAL CONTROLS OF RIVERINE ECOSYSTEMS OF THE NAPO RIVER (AMAZON BASIN): IMPLICATIONS FOR THE MANAGEMENT AND CONSERVATION OF BIODIVERSITY

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Rivers and floodplains on the Andean-Amazon interface have been much less studied but are clearly distinct in their hydrological regimes and thus the ecological roles that floodplain inundation plays in these ecosystems. Flooding occurs seasonally in multiple discrete events that control the water regime of floodplains, fish migration, plant phenology, and human activities associated with these processes. Yet at the outset of this research we lacked even a fundamental description of the hydrological features of these river systems, which are lined with vast floodplains. The Napo River is a major Amazon tributary that drains ~10^5 km^2 and flows through the Andean foreland, a sparsely inhabited rainforest region of exceptional biodiversity. The Napo River corridor includes a diversity of floodplain and lacustrine ecosystems, many of which are hydrologically connected to the main stem of the river. Large-scale hydrological modifications have been proposed in the basin, including the Napo barge waterway along the lowland reaches of the river in Ecuador and Peru, the Mazán hydroelectric project near its confluence with the Amazon, and the Coca Codo Sinclair hydroelectric project in the Andean portion of the basin. These works would modify the geomorphology and hydrology of the river channels, and impacts may extend far inland where extensive floodplains exist, as well as far upriver and downstream, with unknown environmental consequences. A comprehensive assessment of the hydrology and ecology of these environments is required to predict and minimize impacts of these kinds of development projects. Thus, with this in mind I set off to improve our understanding of the ecohydrological relationships between the Napo River and its floodplains. To address this goal

during nine field campaigns conducted from 2007 to 2013 I used a combination of field observations and water sampling, deployment of sensor networks (including unattended sensors and water collectors), and ground truthing of remotely sensed imagery. Study sites were reached by boat along ~800 km of river reaches in Ecuador and Peru. Floodplains and wetlands were explored on foot with guides from the local communities and a research assistant, during low water when they were accessible. More than 1000 water samples were collected for major solute analysis to determine the water sources (i.e., river overflow vs local rainfall or runoff) of inundation. Observations of the spatial distribution of inundation and associated vegetation were made to aid in interpretation of field and remote sensing data, and flood regimes (hydroperiod, depth of flooding) of more than 100 sites along the river were determined. Among the outcomes of this project are: 1) the development of a method to assess inundation in different environmental settings using the diel amplitude of temperature, 2) the identification of the main sources of flood waters in the floodplains using major solutes, and 3) the determination of the hydrological regimes of the Napo River floodplains using the approaches listed above. Results obtained through this work improved our understanding of the ecohydrology and diversity of tropical floodplains and wetlands, and serve as a basis for future studies on how hydrology determines the structure and composition of tropical floodplain communities and ecosystem processes, and provide information crucial for the assessment of potential negative impacts on these environments caused by proposed river development projects. This study will help natural resource managers and other decision makers set priorities for conservation and develop guidelines and strategies for the wise use of environments in the region.

To the Napo River, its people and its biodiversity

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INTRODUCTION

About half of the world's wetlands have been lost because of land drainage, accelerated urban growth, construction of dams, and the development of waterways (Revenga & Mock 2000). In the Amazon Basin, extensive and diverse wetlands (floodplains, swamps, lakes, etc.) remain in relatively natural condition but increasingly face similar threats (Junk 2002). Floodplain environments, which occur along major lowland river systems, maintain fertile soils, absorb flood waters, and retain sediments and nutrients (Dunne et al. 1998). They are inhabited by many species of conservation interest, including threatened and endangered animals (e.g. manatee, giant otter, migratory catfish, etc.) (Keddy et al. 2009). Furthermore, these ecosystems are important sources of food and other ecosystem services for local inhabitants (Kvist and Nebel 2001). In spite of their widely acknowledged cultural and economic importance, Amazonian floodplains increasingly are being modified by timber extraction, agriculture and cattle ranching (Junk 2002, McClain 2008). Yet the most wide-reaching, systemic threat to these ecosystems may be large-scale hydrological modifications of the river systems (Finer and Jenkins 2012, Kareiva 2012).

Currently, a proliferation of proposals to develop waterways, dams and water diversion projects threatens the hydrologic underpinnings of floodplain ecosystems in the Amazon Basin (Finer and Jenkins 2012). An initiative known as *Integration of South American Regional Infrastructure* (IIRSA, by its initials in Spanish) involves twelve South American countries in the creation of a new "intermodal" transport network of rivers and roads (IIRSA 2009). The Amazonian hub, a critical component of IIRSA's plan, includes a number of river navigation and road improvements that are identified as high priority projects. Among these is the waterway planned for the Napo River of Peru and Ecuador, which is envisioned to make year-round barge-train navigation feasible, serving as a transport link between Pacific ports, Andean highways, and the mainstem Amazon River. In addition, a large hydroelectric project, the CH-Mazán, is being bid internationally to develop a dam that would block the mainstem of the Napo River near its confluence with the Amazon close to the locality of Mazán and divert ~85% of its flow toward the Amazon River to generate electricity for the city of Iquitos in Peru (GRL 2013). Also, already being developed is another large dam, the Coca Codo Sinclair, located in the Andean portion of the Napo River basin, with unknown environmental consequences for downstream ecosystems (GDE 2014)

The relatively unaltered state of many Amazonian river-floodplain ecosystems represents a major conservation opportunity that must be considered in light of these large-scale development projects. Systematic conservation planning to classify representative ecosystem units and set priorities across broad regions is imperative but challenging, not only because the regions are vast and remote, but also because the hydrological connectivity conferred by the rivers makes downstream areas vulnerable to upstream impacts (Thieme et al. 2007).

The Napo River is a major Amazon tributary that drains ~10^5 km^2 and flows through the Andean foreland, a sparsely inhabited rainforest region of exceptional biodiversity (Celi 2005, Da Silva et al. 2005). The Napo River corridor includes a diversity of floodplain and lacustrine ecosystems, many of which are hydrologically connected to the main stem of the river. River levels fluctuate up to five and nine meters (near the Andean foothills and towards the lowlands, respectively) and each year inundation occurs in several events, mostly during the rainy season. Scientific understanding of Neotropical floodplains comes mainly from work on the central Amazon near Manaus (Junk 1999) as well as on the mainstem Orinoco River in Venezuela

(Lewis et al. 2000) and on a few savanna floodplains such as the Pantanal in Brazil (Hamilton et al. 2002). Rivers and floodplains on the Andean-Amazon interface have been much less studied but are clearly distinct in their hydrological regimes and thus the ecological roles of floodplain inundation differ in these ecosystems (Hamilton et al. 2007). Flooding occurs seasonally in multiple discrete events that control the water regime of floodplains, fish migration, plant phenology, and human activities associated with these processes. Yet at the outset of this research we lacked even a fundamental description of the hydrological features of these Andean-Amazon river systems, which are lined with floodplains whose vast extent has only recently been confirmed by remote sensing (Alsdorf et al. 2007a, Hamilton et al. 2007).

Recent years have seen much growth in ecotourism along the Napo River in Ecuador, with several lodges managed by local indigenous communities specializing in wildlife observation. Notwithstanding the increasing ecotourism in the Napo, this region is targeted for industrial development that may not be congruent with environmental conservation. The Napo Waterway and the Mazán-Napo hydropower projects are examples of this (IIRSA 2009, GRL 2013). Also, petroleum extraction continues to expand along the lowland Napo in Ecuador and Peru, contributing substantially to their economy but generating a great deal of controversy regarding its environmental and social impacts (Finer et al. 2008).

River channels and flow regimes can readily be modified by impoundment, dredging, and removal of rock outcrops (Poff et al. 1997, Hamilton 1999). Impacts of these hydrological alterations extend far inland from the channels where extensive floodplains exist. Also, impacts can extend far upriver where rivers have little change in elevation, as is the case throughout the lowlands of Amazonia. Little is known about the hydrology of floodplains of many of these rivers. Hence, the extent of influence of these proposed projects can be difficult to determine, not to mention how those changes would alter hydrology and, consequently, biodiversity, ecosystem services, and people's livelihoods.

Transformation of the Napo River into a year-round industrial barge channel, as envisioned by IIRSA, would require substantial interventions to increase and stabilize its channel depth. In spite of the lack of feasibility of the project as originally planned based on an International Development Bank funded study(Serman and CSI 2010), pressure from governments and economic groups creates uncertainty about the application of the recommendations given in the report, as has occurred in the past in other regions (e.g., Hydroid Paraguay). Also based on the lack a comprehensive environmental impact assessments for some of the proposed work in the Napo River Basin (e.g. Coca Codo Sinclair and Mazán hydropower projects), potential engineering works, including dredging and impoundments, could dramatically alter the hydrology and ecology of this river system with unforeseen impacts on biodiversity and ecosystem services.

It is difficult to predict how Napo River channel alterations would impact adjacent floodplain ecosystems because of the complexity of the hydrological relationships between the main river and its floodplains. Large-scale river channel modifications could increase or decrease the hydrological connectivity between these environments. For instance, dredging river beds could lower the water level of extensive reaches of the river and prevent periodic flooding of closely connected swamps, and even result in drainage of these environments and major changes in the plant and animal communities that inhabit them. On the contrary, damming the river channels could cause increased connectivity between the river channel and other environments in areas with lower gradient and may increase the cover of lacustrine environments, causing more frequent flooding of inhabited levees, preventing locals from using floodplains for agricultural purposes, increasing the potential of groundwater and surface water contamination, etc. (Jackson and Sleigh 2000, Wei et al. 2009, Marques et al. 2011). A comprehensive assessment of the hydrology and ecology of these environments is required to predict and minimize impacts of these kinds of development projects. Thus, with this in mind I set off to improve our understanding of the ecohydrological relationships between the Napo River and its floodplains.

The goal of this dissertation research was to investigate the eco-hydrology of the lowland Napo River and its floodplains and wetlands. The aims were: 1) To identify the spatio-temporal variability of water levels in areas directly flooded by the Napo, and indirectly flooded through river backwater effects that delay the drainage of local precipitation or runoff; 2) To assess the extent and diversity of floodplains and wetlands in relation to their hydrology; and 3) To understand the role of river-floodplain hydrological connectivity and how alterations to river hydrology and geomorphology would impact connected floodplains and wetlands.

To address these goals I used a combination of field visits and water sampling, deployment of sensor networks, the development of some novel field methods among other things, and ground truthing of remotely sensed imagery. With support from several grants and fellowships, nine field sampling expeditions were conducted from 2007 to 2013. During these campaigns, study sites were reached by boat along ~240 km of river reaches in Ecuador and ~620 km in Peru. Floodplains and wetlands were explored on foot with guides from the local communities and a research assistant, during low water when they were accessible. More than 1000 water samples were collected for major solute analysis to determine the water sources (i.e., river overflow vs local rainfall or runoff) of inundation, location of inundation and field observations were made to aid in interpretation of field and remote sensing data, and flood regimes of more than 100 sites along the river were determined.

Unattended sensors and water collectors were critical to our approach because inundation is difficult to predict in these environments and very often impedes access to the densely forested floodplains. To understand the flooding regime of the Napo River and associated environments I used an innovative approach in which miniature temperature loggers (Thermochron i-Button, model DS1921G or H #F50, Dallas Co.) were installed at low water and left to record flood regimes across transects extending inland from the river. The relative differences in diel changes in water temperature, in comparison with changes in air temperature above the level of flooding, allowed determination of when the loggers were under water, and consequently the extent and timing of flooding. Thus, arrays of up to 4-6 loggers were installed on trees at various elevations from near the ground to several meters above it. Over 500 of these data loggers were deployed at different depths and points (109 locations) along 41 transects extending up to 6 km into floodplains and wetlands along the Napo River. Transects were representative of the diversity of floodplains/wetlands in the Napo corridor, and had characteristic vegetation structures and compositions. These data loggers were deployed during low water and stayed in the field recording data for up to 4-36 consecutive months before they were retrieved in subsequent campaigns.

To assess the accuracy of the temperature sensor approach under different conditions I conducted a comparative study among some of the locations along the Napo River (wet tropics) with locations in northern and Central Australia (dry-wet tropics and subtropics) and temperate sites in Michigan using indirect (temperature based) and direct (pressure based) water level records. Information from the pressure transducers (HOBO U20-001-01, 04, Onset Computer Corporation) was used to improve water level estimates obtained with Thermochron iButtons. These investments in equipment and sampling allowed for collection of data on inundation in remote and inaccessible sites, revealing flooding patterns both within and across years. Details of this work are described in Chapter 1: *Measuring Floodplain Inundation using Diel Amplitude of Temperature.*

To determine the source of water in the floodplains (e.g. river vs. local runoff), over 400 remote water samplers were deployed to collect water samples during flooding events for analysis of their major solute chemistry (Ca^{2+}, Mg^{2+}, Na^{-}, Cl^{-}, silica, etc.). The samplers were PVC pipe collectors that filled with floodwater and retained it with minimal evaporation or contamination. They maintained sample integrity for months in the face of rainfall and evaporation. These water samplers were placed and collected at the same locations, depths and times as the temperature data loggers to be able to relate the water chemistry measurements to the timing and origin of the flooding events. Different concentrations and proportions of these solutes in water samples indicated different kinds of flooding water in the floodplain. A description of the approach employed to identify best indicators of sources of inundation and the patterns in the chemistry of standing waters in the floodplains found along the river are shown in Chapter 2: *Sources of flood waters in the Napo River floodplain (Amazon Basin) as indicated by major solute chemistry*.

Analysis of the data collected with the aforementioned approaches in light of the natural flow regime concept (sensu (Poff et al. 1997)) was conducted to determine the flood regime of all field sites and to assess the degree of river influence on the floodplains along the different river reaches. This work entailed looking at the variability in the main components of the flood regime: magnitude, duration, frequency, and timing of inundation of each study site and subsequently relating these hydrological patterns to the sources of water in the floodplains and conducting non-parametric analyses of variance to determine spatial and temporal patterns of inundation. Overall, we found a continuum of flood regimes across floodplains along the Napo

River, ranging from deep and long-lasting inundation to shallow and short-lasting inundation. Approximately 75% of these floodplains were influenced by the river in different degrees, from complete to partial river-controlled hydrology. The 25% of the remaining floodplains were mostly controlled by local waters, and probably are perched above the river, although historical records indicate that these locations could be influenced by the river during extreme flooding events. Additional details about the approach employed in these analyses and its outcomes are described in Chapter 3: *The hydrological regimes of the Napo River floodplains, Andean Amazon*.

Results obtained through this work improved our understanding of the ecohydrology and diversity of tropical floodplains and wetlands, with emphasis on floodplains of the Andean Amazon. It serves as a basis for future studies on the role of hydrology on the structure and composition of tropical communities and ecosystem and global processes, including the effects of climate change. It provides information crucial for the assessment of potential negative impacts on these environments caused by the development of river development projects and gives recommendations to local communities and other stakeholders to prevent or mitigate these impacts. This study will help natural resource managers and other decision makers to set priorities for conservation and delineate guidelines and strategies for the wise use of environments in the region.

CHAPTER 1. MEASURING FLOODPLAIN INUNDATION USING DIEL AMPLITUDE OF TEMPERATURE

Abstract

Assessment of inundation patterns across large and remote floodplains is challenging and costly. Inexpensive loggers that record the damping of the diel amplitude of temperature (DAT) when submerged compared to overlying air can indirectly indicate inundation. I assessed the efficacy of this approach in tropical, subtropical and temperate floodplains by comparing the discrepancy (in number of days per year underwater) between direct water level measurements (pressure transducers) and indirect records ascertained from the DAT. The approach worked better in wet-dry floodplains and humid tropical floodplains than in subtropical and temperate sites. However, the relatively small DATs of air in humid and densely vegetated settings made estimation of inundation more challenging due to less damping relative to air when sensors were submerged compared to the drylands, where a large diel range of air temperature was markedly damped beneath the water. In addition, very shallow waters can track the air temperature, making their DATs not much lower than in the air. The indirect temperature approach must be calibrated for a particular ecosystem using direct water-level measurements to define threshold DATs that are indicative of submergence of the sensors. Temperature provides an inexpensive indicator of duration of inundation that can be particularly useful in studies of large and remote floodplains.

Key words: inundation**,** floodplains, water temperature, sensors

Introduction

Inundation is the principal driver of the ecology of floodplains, influencing diversity and phenology of plant and animal communities, biogeochemical cycles, and the interactions that humans have with these ecosystems (Bourgoin et al. 2007, Correa 2008, Tomasella et al. 2013). Understanding the inundation regime is crucial to manage and protect floodplains, yet its complexity over space and time makes this task challenging, and sometimes leads to oversimplifications in our understanding of the functioning of floodplain ecosystems.

Part of the problem lies in the cost of measuring hydrological processes, including water level fluctuations, over large areas and long spans of time, particularly in remote floodplains that are difficult to access during inundation. Automated equipment (e.g. pressure transducers to measure water level) can serve this purpose well, but the relatively high cost of these units limits their application over extensive areas (Conly et al. 2004, Greswell 2009). Often these units work in conjunction with a second unit that corrects measurements for barometric pressure, which can double the cost of monitoring stations if placed far apart. Another option entails direct observation and recording by local inhabitants or hired personnel (Danielsen et al. 2009), which in spite of being an important participatory approach is restricted to specific environments, distances, and times that people are available.

Remote sensing has often been used to measure seasonal inundation regimes over extensive and remote areas (Alsdorf et al. 2007b, Hamilton et al. 2012). For instance, researchers have used optical and microwave remote sensing to measure changes in the extent of inundation over large regions (Alsdorf et al. 2007a, Wilson et al. 2007, Lee et al. 2011, Ward et al. 2012), and radar interferometry to assess temporal changes in water level (Alsdorf et al. 2001, Jung et al. 2010, Poncos et al. 2013). Despite the capability to acquire imagery from airborne or spaceborne sensors over broad areas, the frequency of retrieval and the cost of the imagery and its processing limit the assessment of inundation patterns over extensive areas, and very dense vegetation can impede the ability to detect inundation by remote sensing. Also, remote sensing analysis requires ground truth work for calibration and validation purposes.

Less costly field approaches are needed that measure inundation over extensive areas and relatively long times. Ward et al. (2012) employed relatively inexpensive sets of Thermochron iButton temperature loggers (Hubbart et al. 2005) to record changes in diel amplitude of temperature (DAT) over time as an indicator of inundation patterns in remote, episodically inundated systems in northern Australia. The high thermal inertia of water attenuates the DAT and is indicative of inundation when compared to the larger diel amplitude of air temperature typical of the air when the sensor is out of the water. Their results suggest that this approach can be effective at estimating inundation, and that temperature loggers provide a relatively inexpensive alternative to assess inundation across large remote areas. At the time of this writing temperature loggers cost about 30-fold less than pressure transducers (US $15 vs. $500). But to what extent can this approach be used in other environmental settings?

In this study I assessed the use of temperature loggers to indicate inundation in contrasting environments, and I considered the environmental factors that need to be taken into account when measuring inundation using temperature-based methods. I evaluated temperature monitoring as an indirect approach to estimate the depth and duration of inundation, comparing the indirect approach to direct (water pressure) measurements of water levels in humid tropical floodplain forests of South America, dryland floodplains of Australia, and a temperate river and its deciduous floodplain forest of the northern United States. I show how the approach works well in some settings and not as well in others, and discuss what environmental factors need to be considered to make the indirect temperature approach viable in floodplains.

Methods

Inundation estimation using direct and indirect approaches

I assessed duration and depth of inundation in the floodplains of the Napo River in the humid tropics of the Ecuadorian and Peruvian Amazon Basin, the Mitchell River in the northern wet-dry tropics of Australia, the Moonie River in drylands of southern central Australia, and the Kalamazoo River in the temperate climate of southwestern Michigan (United States) using co-located iButtons (indirect method) and pressure transducers that record water levels (Table 1.1). Results of the two approaches (direct and indirect) to estimate inundation were compared to assess the viability of the indirect temperature approach, and to determine the optimal method to estimate inundation using temperature records.

Table 1.1 Study sites in Australia, Ecuador, Peru and the USA used for comparisons of indirect and direct assessments of water level.

River system	Region	Latitude / Longitude range	Biome	Climate	No. of sites	Study period
Mitchell	Northern Australia	15.35-16.71º S/ 141.72-143.41º E	wet-dry savanna	dry tropical	5	Oct 08-May 09
Moonie	Central Australia	28.93º S / 148.74º E	wet-dry savanna	dry subtropical	1	Oct 07-Apr 08
Napo	Western Amazon	0.73-3.03º S / 75.69-73.15º W	Rainforest	humid tropical	14	Dec 08-Dec 09
Kalamazoo	Michigan	42.32ºN / 85.36º W	deciduous forest	Temperate	2	Aug 12-Jun 13

The **direct** method consisted of pressure transducers (PTs)—HOBO (U20 & U10) or Van Essen (TD Divers & Baros)—that recorded depth of inundation over time after correcting the records for the local barometric pressure. Pressure transducers as well as temperature sensors were installed during low water levels at a short distance above or below the water level at the time. Barometric pressure was recorded using separate loggers deployed on trees out of reach of flooding in the floodplains, but in close proximity. PTs recorded six times per day at four-hour intervals with an accuracy of ±0.3-0.5 cm.

The **indirect** method entailed mounting several (4-6) temperature loggers—model 1921G or 1921H Thermochron iButtons (IBs)—at various heights in the same floodplain sites as the PTs, including at least one above the reach of flooding (reference IB). The sensors were sealed in 10-mil polyethylene film with minimal air and stapled to tree trunks in positions where they were not subject to direct sunlight. The IBs recorded temperature six times per day at an accuracy of ±1ºC and at 0.125 or 0.5ºC resolution. Daily records were used to estimate the DAT, which was interpreted to indicate the duration of inundation at the different elevations above the soil surface based on its attenuation when IBs were underwater compared to the reference IB in the air. DAT thresholds (hereafter called 'thresholds' for simplicity) were used to determine when IBs were under or above water, and thus to estimate hydroperiods, following a binary (Boolean) logic system.

Threshold determination

Sensor-specific DAT thresholds (i.e., specific to the site and the sensor height above ground) were determined based on the lowest hydroperiod discrepancy (hereafter 'discrepancy') between the direct and indirect approaches. The sensor-specific thresholds were averaged over the vertical profile of sensors to obtain **site thresholds** that were subsequently averaged within each region to obtain **regional thresholds** (Figure 1.1). Thus I compared discrepancies between hydroperiod estimates obtained with the direct method and the indirect method based on three approaches to estimate thresholds (sensor specific, site, and regional) to identify the optimal method to assess inundation over large areas using temperature records.

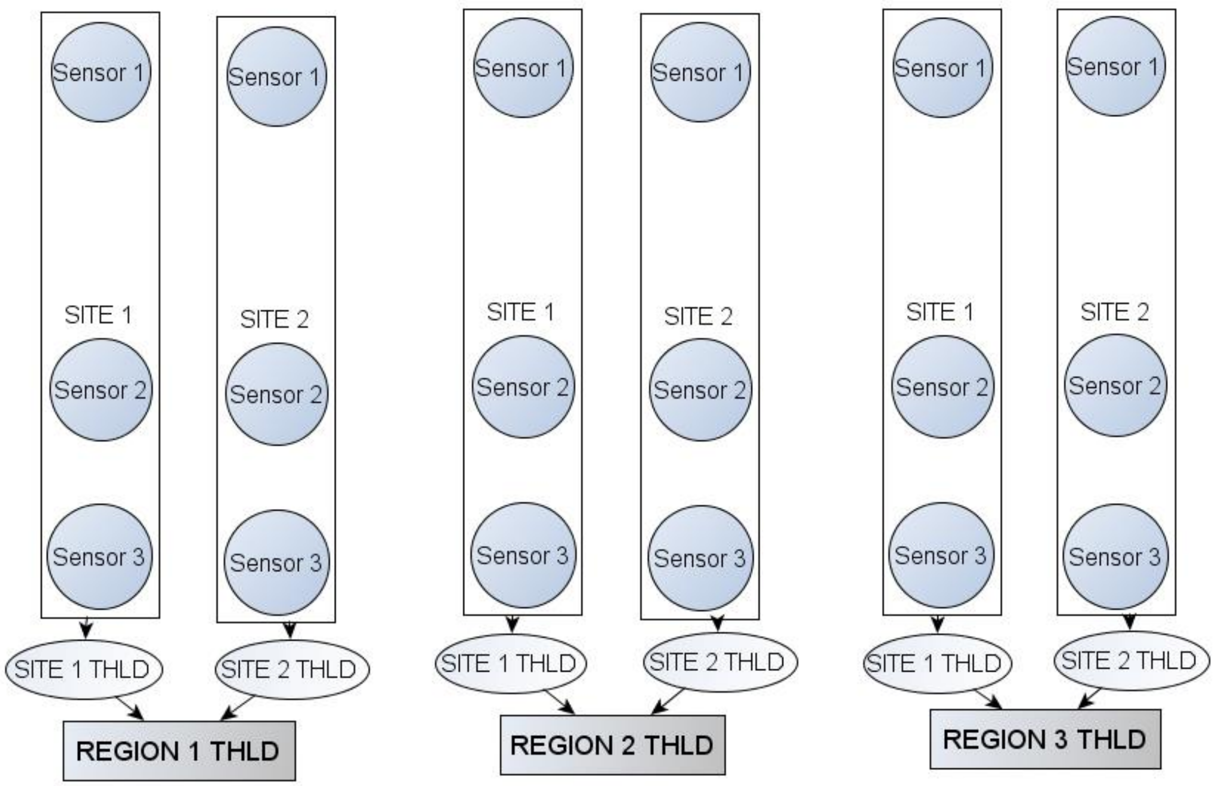

Figure 1.1. Schematic representation of temperature loggers mounted at different elevations above the ground in floodplain sites of three study regions. Sensors 2 and 3 are closer to the ground and subject to inundation and sensor 1 is above the reach of flood waters. Thresholds (THLDs) of the diel amplitude of temperature indicated when the sensors were underwater at sites with co-located water level sensors. Sensor-specific thresholds for each height at each site were averaged to obtain site thresholds that were in turn averaged to obtain regional thresholds.

In addition to the approach presented here to estimate DAT thresholds, other statistical analyses were conducted to define dynamic thresholds that adjusted to the variable spatial and temporal conditions in one of the regions of study (Napo) and to account for the variability in DATs over time across the vertical profile. Those analyses included smoothing of the DAT of the uppermost (reference) IBs using LOESS non-parametric regression and choosing dynamic shifts linked to the scale of variability of the LOESS curve to define an inundation threshold that varied over time. I also tried interval regressions of the DAT records collected along the vertical profile, and the censored depth data were examined to assess hydroperiod and depth of inundation, an approach that relied on the aforementioned threshold definition. These analyses did not improve the accuracy of the hydroperiod estimations; thus for simplicity and broader applicability of the indirect method of inundation assessment I decided to follow the threshold calibration approach described in this study.

Effects of temporal and spatial variability on diel temperature variation

To assess the effects of temporal and spatial variability on diel temperature variation, and therefore on threshold definition, I conducted pair-wise comparisons of DATs of IBs during submersed and emersed conditions and assessed their significance using t tests. This comparison was conducted across different spatial scales (sites within regions and vertical gradients across sites) and during periods of the year with different ranges of DAT variability (hereafter called for simplicity thermally stable and thermally variable seasons). Seasons were defined based on whether the monthly means of the DAT (MMDAT) of reference IBs (in the air) representative of each region were above or below the annual mean of the MMDATs. Results from this analysis gave insight into the underlying mechanisms that control diel variation in air and water temperature in floodplains and defined thresholds to estimate hydroperiods based on temperature records.

Results

Inundation patterns

The duration and depth of inundation estimated using the direct (pressure-based) method varied greatly among the study sites (Figure 1.2). Locations were flooded from 3.3 to 12 months of the year, and to a maximum depth ranging from just 12 cm in one location to almost 12 m in another. The median depth of inundation at individual sites ranged from 3 to 229 cm (Figure 1.3).

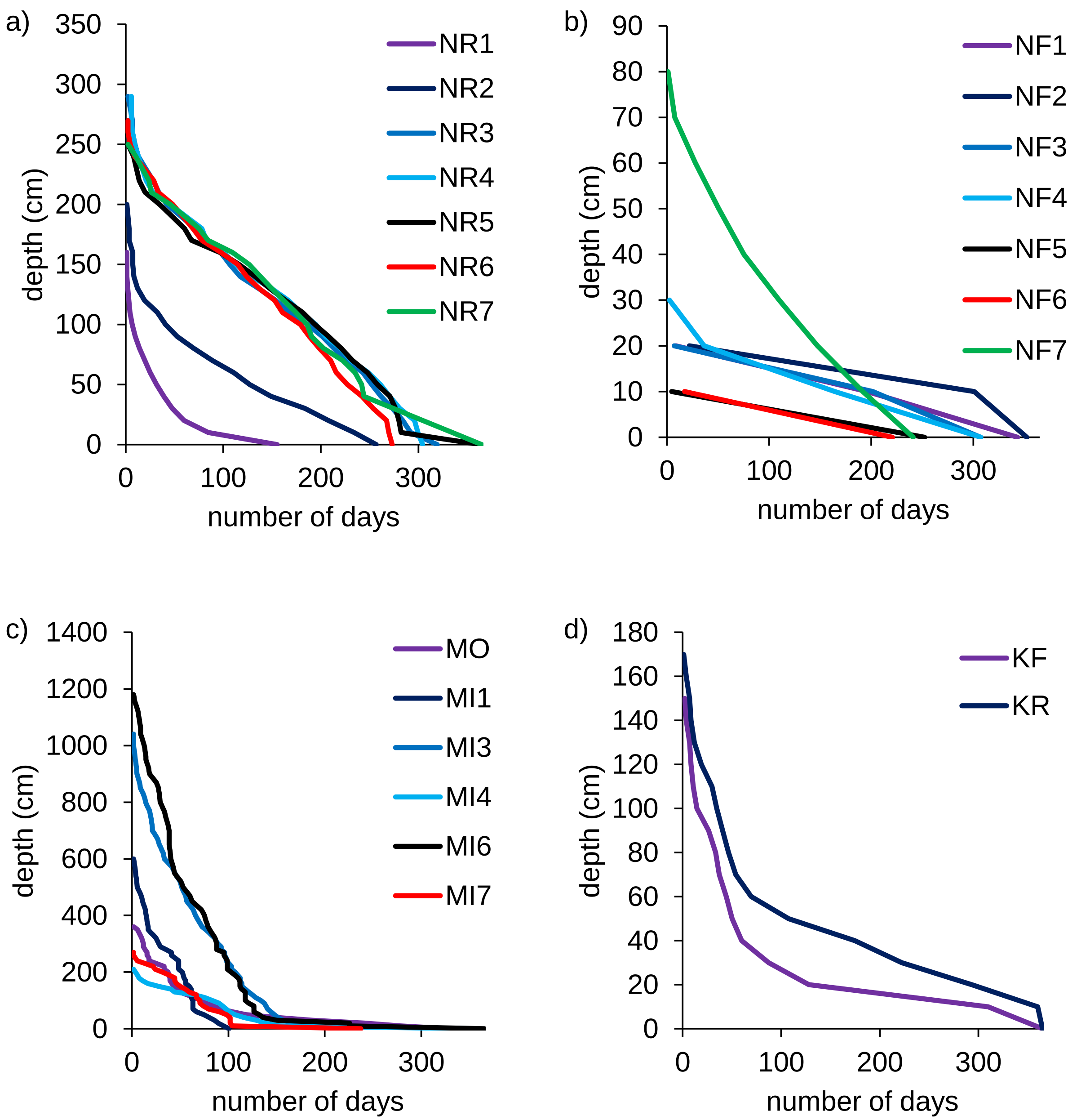

Figure 1.2. Hydroperiods based on pressure transducer measurements in the study regions: a) Napo River –NR (n=7) and b) Napo floodplains –NF (n=7) (tropical South America), c) Moonie –MO (n=1) and Mitchell Rivers –MI (n=5) (central and northern Australia respectively), and d) Kalamazoo River –KR (n=1 site) and floodplain –KF (n=1) (northern U.S.).The magnitude of the y axis varies among regions.

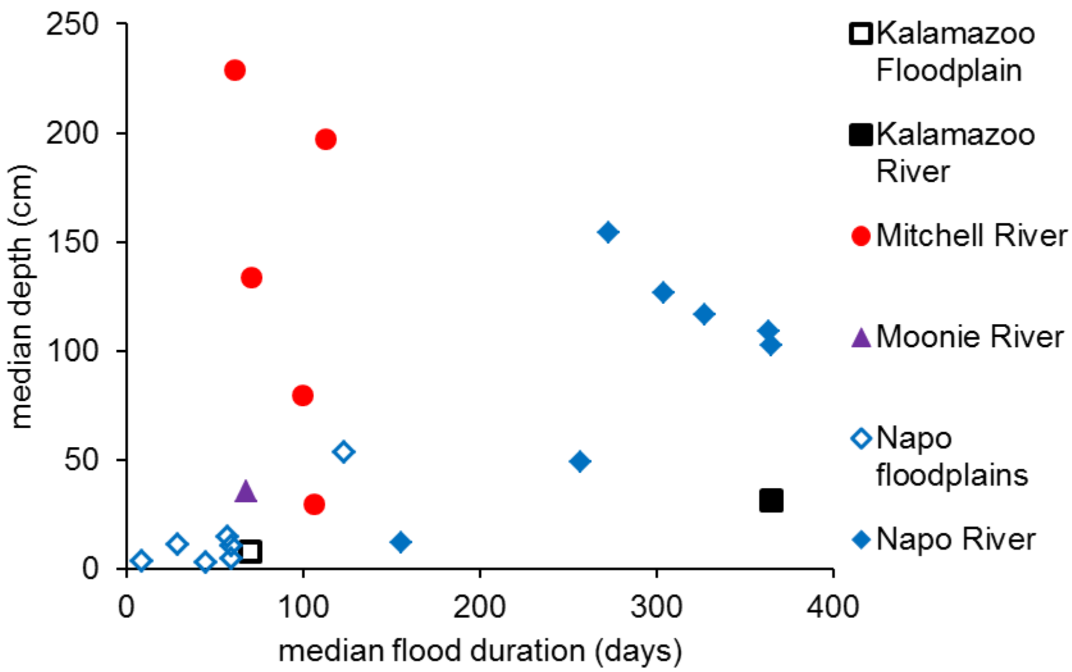

Figure 1.3. Median flood duration and median water depth of the Kalamazoo River and floodplain (northern U.S.), the Moonie and Mitchell Rivers (central and northern Australia respectively), and the Napo River and floodplains (tropical South America) based on the pressure transducer measurements.

Temperature thresholds and hydroperiod discrepancies

Inundation estimated with the indirect temperature approach yielded results that agreed approximately with the direct measurements (Figure 1.4), although the discrepancy between the two methods varied by region and whether the DAT thresholds used to estimate hydroperiods were specific to the sensor, averaged for the site (vertical profile), or averaged for the region (Table 1.2). The means of sensor-specific thresholds and discrepancies (absolute values) for sites within each region ranged from 0.67 to 5.93 ºC and 0.33 to 3.20 days, respectively. The overall mean of the sensor-specific discrepancies was 1.70 ± 1.25 days, ranging from 0.33 day in the Moonie River floodplain to 3.20 ± 3.11 days in the Kalamazoo River floodplain (Table 1.2).

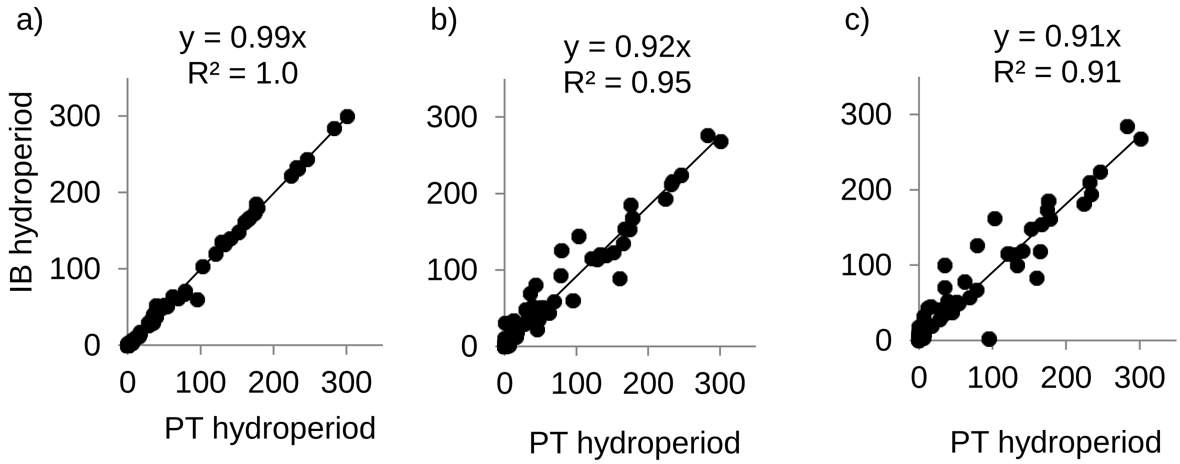

Figure 1.4. Relationship between hydroperiods estimated with direct methods (pressure transducers – PTs) and indirect (temperature loggers – IBs) measurements obtained after applying a) sensor-specific, b) site-specific, and c) regional DAT thresholds.

Table 1.2. Comparison of DAT thresholds and resultant hydroperiod discrepancies between direct and indirect hydroperiod estimation in the study regions.

	Threshold (°C)		**Discrepancy (days)**		
Location	**Sensor specific**	**Site specific (regional mean)**	**Sensor**	**Site**	**Regional**
Napo floodplains	0.50-1.90	0.67±0.35	1.43±1.08	4.29±4.14	12.88±10.66
Napo River	0.50-2.10	1.01±0.35	1.92±1.07	11.08±8.04	12.16±8.47
Mitchell River	1.90-9.00	4.21±1.38	1.40±0.56	9.97±12.26	10.37±12.16
Moonie River	2.60-7.60	5.93	0.33	13.33	13.33[a]
Kalamazoo River & floodplain	1.50-5.00	2.56±0.65	3.20±3.11	24.75±6.01	26.10±4.38[b]
All sites	0.50-9.00	2.00±1.79	1.70±1.25	10.29±9.38	13.32±9.97

Table 1.2 (cont'd)

[a] The DAT thresholds are summarized as ranges for each location (sensor-specific) as well as the means and standard deviations of the site thresholds (regional means) employed to estimate regional discrepancies. Site discrepancies were estimated using the mean of the sensor-specific thresholds employed in each site.

[b] Only one site was monitored in the Moonie River.

[c] Only two sites were monitored in the Kalamazoo River system.

For studies across broad regions, it would be desirable to be able to deploy a smaller number of calibration sites (i.e., co-located pressure transducers and temperature sensors) that inform the interpretation of data from a larger number of temperature monitoring sites. Such an approach requires definition of the optimal threshold to apply across the broader study area (region). Within a region, site-specific discrepancies were greater than sensor-specific ones because thresholds varied with sensor position in the vertical profile (Table 1.2). Regional discrepancies were still greater, reflecting site-to-site spatial variability that causes uncertainty when applying calibrations from a subset of locations to a broader region (Table 1.2). There was no relationship between DAT thresholds and hydroperiod discrepancies for specific sensors (Figure 1.5), nor was there one when sensors were averaged for sites or the overall regions (Figure 1.6).

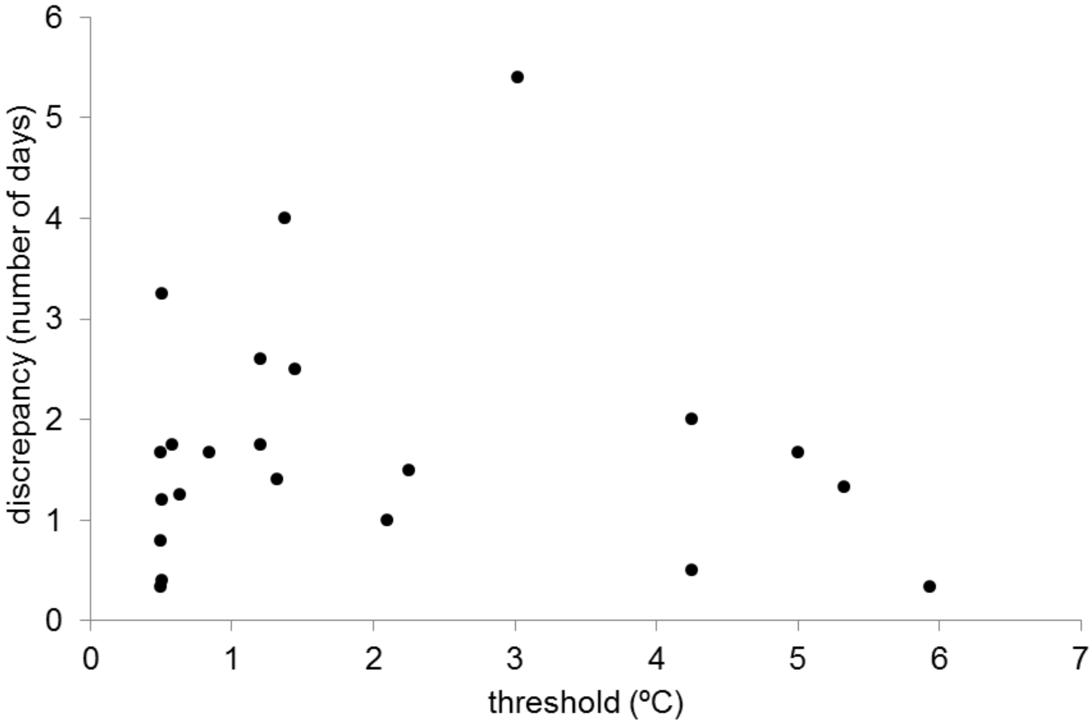

Figure 1.5. Average discrepancies (in number of days inundated) between direct (pressure) and indirect (temperature) methods of estimating inundation in relation to the site-specific thresholds of diel amplitude of temperature. Site-specific thresholds are the means for the thresholds for the sensors at that site. The data are not significantly correlated ($\alpha = 0.05$).

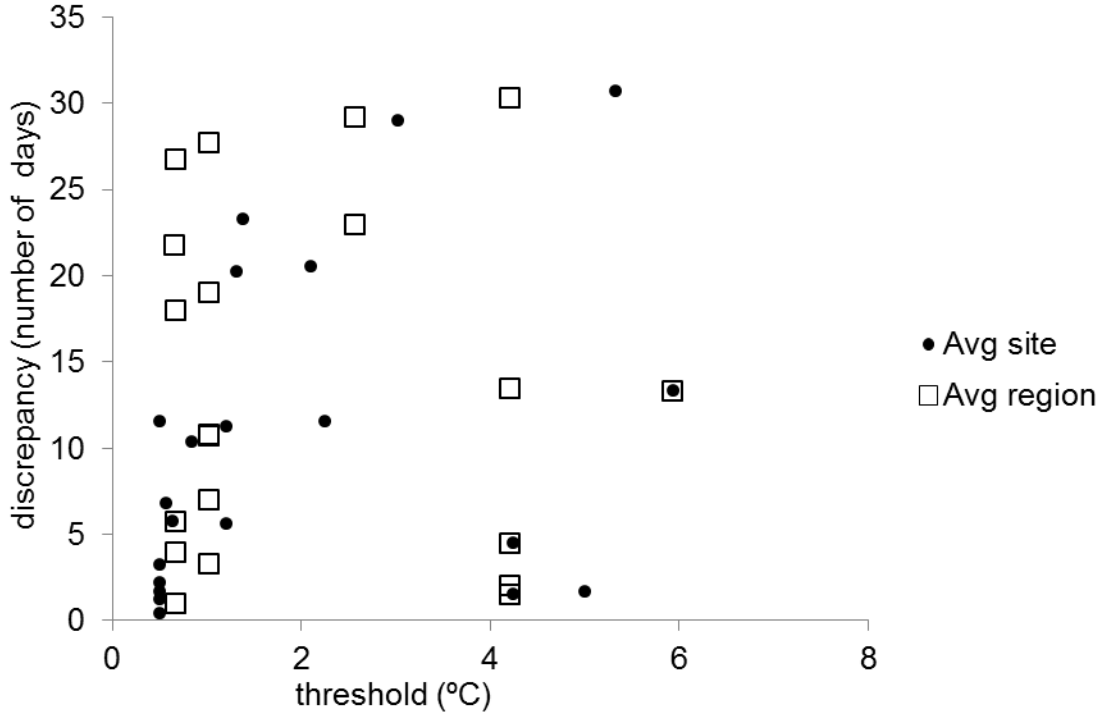

Figure 1.6. Average discrepancies between direct and indirect (temperature-based) methods of hydroperiod estimation using average site thresholds (Avg. site) and average regional thresholds (Avg. region) across the study locations.

Effects of temporal and spatial variability on inundation estimates

Temporal and spatial variability of temperature affected inundation estimates using the indirect approach, both across vertical gradients within a site and across sites, as indicated by the difference in diel amplitude of temperature (ΔDAT) between different environmental conditions (Table 1.3). The tropical/subtropical savanna floodplains in Australia had larger mean ΔDATs between measurements recorded above and beneath the water compared to the other environments studied (~1–20 vs. ~1–4 ºC) (Figures 1.7–1.9) with a mean ΔDAT of 8.01 ± 2.10 ºC (i.e., the DAT underwater averaged 8.01 ºC smaller than that in air; Table 1.3), except for the flooding season in the temperate zone when ΔDATs of air and water were not very different

(Figures 1.10 & 1.11, Table 1.3 - rows A and B). Seasonal variability of DATs in the Australian savannas was large and relatively similar across the region (Table 1.3 - row C). This trend was also similar across the vertical profile (Table 1.3 – row D), but was minimized during flooding (Table 1.3 - rows E and F).

Table 1.3. Average differences in diel amplitude of temperature (ΔDAT, ºC) between different environmental conditions.

Row	**ΔDAT**	**Vertical location**	**Tropical rainforest, Ecuador & Peru**	**Tropical/ subtropical savannas, Australia**	**Temperate deciduous forest, Michigan USA**
A	Between air & water	L	**1.88±1.05** **(251-337, <0.0001)**	**8.01±2.10** **(183-203, <0.0001)**	**1.99±5.44** **(301-303, <0.0001)**
B	Between air & water (during flooding or near flooding)	U	0.96±0.77 (251-337, **<0.0001**-0.35)	**8.53±3.76** **(194-203, <0.0001-0.001)**	**5.28±1.51** **(301-303, <0.0001-0.01)**
C	Between seasons	L	0.99±0.68 (309-337, **<0.0001**-0.25)	**6.97±2.46** **(183-203, <0.0001)**	**1.81±1.42** **(301-303, <0.0001-0.01)**
D	Between seasons	U	0.75±0.46 (302-337, **<0.0001**-0.87)	**5.82±2.39** **(176-203, <0.0001)**	3.03±5.64 (301-303, **<0.0001**-0.11)
E	Between loggers during emersed period of L and U	L & U	1.13±0.82 (26-588, **<0.0001**-0.96)	2.32±1.90 (30-326, **<0.0001**-0.63)	0.63±0.26 (327-489, 0.26-0.32)
F	Between loggers during	L & U	**1.92±0.84**	0.65±3.52	0.94±1.19

Table 1.3. (cont'd)

	flooding of L and U		**(8-446, <0.0001)**	(66-334, **<0.0001**-0.85)	(113-279, **<0.0001**-0.62)
G	Between loggers during flooding of L and emersed period of U	L & U	**2.88±1.32** **(251-337, <0.0001)**	**9.18±2.28** **(183-340, <0.0001)**	4.34±2.70 (392-514, **<0.0001**-0.11)

[a] Rows A and B compare DATs between air and water for the lowermost (L) and uppermost (U) loggers placed in the floodplains in the three study regions during all applicable dates. Rows C and D compare DATs between thermally variable and thermally stable seasons as defined based on diel air temperature variability during the study. Rows E-H compare DATs between loggers during specific hydroperiod conditions. In parentheses are ranges of degrees of freedom and p-values of pairwise comparisons, with significant (α = 0.05) differences marked in boldface.

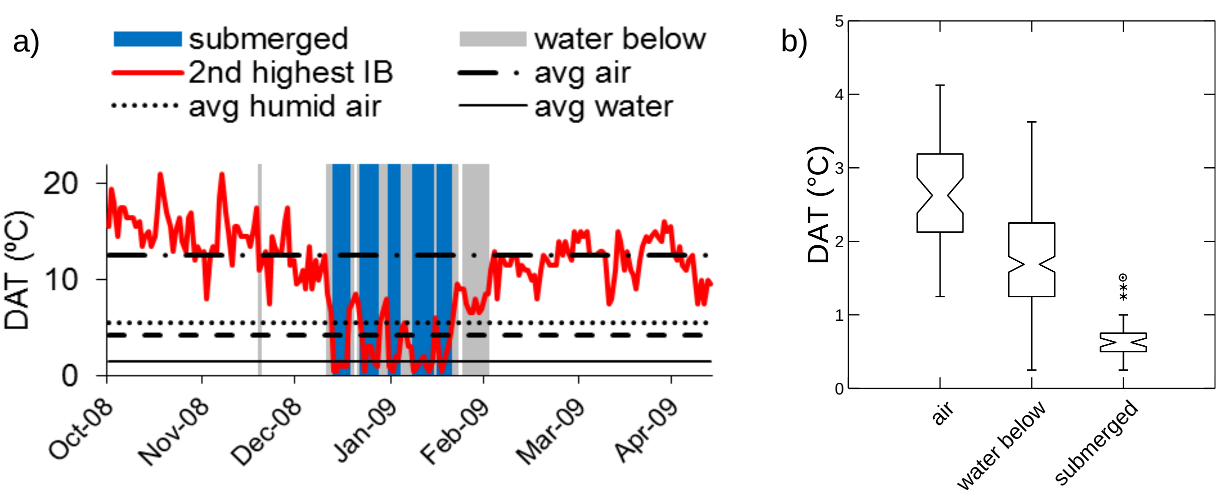

Figure 1.7. Diel amplitude of temperature (DAT) of the second highest IB deployed in a tropical dryland floodplain (Rosser Creek site in the Mitchell River watershed, Australia). Horizontal lines depict the regional threshold used to estimate the hydroperiod as well as the average DATs of the IB in the air, in the water, and in the air during the presence of water below the IB (humid air). The vertical shading in blue shows when the logger was under water and the gray shading shows when the logger was in air but there was standing water underneath it.

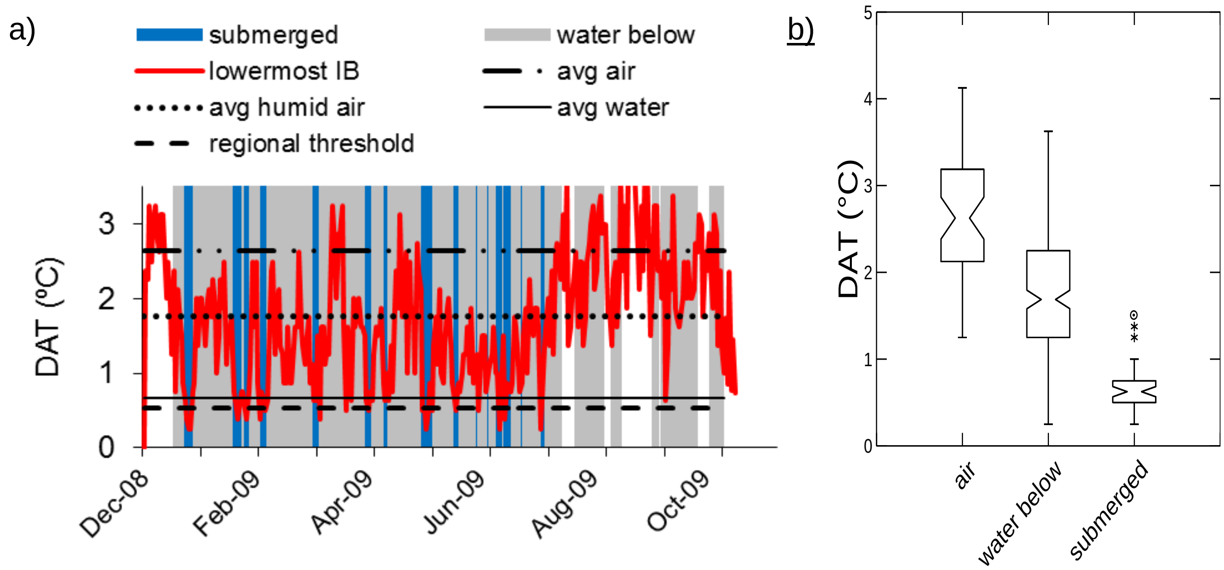

Figure 1.8. DAT of the lowermost IB deployed in the floodplain in a humid tropical forest floodplain (Napo River at Paulacocha, Peruvian Amazon). See Figure 1.6 for explanation of horizontal lines and vertical shading.

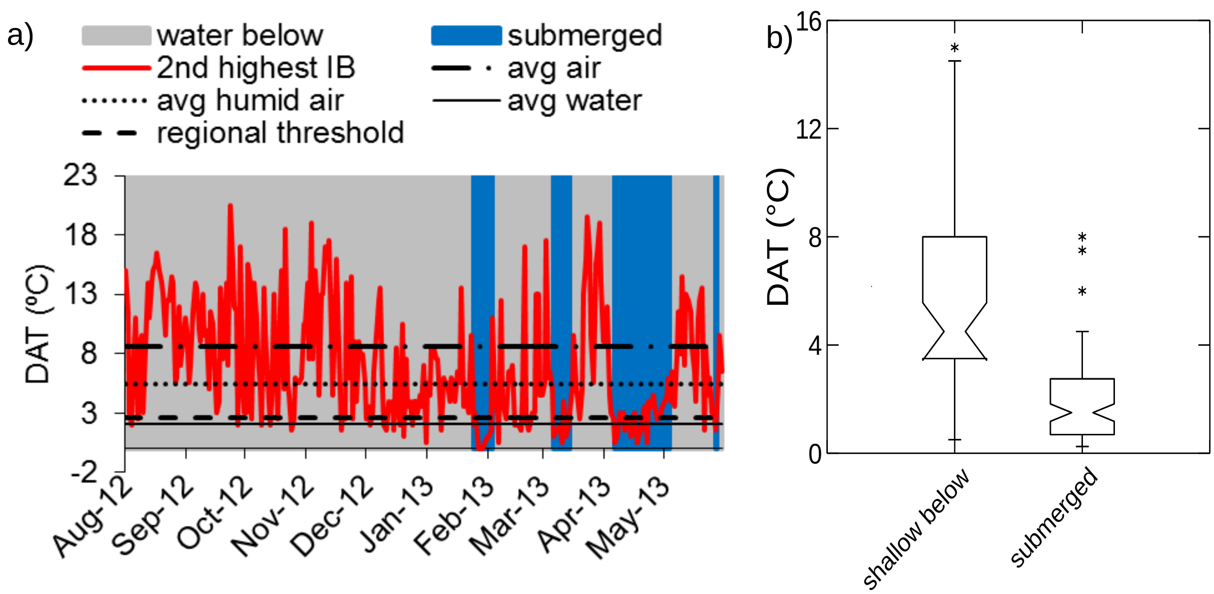

Figure 1.9. DAT of the second highest IB deployed in a humid temperate floodplain (Kalamazoo River, Michigan). See Figure 1.6 for explanation of horizontal lines and vertical shading.

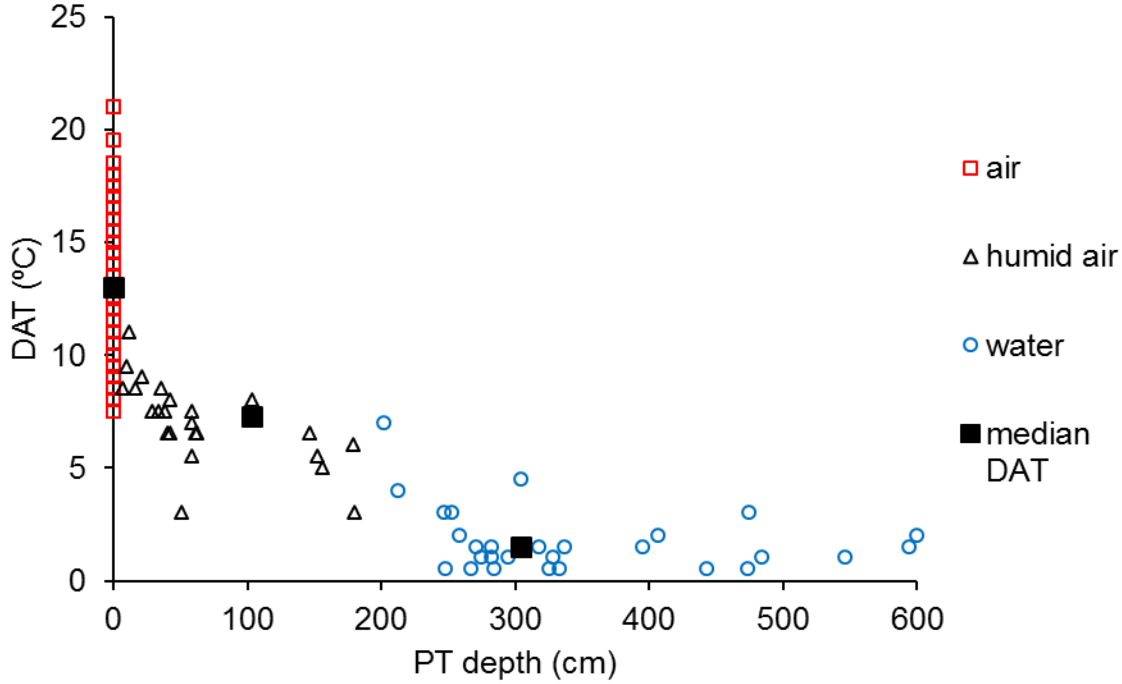

Figure 1.10. Diel amplitudes of temperature (DATs) of second highest iButton deployed in the Rosser Creek site in the Mitchell River watershed, Australia, from 2008-2009 during different hydroperiod conditions compared to water level records of a co-located pressure transducer (PT). Median DATs for each condition—air above dry land (air), air above standing water (humid air), and underwater (water)—are also shown.

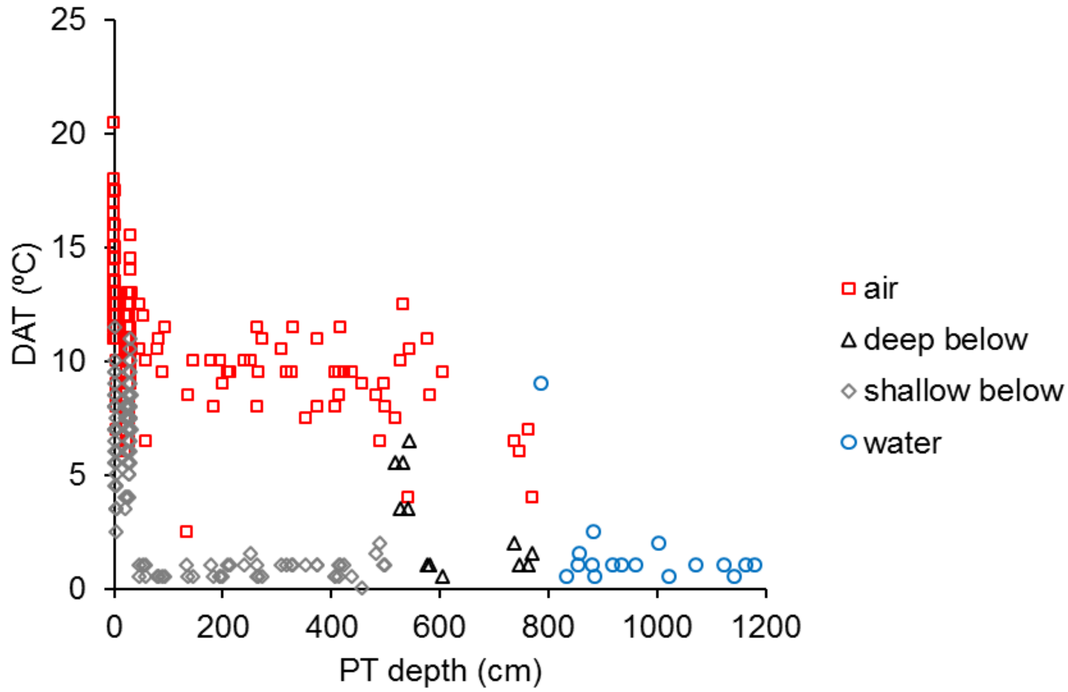

Figure 1.11. Diel amplitudes of temperature (DATs) of second highest iButton deployed in a deeply inundated Alice River site in the Mitchell River watershed, Australia, from 2008-2009 during different hydroperiod conditions compared to water level records of a co-located pressure transducer (PT): underwater (water), air above dry land (air), air above deep water (deep below), and air above shallow water (shallow below).

In contrast to what I observed in the seasonally flooded Australian savannas, the tropical rainforest and the temperate deciduous forest showed much smaller ΔDATs between water and air (Figures 1.12 & 1.13, Table 1.3 – rows A & B). Also temporal variability was lower but increased during flooding, especially in the temperate forest (e.g. Figure 1.8, Table 1.3, rows C-F). DATs in the tropical rainforest forest showed more subtle differences in the vertical profile that increased during flooding (Figure 1.9, Table 1.3).

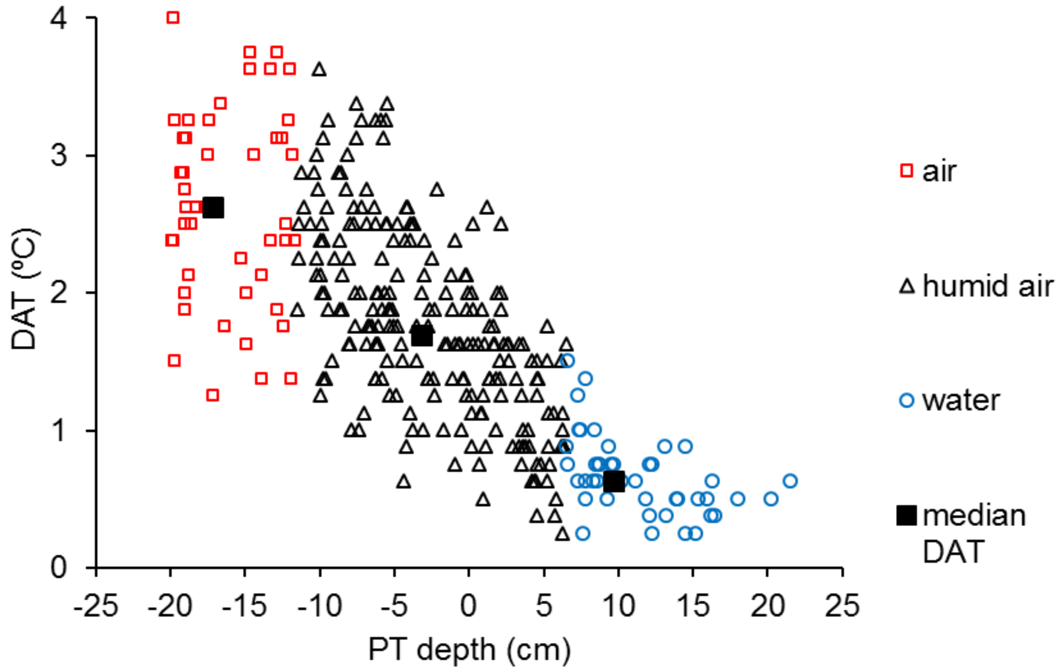

Figure 1.12. Diel amplitudes of temperature (DAT) of the lowermost iButton deployed in the floodplain in a humid tropical forest floodplain (Napo River at Paulacocha, Peruvian Amazon) from 2008-2009 during different hydroperiod conditions compared to water level records of a co-located pressure transducer (PT). Median DATs for each condition: air above dry land (air), air above standing water (humid air), and underwater (water) are also shown. The baseline elevation for the water levels was above the PT elevation.

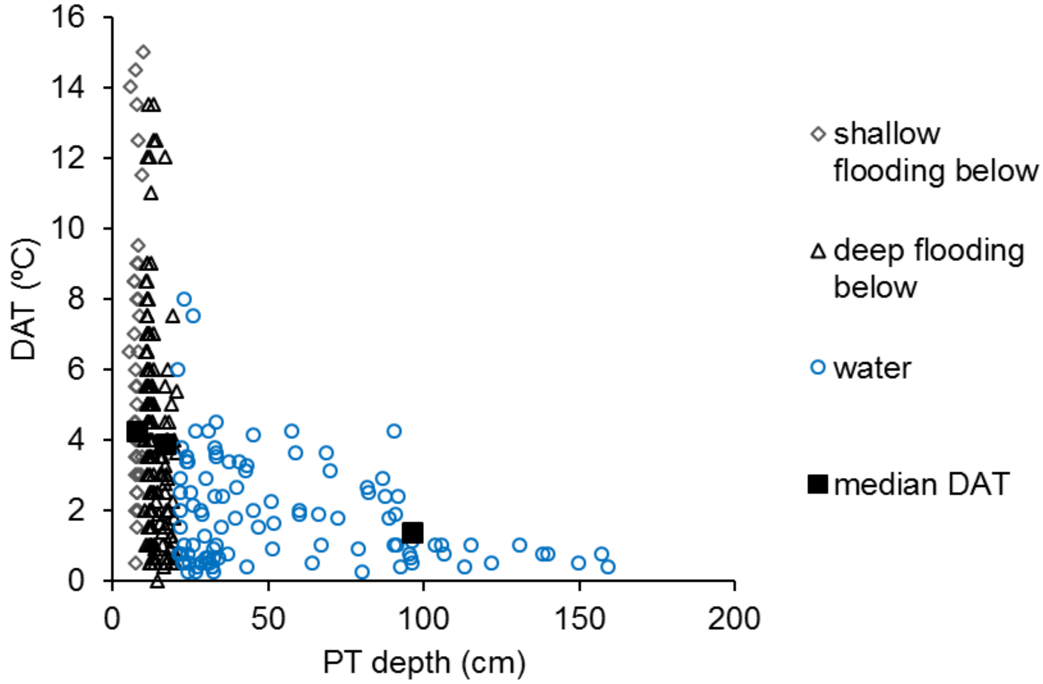

Figure 1.13. Diel amplitudes of temperature (DAT) of the second lowermost iButton deployed in a humid temperate floodplain (Kalamazoo River, Michigan) from 2012-2013 during different hydroperiod conditions compared to water level records of a co-located pressure transducer (PT). Median DATs for each condition: air above shallow or deep flooding, and underwater are also shown.

In general I observed that at a particular site lower DATs were recorded when there was standing water below the sensor, as illustrated by the decrease in the DATs of loggers as the depth of water beneath the IB increased (e.g. Figures 1.10 – 1.13).In the dry tropics and subtropics this pattern was accentuated (Table 1.3 - rows E - G), probably because of the stronger seasonality effects (rows C & D). Overall, seasonality in the DAT in air had a larger effect on DATs higher in the vertical profile in the temperate deciduous forest and closer to the ground in the wet-dry savannas and the humid tropics (Table 1.3, rows C & D). However, a greater depth of inundation reduced the difference between DATs of air and water in all the study regions (Table 1.3, row F), contrary to what happened when the upper logger was emersed (Table 1.3, row G).

Discussion

Overall, I found that temperature could serve as an indicator of inundation in all of the study regions, based on the comparisons to the direct water pressure measurements. The accuracy and applicability of the indirect approach relied on DAT threshold determination. In spite of the effects of temporal and spatial variability, regional thresholds can be applied for inundation assessment, albeit with lower accuracy. The advantage of this approach is that a network of indirect temperature measurements can be deployed across large areas at relatively low cost, installing standard water level loggers at a smaller number of representative calibration sites.

Direct vs. indirect hydroperiod estimations

Individual estimates of inundation using the indirect approaches (site- and sensor-specific) had relatively small discrepancies when compared against pressure transducer measurements. On average, results measured with the sensor-specific threshold were 97% accurate (91% if using the average site threshold), even at different threshold magnitudes and ranges. Unfortunately, this approach was difficult to extrapolate to other sites even in the same region due to the specificity of the thresholds for each height in each location. The choice of a regional threshold gave a 76% confidence level, which in spite of being lower still allows estimation of hydroperiods for a wider range of environments within a particular region and without compromising the utility of the approach.

Effects of spatial and temporal variability of temperature on inundation estimation

Analyses described above support the idea that hydroperiod estimates do not rely on the threshold magnitude but mostly on its range, and that obtaining regional threshold estimates enables the application of the approach over a wider range of sites. However, there are several factors that can influence the accuracy of this approach and that should be considered when using the indirect temperature method for assessing inundation.

One of the main considerations is the temporal variability in the DAT of the air. This can be seen in the average and extreme values, as well as in the range of variability over time. The humid tropical region showed relatively small changes in temperature on a seasonal and diel basis, compared to the tropical/subtropical savannas and temperate deciduous forest that varied much more seasonally as well as over the diel cycle.

In this sense, smaller seasonal variations in DAT simplified the choice of a threshold over time, but when the DATs were too small they made it more difficult to detect whether a sensor was submersed or emersed. This situation happened mostly during the very humid conditions in the Napo sites (e.g. Figure 1.12). Also, in a few occasions I observed larger DATs of sensors underwater that resembled DATs of the overlying air (e.g. Figure 1.11); these cases tended to have shallow inundation depths (potentially combined with some physical properties of the water, like color, turbidity, or stagnancy (e.g. (Houser 2006, Gaiser et al. 2009)). The thermal inertia of a water column is expected to be lower as it becomes shallower, and turbid or colored waters absorb more solar radiation near the water surface, so this result is not unexpected.

In contrast, during episodic inundation events in the Moonie River, large seasonal changes in DAT mimicked flooding when cooling of air temperature did not coincide with inundation

(Figure 1.14). This can be more prevalent in arid zones or temperate zones where DATs of air during the colder months of the year could resemble DATs of water.

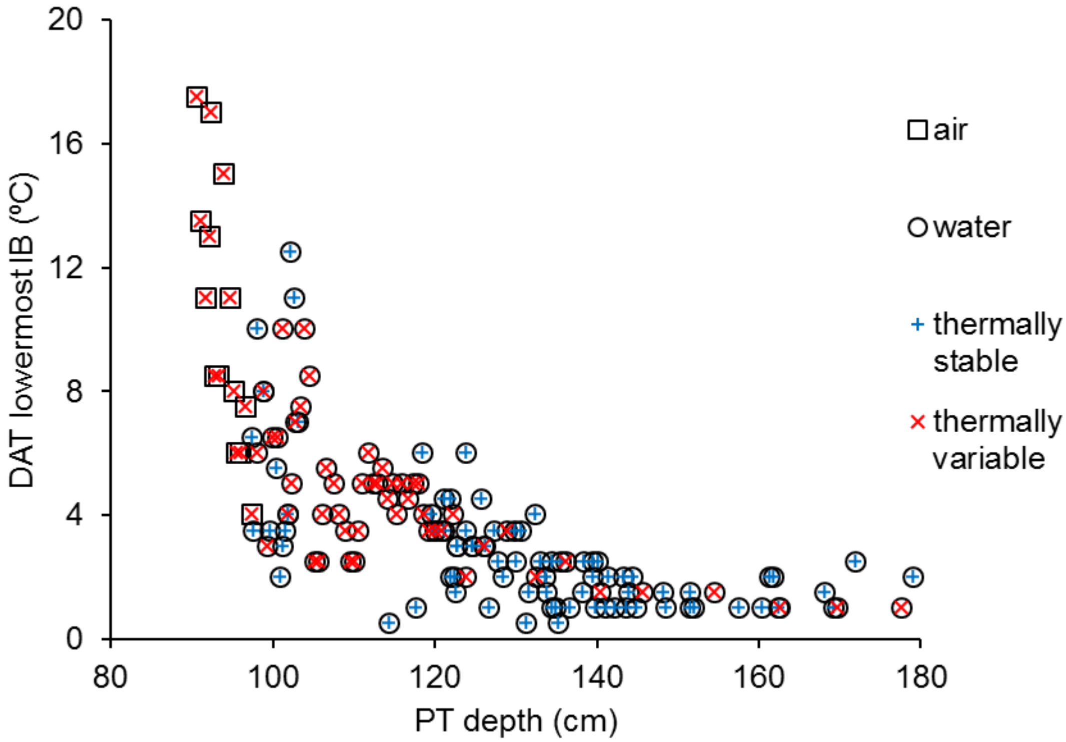

Figure 1.14. Diel amplitudes of temperature (DATs) of the lowermost iButton deployed in the Moonie River, Australia, from 2007-2008 during different hydroperiod conditions compared to water level records of a co-located pressure transducer (PT) (underwater (water), air above dry land (air)), and coded by seasons (thermally stable and thermally variable) based on DAT variability.

Overall, spatial and temporal thermal variability tends to result in either overestimation of inundation hydroperiod in more humid conditions or underestimation in dryer conditions. Thus, there are more chances of inundation overestimation in the humid tropics than in the savannas and deciduous forest, but the opposite can be seen in the latter regions. A relatively similar pattern was found across the vertical profile within sites, which indicates that the air higher above the ground tends to be less humid than closer to it. Also, this pattern can be replicated over time in a single location or region, as chances of overestimating inundation increased when humid conditions prevailed.

Summary and Conclusions

The indirect temperature approach can serve to assess inundation across extensive, remote areas at relatively low cost compared with direct water-level sensing methods. Based on the hydroperiod discrepancies between the direct and the indirect approaches using regional DAT thresholds, the indirect method worked better in the dry and humid tropical floodplains than in the subtropical and temperate ones. However, attention should be paid to the environmental settings where this method is to be applied, and an initial evaluation should be conducted to assess the effects of these conditions on the relative temperatures of air and water, and therefore on the prospect of success in applying this approach in a particular system.

Coincidence of flooding with more thermally stable seasons could lead to overestimation of length of inundation. There was less diel variation in air temperatures during the cooler periods of the year in the temperate floodplain river, and in the densely forested settings of the humid tropical floodplain, particularly in the air overlying deep inundation. A relatively small diel range of air temperature makes inundation more difficult to identify from damping of temperature when sensors go under water. Also, diurnal warming of shallow waters could lessen the differences between air and water temperatures and lead to underestimation of the duration of inundation. Testing this approach in other regions and other environmental conditions could give more insight into these issues, and on the broader applicability of the indirect methods of inundation assessment.

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CHAPTER 2. SOURCES OF FLOOD WATERS IN THE NAPO RIVER FLOODPLAIN (AMAZON BASIN) AS INDICATED BY MAJOR SOLUTE CHEMISTRY

Abstract

Water samples were collected by direct sampling and by using Rising Stage Samplers (RSS) and analyzed for major solute chemistry to assess sources of flood waters in remote floodplains of the Napo River, a major Amazonian tributary in Ecuador and Peru. Evaporative concentration, leaching and water exchange experiments were conducted in the field to test the reliability of the RSS method. Multivariate analyses identified solutes that best indicated sources of flood water sources in the floodplains. The RSSs maintained sample integrity for several months with minimal loss to evaporation (8.6%/year). The optimal combination of solutes for distinguishing sources of flood waters included calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), and silicate. Two main water sources were identified based on these solutes: Andean waters carried by the river and local rainfall and runoff. The proportions of solutes in both end members were similar, although the Andean Rivers carried higher concentrations, especially in the upper reaches. Downstream dilution of river waters by local water inputs indicated the contribution of lowland portions of the catchment to the river water budget and chemistry. Chemistry of flooding waters in the floodplains spans a continuum between these end members with corresponding differences in their flood regimes. This variability in the sources of waters and flood regimes has implications for the ecology of these environments. The approach applied here worked well in this remote and extensive tropical area and could be used to monitor sources of flooding in other regions and environments.

Key words: flooding, tropics, rising stage sampler, solute chemistry

Introduction

Certain major solutes in surface waters display relatively conservative behavior and can be used as natural hydrological tracers of water sources (Hamilton and Lewis 1987, Forsberg et al. 1988, Devol et al. 1995, Lesack and Melack 1995, Harvey et al. 1996, Hamilton et al. 1998, Hamilton et al. 2005, Zhang et al. 2009, Mondal et al. 2010). The major solute composition of waters varies with the geochemistry, hydrology, nutrient availability, and other biogeochemical features of ecosystems. For instance, in the Amazon Basin black water rivers have high dissolved organic carbon concentrations and are relatively poor in ions and nutrients, whereas white water rivers tend to have lower dissolved organic carbon concentrations and higher ion and nutrient concentrations, as well as a higher inorganic suspended sediment load (Richey et al. 1990). Advantages of using major solutes in ecological or environmental studies include their relatively conservative nature, the ability to use more than a single tracer, and lower cost of analysis compared to other potential tracers (e.g., stable isotopes). However, their concentrations can be affected by environmental contamination and evaporative concentration. Some of these issues can be minimized or taken into account in subsequent data analysis.

In floodplains that potentially receive water from multiple sources, major solutes can elucidate the origin of water (e.g., precipitation vs. groundwater vs. riverine overflow) based on distinct geochemistry of the sources (Brown et al. 2006, Williams et al. 2006). Generally, water from precipitation is low in major solutes, and infiltrating water gains solutes from mineral weathering along soil and groundwater flow paths. Mixing models have been used extensively to assess sources of water (and specific contributions of those sources to the water budget) of aquatic systems, and rely on the accurate definition of end members (Hooper 2003, Klein-BenDavid et al. 2005). Direct and extensive water sampling can identify potential end members, although in large and remote areas comprehensive sampling can be complicated and costly. Failure to sample multiple locations across a large area can increase errors due to spatiotemporal variation, and can lead to misinterpretation of the results. Another option is to deploy networks of automated samplers that collect water simultaneously and at a fixed rate (Harmel et al. 2010), but unfortunately the elevated costs of such equipment limits their application.

Alternatives to these sampling approaches include rising stage samplers (RSS), which can be active or passive, with active RSSs most commonly used (Riekerk 1993, Mackay and Taylor 2012). Active RSSs are triggered by specific flooding events and collect water samples on an event basis while passive RSSs collect and integrate water samples over time or during an episodic event like storm flow in streams. Among the benefits of active RSSs are the collection of samples during flood peaks and their utility in remote locations and unmanned conditions (Mackay and Taylor 2012), although they require a power source.

Passive RSSs in contrast are an inexpensive alternative that can be deployed in larger numbers and do not require a power source. These may simply be containers that fill when the water level rises over them and maintain sample integrity after the water level falls, until the water can be collected. A disadvantage of passive RSSs is the more difficult identification of the timing and contributions of each flooding event to the integrated sample because they may potentially be influenced by multiple flooding events.

In this study, I used major solute chemistry of water collected in passive RSSs as well as direct collection ("grab samples") to assess spatiotemporal variation in sources of flood waters in the remote and extensive floodplains of the Napo River, a major Andean tributary of the Amazon River in Ecuador and Peru. Knowledge of the sources of inundation in these poorly studied floodplains is fundamental for hydrological and ecological studies and to be able to predict how river channel modifications such as dredging or damming may affect fringing floodplains and the people who depend on them for food and fiber. Results indicate that certain solutes (e.g., Mg^{2+}, Na^{+}, Cl^{-}) worked better at characterizing end members under some environmental settings in the study area and others (e.g., K^{+}, Ca^{2+}, silicate) were more useful in other environmental conditions. Based on major solute concentrations in the RSS and grab samples, I identified the relative importance of different sources of inundation (Andean river water vs. local rainfall and runoff) across a large range of floodplain settings. These results are consistent with the flood regime of these environments and have implications for their ecology.

Methods

Design of the rising stage samplers

The RSS sampler design consisted of a 51-cm segment of 2.2-cm-diameter chlorinated polyvinyl chloride (CPVC) pipe (3/4" CTS CPVC 4120 Hi Temp, http://www.genovaproducts.com) capped on both ends with CPVC pipe caps. PVC pipe was selected because it could be purchased at low cost, and it would hold up well in field deployments that could include strong currents, floating debris, and investigation by curious animals (e.g., monkeys). Near the top of the pipe I drilled a number of 3 mm (1/8") holes over a 6 cm distance to allow for entry of water, and covered the holes with a wrap of polyethylene window screen held in place with polyethylene cable ties and a plastic rain cover. The samplers held ~100 mL of water after water level fell below the openings. After fabrication the RSSs were leached in a tub of water.

The RSSs were mounted on tree trunks in shaded locations using pipe holders. Generally I installed 3-6 samplers at vertical intervals of 10-100 cm, starting close to the ground and extending close or above the highest record of previous floods according to local guides. The RSSs were deployed together with iButtons to record temperature, which were sealed in polyethylene and stapled to the tree trunks at the level of water entry into the RSS; the temperature record was used to assess timing and magnitude of inundation (Chapter 1).

Leaching test of the samplers

This experiment assessed the likelihood of contamination of water held in RSSs by solutes leached from sampler materials, and therefore showed the best materials for fabrication of RSSs to avoid using solutes as tracers that might be subject to leaching effects. For this purpose, RSSs made from 14 different types of PVC filled with reverse-osmosis (RO) processed water were held in the lab for several days and sampled once to assess patterns in solute leaching over time. A sample of the RO source water was kept in a polyethylene bottle over the same time period. Samples were analyzed for major cations and anions using two coupled Dionex ion chromatographs, both equipped with membrane suppression and conductivity detection. Silicates were measured following a modified version of the colorimetric analysis described by Wetzel and Likens (1991). The detection limits were ~0.02 mg/l for ion chromatography, and ~0.2 mg Si/l for the silicate analysis.

Evaporative concentration test of the samplers

An experiment was conducted to assess evaporative concentration (EC) rates in RSSs in a humid forested lowland area and a drier forested upland area adjacent to the Turkey Marsh pond, located on the Kellogg Biological Station (KBS) grounds in Hickory Corners, Michigan, from July to November 2007. The purpose of this experiment was to assess the effect of different dimensions and locations of RSSs on the EC rates of water held in the samplers. Indirectly, I assessed the effect of outside temperature and humidity on EC rates inside the RSSs by selecting locations close to and far from the wetland, which lies in a depression and is surrounded by dense vegetation, in contrast to the relatively open and drier forest understory.

Two designs of RSSs were deployed for the purpose of revealing EC effects. The design described above and used in the Napo region is denoted here as narrow-long (NL), and was compared to a wide-short (WS) design, deploying sets of both designs in the field during the warm season. The higher surface/volume ratio of the WS samplers would make them much more subject to evaporative concentration of the solution inside, whereas the identical number of water entry holes should make both kinds of RSSs equally prone to air exchange and hence evaporative losses. The RSSs were filled with ~100 ml of a 250 mg/l NaCl solution and deployed in 16 locations, eight near Turkey Marsh pond and eight on oak-hickory forest uphill from the wetland. The NL RSSs were 1.7 cm inner diameter and 51 cm long, and WS RSSs were 3.81 cm inner dia. and 18 cm long. When filled with ~100 mL of water, the surface/volume ratios were 0.023 (NL) and 0.114 (WS), a five-fold difference. All RSSs had 10 small perforations (3 mm each) at 3-6 cm from the top that were covered with a 500-micron polystyrene mesh (SunGuard 90 Solar Screening) and a plastic rain cover. RSSs had rubber plugs on both ends (bottom sealed with caulk) and were affixed to the north sides of trees at 70-80 cm above the ground. Additionally, a control set of RSSs (NL and WS) with tape-covered holes was deployed in the field, and a sample of the original solution was kept in refrigeration in the lab. Subsamples of the solution kept in the RSSs and in the lab were analyzed by ion chromatography.

Water exchange test of the samplers

This test looked at the potential effects of flooding events on water collected in the RSSs during previous events. Solute exchange rates were estimated by filling the RSSs with a known ion solution and then submerging them in RO water. For this purpose, I filled four RSSs with a 50 mg/l NaBr solution and submerged them in RO water for seven days. Water samples from inside the RSSs and from the water in which they were submerged were analyzed using ion chromatography to see how much the solution had been diluted by ion exchange with the relatively ion-free water outside.

Selection of solute tracers to distinguish sources of flood waters

Analysis of water samples from the RSSs is informative only if one has information on the solute chemistry of potential sources of flood waters, as well as which solutes are likely to be conservative and can be used as end members for linear mixing models when concentrations in the samples lie between the concentrations of potential water sources. Solute concentrations in source waters (“end members”) were determined after extensive sampling of the waters of diverse aquatic environments in the study area to identify the solutes that best separated those waters and were sufficiently conservative to maintain the signature of the system over time while on the floodplain and while stored in the RSS. Grab samples of potential water sources (rain-fed swamps, lowland tributaries and lakes, and Andean rivers) were taken at various times of the year from throughout the study region for this purpose.

Principal components analyses (PCA) and non-metric multidimensional scaling (NMDS) were conducted with the software PRIMER-5 to assess the correspondence of grab and RSS samples of selected end members, to identify outliers (Barnett and Lewis 1994), and to identify the solutes that accounted for most of the variability among samples. Also, one- and two-way analyses of similarities (ANOSIM) were conducted using the same software to assess the effects of sample types (grab vs. RSS) and sampling date on the selected end members. These analyses also helped understand the spatial and temporal variability of selected solutes among end-member samples.

Below I present results of the experiments conducted to assess the RSS design, and describe the optimal methods to assess sources of inundation based on solute chemistry in grab samples and in water collected with passive RSSs.

Results

Rising stage sampler leaching

The leaching experiment in the laboratory showed that most of the types of PVC tested leached large amounts of Ca^{2+} (final concentration corrected for source water concentration: 6.09 ± 5.65 mg/l) and SO_4^{2-} (1.34 ± 1.99 mg/l) (Figure 2.1). Concentrations of leached Na^+ and Cl^- were lower (0.35 ± 0.15 and 0.29 ± 0.15 mg/l, respectively), and those of K^+, Mg^{2+} and NO_3^- were negligible, making K^+ and Mg^{2+} better candidates as potential indicators of sources of inundation (NO_3^- is not expected to be conservative). The PVC I chose for construction of the RSSs for this study (3/4" CTS Genova - CPVC 4120 Hi Temp) did not leach nearly as much Ca^{2+} and SO_4^{2-} as the other PVC samples (Figure 2.1).

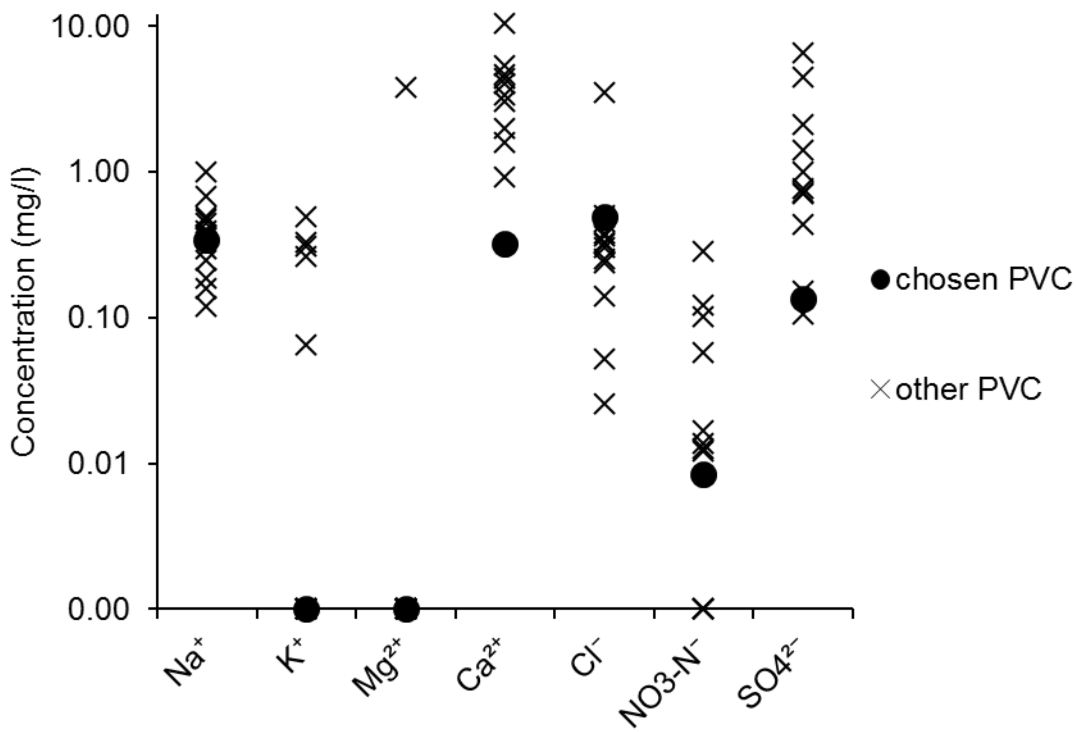


Figure 2.1. Concentration range of major ions leached from 14 different types of PVC pipes. Black circles represent the ion concentrations leached from the PVC chosen to build the RSSs. Note log scale on y-axis.

Rising stage sampler evaporative concentration

In the EC experiment done at KBS, the influence of EC on the concentrations of ions in water stored in the RSSs is expressed as the percentage increase in concentration of Cl^- in water stored in the RSSs that were filled with a NaCl solution of known concentration and deployed outdoors for 114 days. The observed increase in concentration was much greater in the WS RSS design with its fivefold higher surface/volume ratio, indicating that it was due to evaporative water loss (Table 2.1), and in both RSS designs the observed increases were greater than in the control with holes sealed by tape. The average daily EC of Cl^- was ~6 times higher in wider and shorter (WS) RSSs than in narrow and long (NL) RSSs (0.135±0.049% vs. 0.023±0.005%), and in both cases it was also higher in dryer uplands than in the more humid lowlands, especially among the WS RSSs (0.161 vs. 0.094%). If left in a warm climate over an entire year, the mean EC rate observed in the NL design would amount to a loss of 8.6%/year.

Table 2.1. Evaporative concentration (EC) from rising stage samplers in the Michigan pilot study [a]

Location	type of RSS	Cl^- EC% (114 days)	SA (cm^2)	V (cm^3)	SA:V (cm^{-1})	Cl^- EC (mm/day)
Lowland	NL	2.0±0.3	2.27	100	0.023	0.079±0.010
Upland	NL	3.1±0.9	2.27	100	0.023	0.121±0.036
Lowland	WS	11.5±2.3	11.40	100	0.114	0.089±0.017
Upland	WS	19.2±8.9	11.40	100	0.114	0.148±0.067

[a] Average and standard deviation of percent EC as indicated by Cl^- in nine narrow and long (NL) and nine wide and short (WS) RSSs left outdoors for 114 days in a dry upland and a humid lowland location at KBS (total n=36), Michigan (July - November 2007). The surface area (SA), volume (V), surface area to volume ratio (SA:V), and EC rates per millimeter and per day are included.

Rising stage sampler water exchange

I found a net loss of Br^- tracer from the RSSs into the surrounding water. The daily loss rate of Br^- while the RSSs were submerged in RO water for seven days was 3.32 ± 0.96%, indicating that the samplers would exchange solutes with outside water during the period of submergence, but slowly enough that they integrate the chemistry of flood waters over periods of days to weeks. At an exchange rate of 3.32% d^{-1}, the average residence time of water and conservative solutes in the RSS would be 30 days.

Identification of water sources

Two distinct end member solutes were identified in the Napo River region based on the major solute chemistry of river and floodplain waters. These are the rivers that originate in the Andes and the rain-fed swamps that are found in locations distal from the Napo River (Figure 2.2). The Andean waters (especially in the upper river reaches) had higher concentrations of dissolved solutes than the waters of the rain-fed swamps, although proportions of solute concentrations (e.g., Na^{+} and Mg^{2+}) in both environments were relatively similar (Figure 2.3).

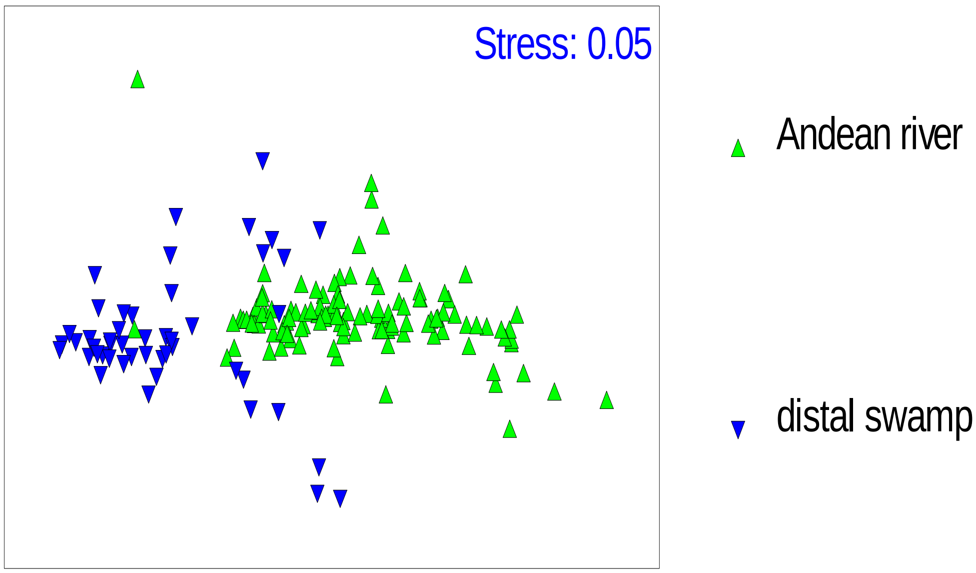


Figure 2.2. Non-metric multidimensional scaling of the solute chemistry of two distinct aquatic environments (end members) found along the lowland Napo River. Scaling is based on the concentrations of five solutes (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and SO_4^{2-}) collected from December 2007 to April 2013 with direct methods (grab samples).

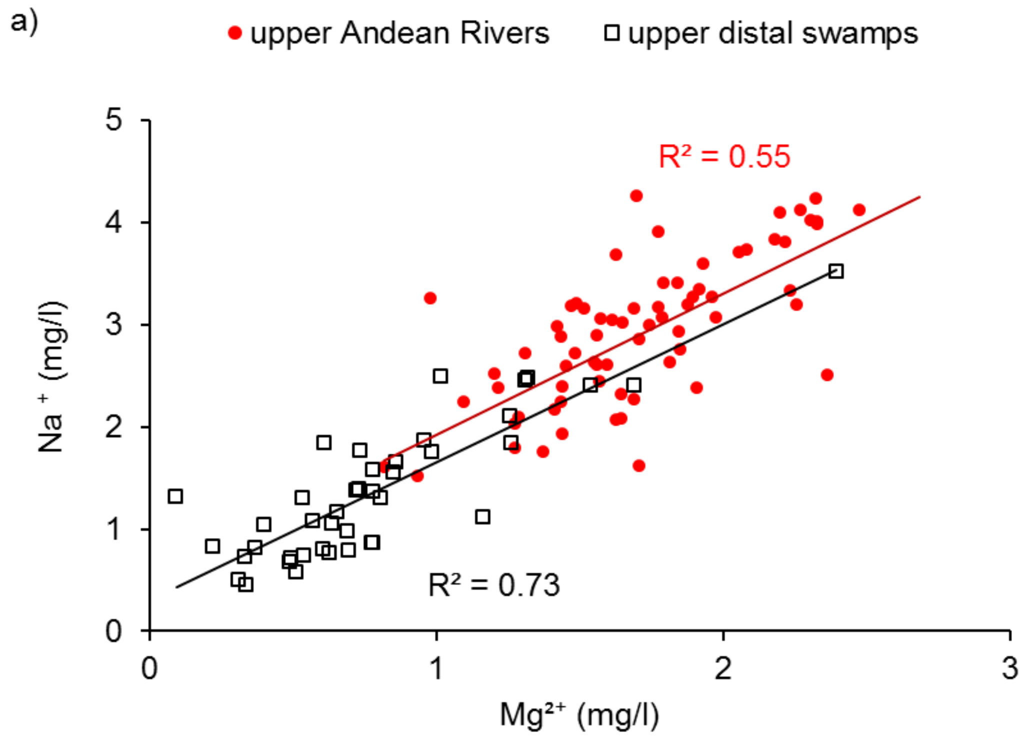
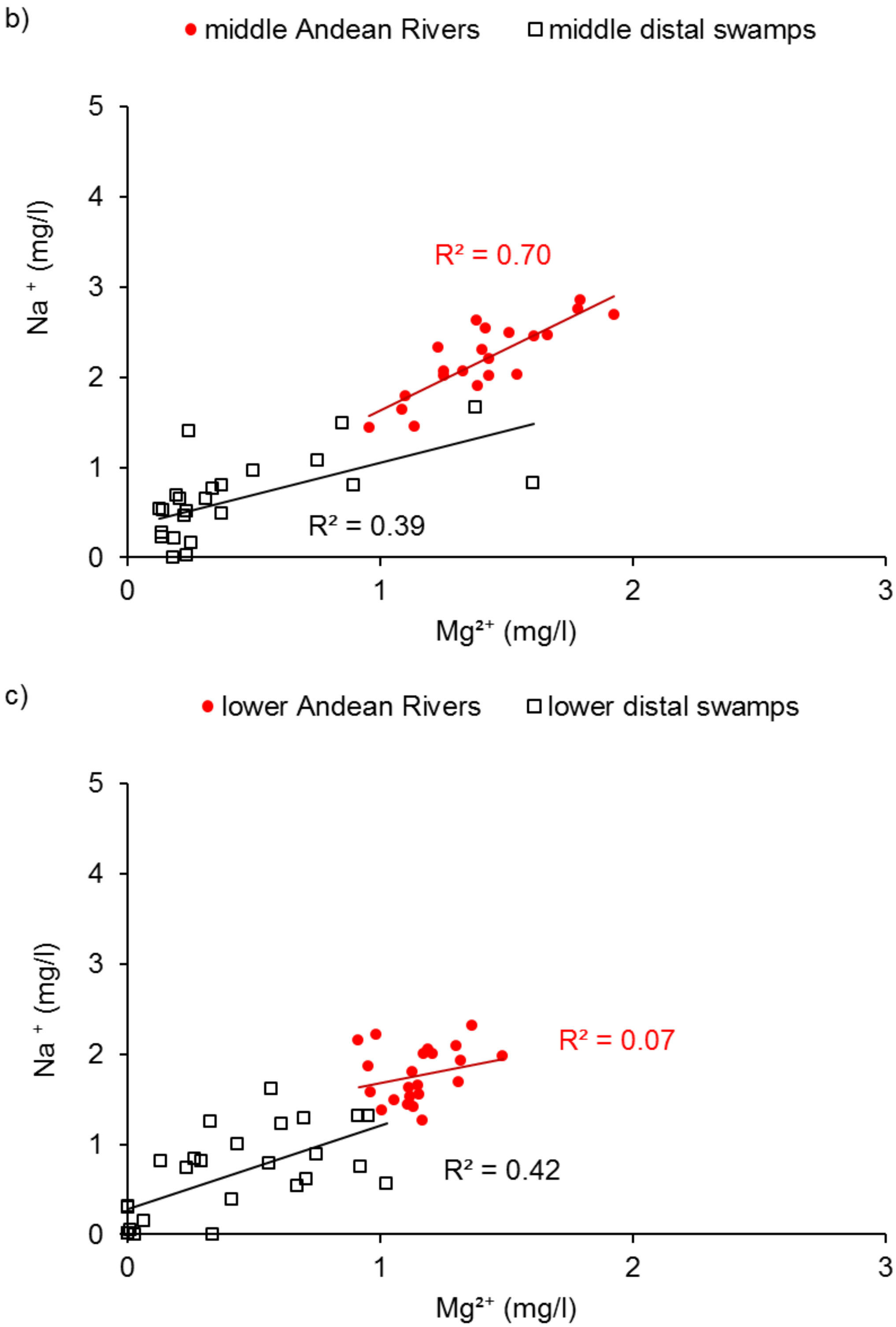


Figure 2.3. Concentrations of Mg^{2+} and Na^{+} in Andean waters and rain-fed swamps (distal swamps) collected from December 2007 to April 2013 with direct and indirect methods (grab and RSS samples), after removing outliers in three sectors of the watershed: upper (a), middle (b), and lower (c). Trend lines are shown separately for rivers and swamps.

Figure 2.3. (cont'd)



Both grab and RSS samples occasionally showed high concentrations of major solutes, extending into the 5-20 mg/L range, for reasons that are unclear. Evaporative concentration cannot always explain the high concentrations because ionic proportions were not congruent with the rest of the samples and the waters were too dilute for mineral precipitation to selectively remove solutes. These high-concentration samples were deemed outliers for the purpose of understanding sources of flood waters.

After removing high-concentration outliers (about 9% of the 1070 measurements) through iterative multivariate analyses (PCA and NMDS), I found that the concentrations of most cations (Ca^{2+}, Mg^{2+}, and Na^+, but not K^+) as well as silicate were highly correlated (r >0.9) in both the Andean rivers and the rain-fed swamps (e.g., Figure 2.3). Correlation coefficients between K^+ and other cations and silica ranged from 0.67 to 0.83. In contrast the anions (Cl^-, NO_3^-, SO_4^{2-}) showed lower to no correlation among each other, with Cl^- and SO_4^{2-} having the highest correlation (r=0.50). Correlation coefficients between anions and cations ranged from 0.2 to 0.8. Results from these analyses showed that the several inter-correlated solutes (e.g. Mg^{2+}, Na^+, silicate) accounted for most of the variability in both the rain-fed swamps and the Andean Rivers (79.3%) (Figure 2.4); silicate was more important in explaining variability in the rain-fed swamps and Ca^{2+} in the Andean rivers (Figure 2.5). Overall, 86.5 % of the variability was explained by a combination of solutes, including SO_4^{2-} and K^+. Three other similar anion-cation mixed components explained the remaining 14% of the variance among samples. In general, SO_4^{2-} did not show a very distinct pattern among environments, and after removing it subsequent analyses increased the variability explained mostly by cations (Figure 2.6).

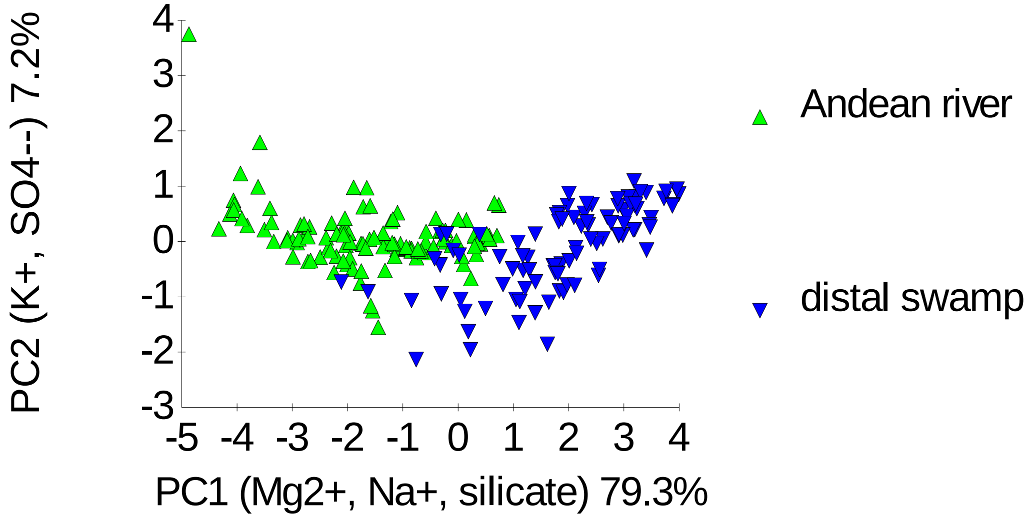


Figure 2.4. Eighty six percent of the variability among water samples in the two clusters that represent the two main end-member environments (Andean rivers and the distal swamps) is explained by two principal components defined by several solutes. The PCA was conducted after removing outliers.

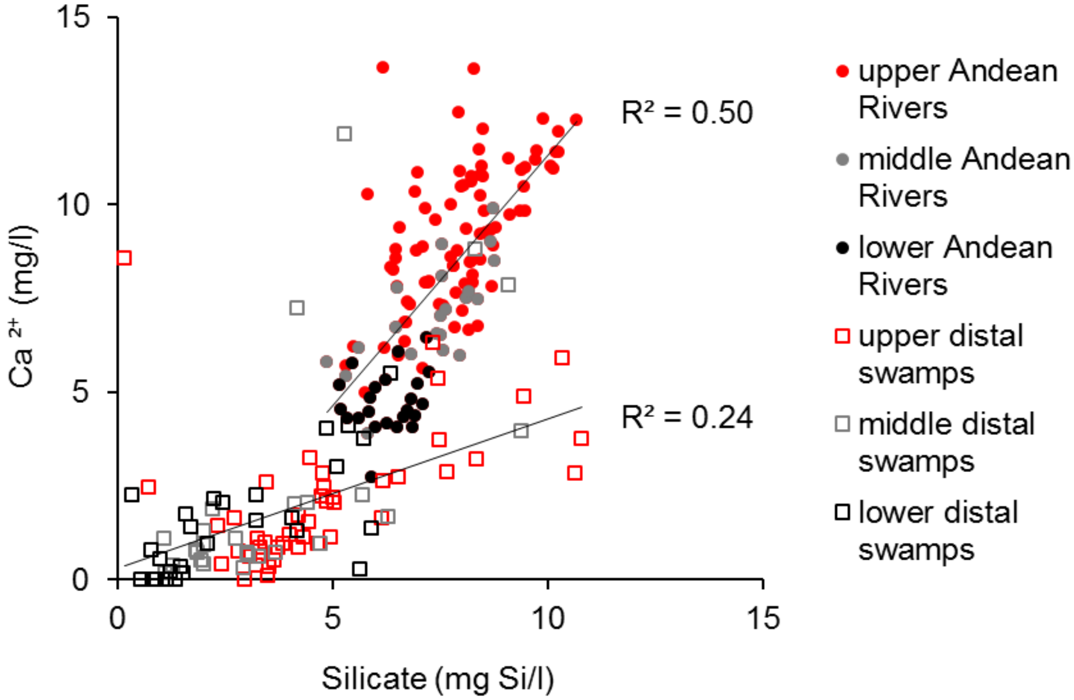


Figure 2.5. Concentrations of silicate and Ca^{2+} in Andean waters and rain-fed swamps (distal swamps) collected from December 2007 to April 2013 by either grab sampling or RSS samplers, after removing outliers in three reaches of the lowland Napo River: upper (a), middle (b), and lower (c). Trend lines are shown separately for rivers and swamps.

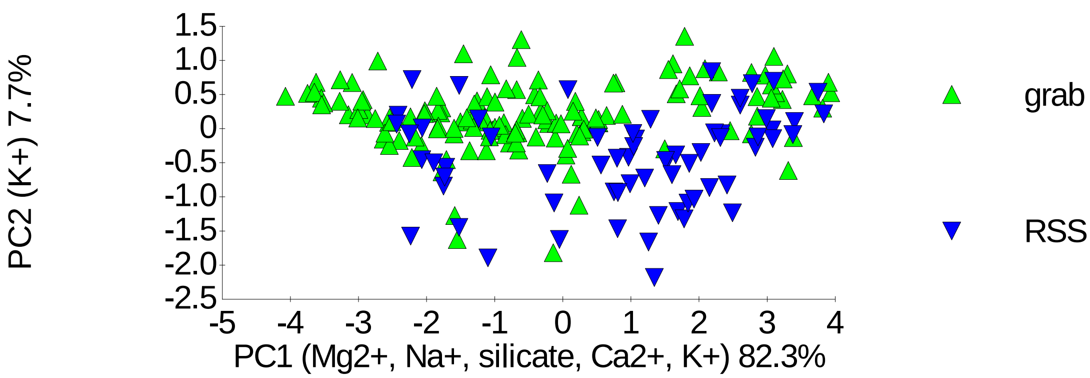


Figure 2.6. PCA of solute chemistry of Andean Rivers and distal swamps by sample type. PC1 and PC2 explain 90% of the variability among samples. PCA was conducted after removing outliers and one of the solute variables (SO_4^{2-}).

Independent of how well different solutes explained the variability among samples, a one-way multivariate analysis of similarities (ANOSIM) showed that the two end members (Andean Rivers and rain-fed swamps) were significantly different in their ion concentrations ($R=0.64$, p-value=0.001).This analysis also showed that samples were significantly different by sample type (grab sample vs. RSS) and sampling date ($R=0.20$ and $R=0.24$, p-value=0.001, respectively) although differences were smaller than those between environments.

Example applications of water source identification

The approach applied above allows estimation of whether standing waters on the floodplains originated as river water vs. local rain/runoff or some mixture of the two. For instance, in the floodplains and river reaches between the Pañayacu and Aguarico Rivers (in the lowland reaches of the Napo River in the Ecuadorian Amazon), the relationship between Mg^{2+} and Na^{+} clearly showed a continuum of sources of inundation, including distal swamps dominated by local runoff of rain-fed swamps and rivers (sometimes perched), proximal swamps and lakes fed by a mixture of rain/runoff and Napo River waters (Andean waters), and streams and tie channels (highly connected to the Napo) that during some times of the year carry mostly river water (Figure 2.7).

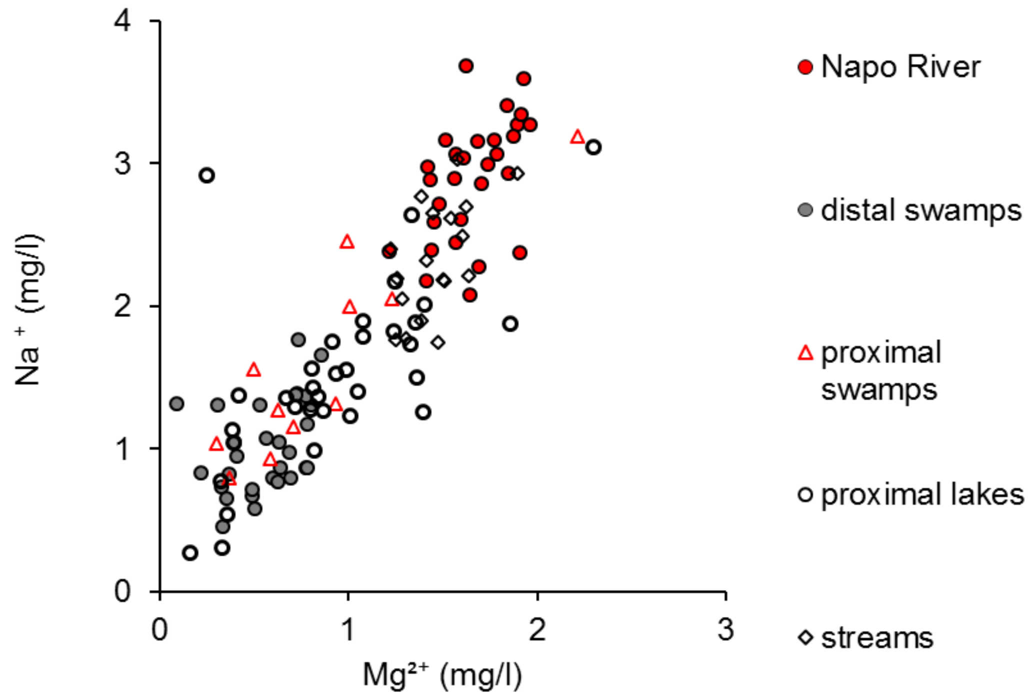


Figure 2.7. Mg^{2+} and Na^{+} concentrations of end member systems and other environments along the Napo River reach between the Pañayacu and the Aguarico Rivers in the Ecuadorian Amazon, from grab and RSS samples collected from December 2007 to April 2013. Streams also include tie channels that connect the river with floodplain basins.

Similarly, in spite of the more ionically dilute waters of the Napo River further downstream in the Peruvian reach, the relationship between Mg^{2+} and Na^{+} was also indicative of flooding of different environments by different water sources (Figure 2.8). For instance, most of the proximal swamps and streams were influenced by rain water and local runoff from rain-fed swamps, and few seemed to be influenced by river waters. The chemistry of proximal lakes fell in between that of rain and river waters, although other processes might have influenced their ion concentrations (e.g. ground water exchange, precipitation, etc.) as suggested by greater variation in the ratio of the Na^{+} to Mg^{2+} (Figure 2.8).

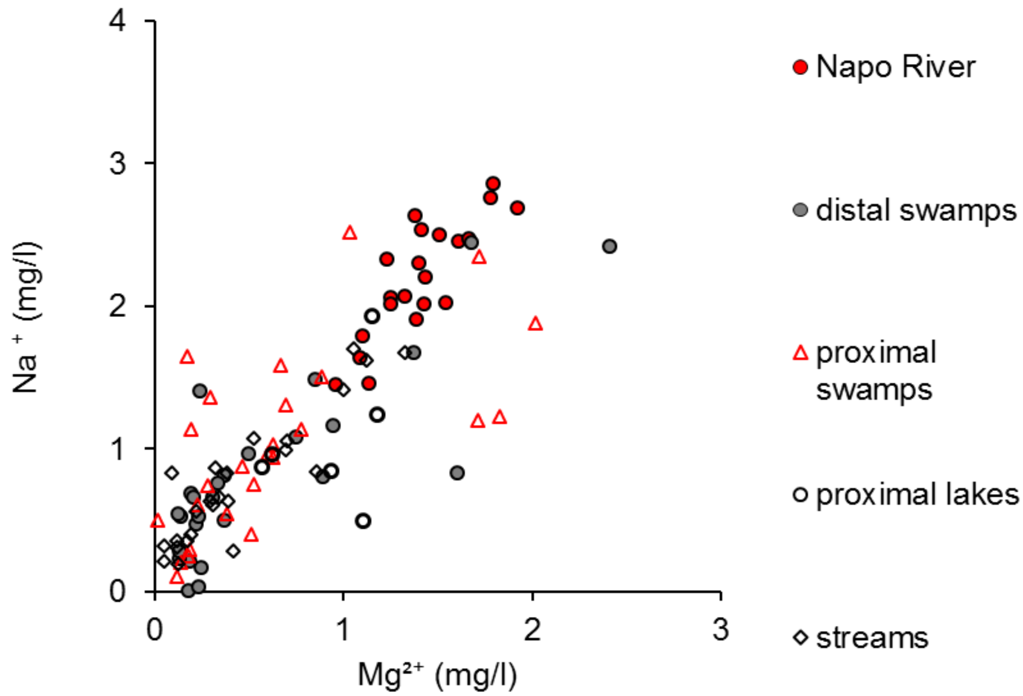


Figure 2.8. Mg^{2+} and Na^{+} concentrations of end member systems and other environments along the Napo River reach between the Aguarico and the Curaray Rivers in the Peruvian Amazon, from grab and RSS samples collected from December 2008 to April 2013 Streams also include tie channels that connect the river with floodplain basins.

Discussion

In this study I have shown how major solute concentrations in RSS and grab samples can identify the major sources of flood waters in the Napo River floodplains. Our analysis showed that the chemistry of samples collected by grab sampling vs. RSS methods was comparable, and that concentrations of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and silicate separated Andean river water from local rain and runoff in the lowland plains, the two main sources of flood waters in these environments. Results also suggested that special attention is necessary to the design of the RSS including the materials used for the sample storage vessel to minimize alteration of the samples through EC and leaching of contaminants. The multivariate analyses helped discern which solutes were most effective in the identification of sources of flood waters in the Napo River floodplains.

The solutes that best separated water sources in the Napo River floodplains are expected to be conservative. Magnesium is typically conservative in ionically dilute fresh waters (Stauffer 1985). Calcium is subject to precipitation as carbonate minerals, but these waters are too ionically dilute and acidic for carbonate precipitation. Silicate is a macronutrient for diatom algae and some higher plants, but Figure 2.5 shows little evidence of selective loss of silicate relative to Ca^{2+} in river or floodplain waters. In other ecosystems, however, such processes would have to be considered in the choice of hydrological tracers. Chloride is commonly chosen as a conservative tracer but its concentrations are generally very low in waters of the region, and the PVC material I chose for the RSS construction leached some Cl^-.

RSS samplers

The experiments conducted in this study showed that with the optimal RSS design and materials (low-leaching PVC, narrow-long design) and characterization of end members, selected solutes can be used to assess sources of flood waters in the Napo River floodplains.

PVC contains additives, including elements (e.g. Ca^{2+}, Cl^-) that are added to enhance physical properties of the plastic. In spite of that, companies often do not disclose their chemical formulas. The leaching experiment I conducted suggested that some types of PVC should be avoided because they leach solutes, whereas others released very small (in some cases negligible) amounts of certain ions (e.g., K^+ and Mg^{2+}), making them suitable for RSS construction. Thus I recommend that initial experiments be conducted to verify that selected materials do not leach analytes of interest. Another alternative would be the use of other plastics with lower leaching, but they would have to be as strong and durable as PVC, or shielded from animals, and they are likely to be more expensive.

The EC experiment showed that the narrow and long (NL) RSS design minimized the loss of the water samples held in the RSSs to evaporation and that evaporative losses over time has only a modest effect on concentrations if the samples are not left in the field for an inordinate amount of time. This is particularly important as in some cases EC could make samples resemble those of more concentrated end members, especially in a case like the Napo River floodplains, where proportions of the solutes are similar in the different end members and concentration is the most distinctive characteristic of end members.

Evaporative concentration could cause significant increases in major solute concentrations over time in standing waters of the floodplains, potentially bringing the concentrations of major solutes from the precipitation range into the Andean river range. However, in the Napo region EC appears not to have a large effect on the concentrations of the solutes measured, probably because the mean annual precipitation exceeds the potential evapotranspiration and the weak wet-dry seasonality of the region (Shuttleworth 1988, da Rocha et al. 2009). Also, the fact that the most distal, isolated swamps do not overlap in major solute concentrations with the Napo River, and that I did not observe significantly higher solute concentrations in the dry-season samples compared to the wet-season ones (Figure 2.9), suggest that EC from standing waters does not increase major solute concentrations enough to confound our interpretation of the end-member mixing model.

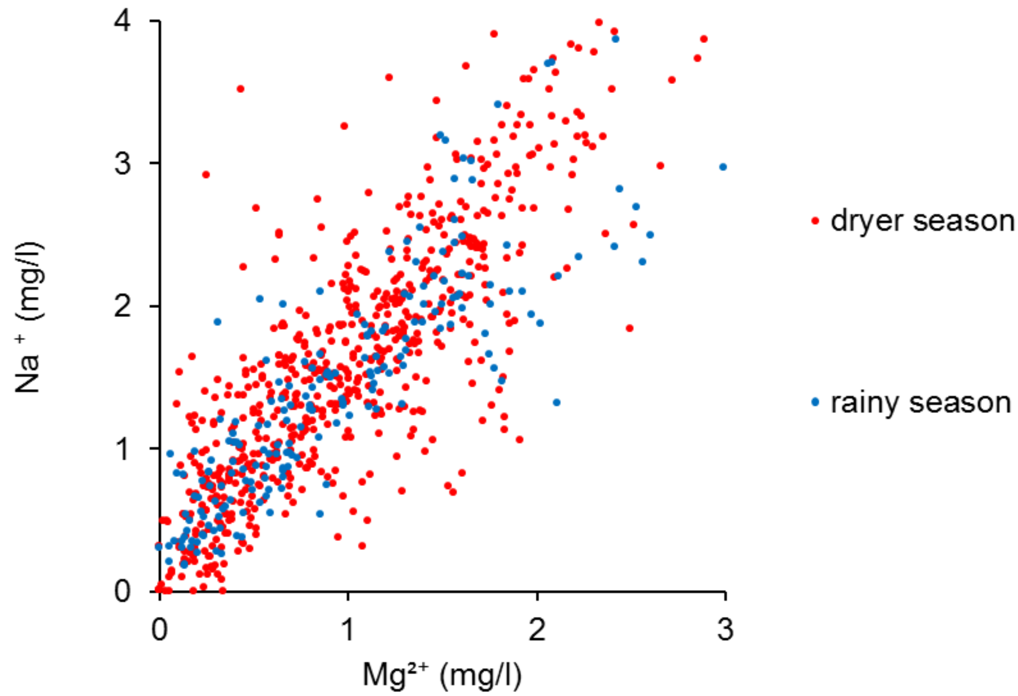


Figure 2.9. Mg^{2+} and Na^+ concentrations of grab and RSS samples collected along the lowland Napo River and its associated ecosystems during the rainy season (June 2010) and relatively dryer seasons (December- 2007-10, March 2008, September 2008, October 2009, March-April 13).

In one of our study areas, I found that a combination of cations (e.g., Mg^{2+} vs. K^+, or Mg^{2+} vs. Na^+) characterized end members effectively, although if EC were to cause the more dilute end member to approach the more concentrated one, one would need to seek combinations of ions that enhance differences in proportions (e.g. Ca^{2+} vs. silicate), as Ca^{2+} was more abundant in river waters than in the floodplains and silicate was prevalent in the floodplains (Figure 2.5).

The location and placement of RSSs had an effect on the EC rate in the samplers. As expected, in Michigan proximity to more humid conditions lowered the EC rates, as seen in the lowland sites in comparison with the drier upland sites (Table 2.1). If sample storage times have to be long (months), accounting for this variability when doing comparisons among RSSs placed in the same location could assist in discerning effects of EC on samples. Also, comparisons could be made among RSSs placed in similar conditions (e.g. height, date and environment).

Other aspects that can influence ion concentrations in RSSs include contamination caused by insects that enter the samplers (ants were sometimes found in the samplers, <3% of the time) and the duration and frequency of the actual flooding events. In the first case, evidence is often obvious (very high ionic concentrations) and such samples can be considered outliers in subsequent data analysis. As for the problem of long-lasting or multiple flood events, it could make it more difficult to discern among sources of flooding when samples from the concentrated end member (e.g. river water) collected in the RSSs are diluted by longer flooding events from the less concentrated end member (e.g. rain).

Conclusions

Major solute concentrations in standing waters of the Napo River floodplain serve to indicate water sources (Andean river water vs. local precipitation and runoff). The best resolution was obtained with Ca^{2+} and Mg^{2+} although Na^{+} and silicate were also indicative. Collection of samples using RSSs was effective for assessing sources of flood waters in large and remote areas. Special attention is needed in the design of RSSs and selection of solutes to minimize evaporative concentration and contamination by leaching from the plastic. Selection of solutes for use as hydrological tracers should be based on their expected conservative behavior given the geochemistry of the waters, and after examination of their concentrations and ratios to choose solutes that distinctly separate end members. Multivariate analysis, including PCA, NMDS, and analysis of variance, can help identify outliers, factor effects, and/or unusual water chemistry of samples, thus facilitating the analysis of data when dealing with large spatial and temporal variability characteristic of extensive floodplains.

In the Napo River floodplains this approach helped us identify two main sources of flooding (Andean Rivers and local precipitation/runoff) and the degree of influence of these end member sources on floodplain inundation as well as downstream changes in the actual river as it increasingly receives local water inputs.

Acknowledgments

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CHAPTER 3. THE HYDROLOGICAL REGIMES OF THE NAPO RIVER FLOODPLAINS, ANDEAN AMAZON

Abstract

Floodplains along the Napo River, one the main Andean tributaries in the Western Amazon, have variable and unpredictable flood regimes compared to those of the well-studied Central Amazon. The river is fringed by diverse fluvial and lacustrine ecosystems, many of which are seasonally connected to the main stem of the Napo River, that provide important ecosystem services to the local inhabitants and lie in one of the most biologically diverse regions on Earth. Little is known about the distribution of floodplains and their hydrological relationship with the river, yet such knowledge is needed as the river corridor faces increasing development pressure including oil extraction, hydropower development, and industrial barge transportation. From 2007 to 2013 I studied the variability in the main components of the flood regime (magnitude, duration, frequency, and flashiness) across more than 100 sites using data loggers that continually recorded water levels and rising stage samplers that collected flood water for major solute analysis to assess sources of water in the floodplains. I found a continuum of flood regimes ranging from deep and long-lasting flooding to shallow and short flooding with widely varying degrees of riverine influence. Also I found significant differences in depth of inundation among the three main reaches of the lowland Napo, with longer and deeper inundation in the uppermost reach. Seventy five percent of the floodplain study sites were directly influenced by Andean river waters (to different degrees), and approximately one fifth were only controlled by the river. Approximately 25% of the floodplains had flooding that was directly controlled only by local runoff or rainfall, although some were indirectly influenced by backwater effects caused by the rising river levels. In addition floodplains proximal (within ~1 km) to the river were significantly different than distal floodplains in terms of the depth and duration of inundation. These diverse ecohydrological patterns seem to be closely connected to the active geomorphological dynamics of the Western Amazon. In contrast to the Central Amazon, the variable flood regimes of the Napo River floodplains preclude life history adaptations of organisms to long and predictable flooding and may favor species that can tolerate flashier inundation regimes that act more as stresses than subsidies for much of the biota. This study provides fundamental information on the ecohydrology of floodplain ecosystems of the Western Amazon that is vital to protect and manage these ecosystems and maintain the ecosystem services that they provide to people.

Key words: Napo River floodplains, Western Amazon, diverse flood regimes, ecohydrology

Introduction

Tropical floodplains play major roles in the water, energy and elemental cycles of the world (Hamilton 2009). In many cases, especially in large river systems, they cover extensive areas, are very diverse, and have complex temporal and spatial dynamics. Through intricate hydraulic/hydrologic interactions with rivers, streams, and other aquatic systems they control water storage and discharge (Mertes 2002, Alsdorf et al. 2007b). Further, they act as complex biogeochemical processors that modify the cycles of elements and gases, and influence global and local climates (Prigent et al. 2007). They are very productive environments that support high aquatic and terrestrial diversity, including threatened species (Revenga and Mock 2000), and sustain important fisheries for local and regional inhabitants (Welcomme 2011).

Among the principal ecological drivers of floodplain ecosystems are the seasonality of rainfall and flooding and the resultant variability of inundation area and water levels (Davies et al. 2008). In South America, these hydrological controls vary depending on river size, location of floodplains, and sources of water (Junk 1997, Hamilton et al. 2002, Hamilton et al. 2007). The largest tropical floodplains cover approximately 20% of the lowlands of the continent, and despite their varied climatic and geological conditions in general they have monomodal hydrologic regimes (Junk 1997, Hamilton et al. 2002). Most environmental research has been conducted on these floodplains along the largest rivers, with relatively few studies examining floodplains associated with medium and small river systems.

Floodplains fringing the largest rivers in South America, including the Amazon, Orinoco and Paraná, usually have large water level amplitudes (Irion et al. 1997, Junk 1999, Lewis et al. 2000, Hamilton et al. 2002), while floodplains in large fluvial depressions or poorly drained areas in the continent (e.g., Pantanal, Llanos de Moxos, Llanos del Orinoco, Bananal, Roraima) have smaller amplitudes (Junk 1999, Hamilton 2002). Another common feature of these floodplains is the predictability of floods that has allowed the adaptation of organisms to pulses of inundation that create seasonal oscillations between terrestrial and aquatic phases (Junk et al. 1989). This flooding pattern has a large impact on the structure and functioning of floodplain ecosystems and on the seasonal development of extensive lentic habitats that support high primary productivity (e.g. ~10,000 mg C m^{-2} d^{-1} in lakes of Central Amazon floodplains) (Davies et al. 2008) and large animal populations (Junk and da Silva 1997).

Floodplains of relatively smaller rivers in the continent (or of large rivers with a higher longitudinal elevation gradient), such as those found in the Western Amazon, have polymodal and less predictable hydrological regimes compared to regimes of larger floodplains (i.e., the

Central Amazon) (Junk 1997). Studies conducted in the Peruvian Amazon have shown that the prevalence of very dynamic geomorphic processes, caused by variable hydrological conditions, determine high rates of habitat change and community succession (Salo et al. 1986, Kalliola et al. 1991, Puhakka et al. 1992, Hamilton et al. 2007). Particularly important in these floodplains are the intense erosional and sedimentary processes and the large spatial variability in water level fluctuations that considerably affect landscape patterns (Puhakka et al. 1992) and that could account for the very high levels of biodiversity of the Western Amazon (Puhakka et al. 1992, Toivonen et al. 2007, Hoorn et al. 2010).

The Napo River Basin, one the main Andean tributaries in the Western Amazon, has variable and unpredictable discharge compared to the Central Amazon, and is fringed by diverse fluvial and lacustrine ecosystems, many of which are associated with the main stem of the Napo River (Steinitz-Kannan et al. 1983, Celi 2005). The relationship between the river and its floodplains had not been studied until the current work, and we did not know the extent and diversity of these ecosystems across the region. Remote-sensing and ground-based research conducted in a somewhat similar region in southern Peru drained by the Madre de Dios River suggested that there is an ecological continuum from river-fed floodplains to more distal wetlands supplied by local rain and runoff (Hamilton et al. 2007). Nonetheless, our understanding of the main components of their hydrological regimes, sensu Poff *et al.* (1997), has been insufficient, in spite of their importance for the ecology of the region and the diverse biological and human systems that they sustain (Galacatos et al. 2004, WWF 2006). Also, the Western Amazon is developing rapidly with potentially serious consequences to the maintenance of its biodiversity and ecosystem services (Celi 2005, Finer and Jenkins 2012, Castello et al. 2013).

Most of what we knew about the hydrology of the lowland Napo River system comes from a few gauging stations on the main river, established only in the last two decades, as well as a few field measurement campaigns conducted along the length of the river (Laraque et al. 2009a). The hydrology and ecology of the floodplains has hardly been studied, and because of the tall and dense forest cover, presently available elevation data for the floodplains are insufficient to determine their potential connectivity with the river. In this context, the purpose of this study was to identify the hydrological regimes of aquatic environments across the floodplains of the Napo River, and assess to what extent the river controls their ecohydrology. The ultimate goal was to improve our understanding of the diversity, extent, and functioning of floodplains in the region and provide recommendations to improve their conservation and management.

I applied a combination of approaches to measure magnitude, duration, flashiness, and sources of flooding in more than 100 locations for up to five consecutive years in some of the study sites. I found a continuum of hydrological regimes along the Napo River floodplains that are linked to the river hydrology to different degrees. Overall, flooding in environments that are proximal to or that have high hydrological connectivity with the river via permanent channels is river-controlled whereas in systems that are distal or that have less or no connectivity with the river flooding is more likely to be controlled by rainfall and local runoff. This research provides insight into the extent and diversity of aquatic habitats of the Napo River, the role that the river has in controlling or influencing their hydrology, and the ecological implications of natural spatiotemporal variation in hydrological regimes. This information is fundamental to evaluate the potential environmental effects of development scenarios that could modify river hydrology, as for example to promote commercial navigation or to generate hydroelectricity, and to inform conservation and management of biodiversity in the region.

Study area

The Napo River Basin drains 100,520 km^2 of largely pristine and hyper-diverse ecosystems of the equatorial Andean Amazon region. Thirty percent of the basin lies at altitudes between approximately 200 and 6000 m.a.s.l. and encompasses a large array of high gradient/slope aquatic and terrestrial ecosystems in the eastern Andes of northern Ecuador and southern Colombia. The remainder of the basin drains diverse lowland rainforests in eastern Ecuador and northeastern Peru until its confluence with the mainstem of the Amazon River around 100 m.a.s.l. (Figure 3.1). At its confluence the Napo River has a mean annual discharge of 6300 m^3/s and contributes 6% of the sediment load of the Amazon River (Laraque et al. 2009b).

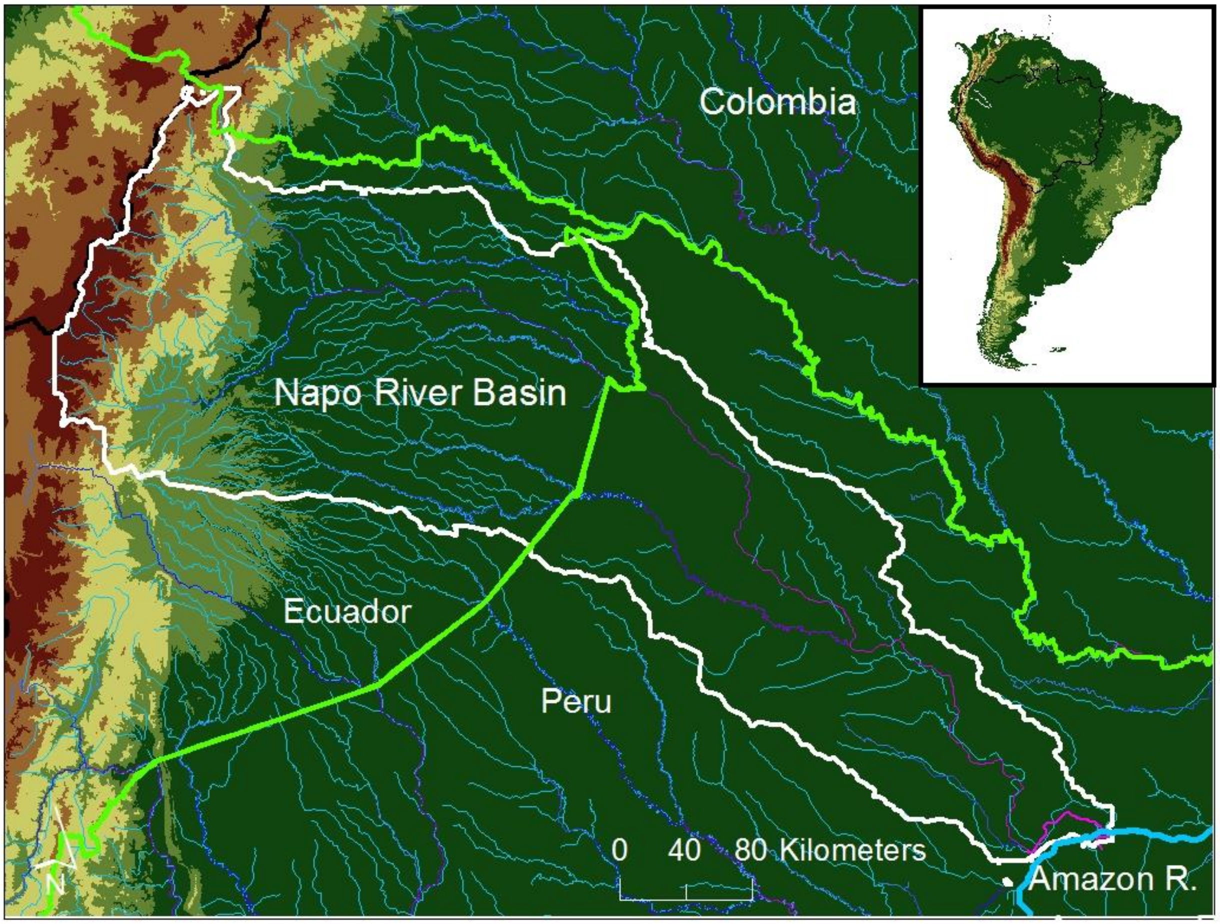


Figure 3.1. The Napo River Basin, Western Amazon. The watershed boundary is shown by the white line and country borders by the green lines.

Water levels fluctuate ~3-5m in the upstream reaches of the lowland Napo River, and up to 10 m closer to its mouth (Figure 3.2), and average river channel depth varies from 0.9 to 2.4 m from upstream to downstream (Serman and CSI 2010). Water level fluctuation is flashy and unpredictable and is mostly linked to precipitation in the highlands, with more frequent occurrence of flooding events during the rainy season from April to July in the western part of the basin (Figures 3.2a and 3.3). Precipitation and river water levels are partially decoupled because the easternmost part of the basin has a more southern hemisphere-dominated climate, where the rainy season occurs from November to February (Figures 3.2b and 3.3). Mean monthly precipitation and air temperatures range from 150 to 350 mm and 24 to 27 ºC, respectively (Figure 3.4).

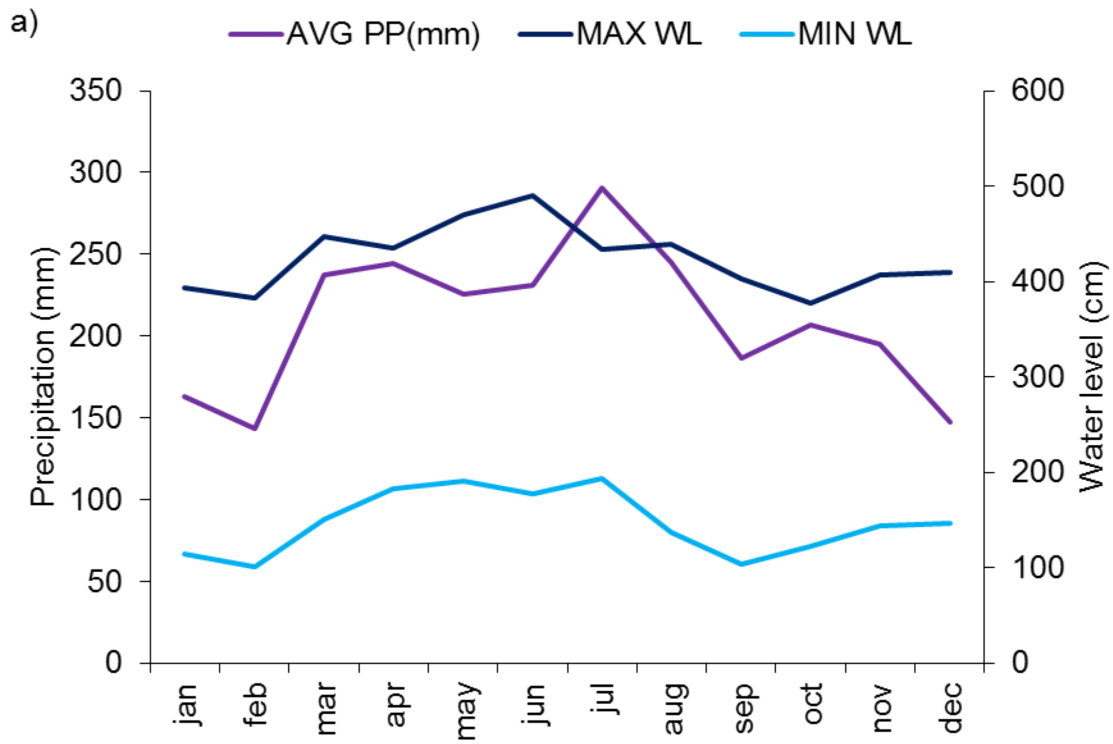
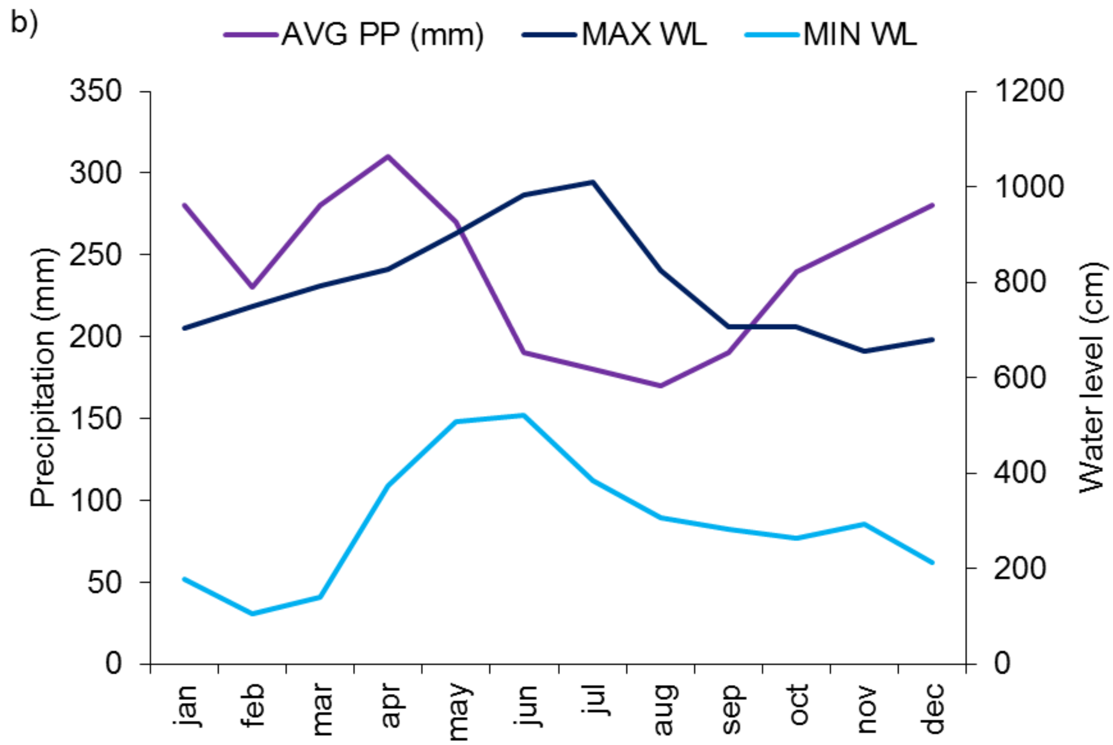


Figure 3.2. Mean monthly maximum and minimum water levels of the Napo River and precipitation in a) the upstream river reach (Nuevo Rocafuerte, Ecuador, years 2001-2011) and b) the downstream river reach (Bellavista, Peru, years 1988-2009). Data from INAMHI – Ecuador and SENAMHI – Peru, HIBAM Project.

Figure 3.2. (cont'd)



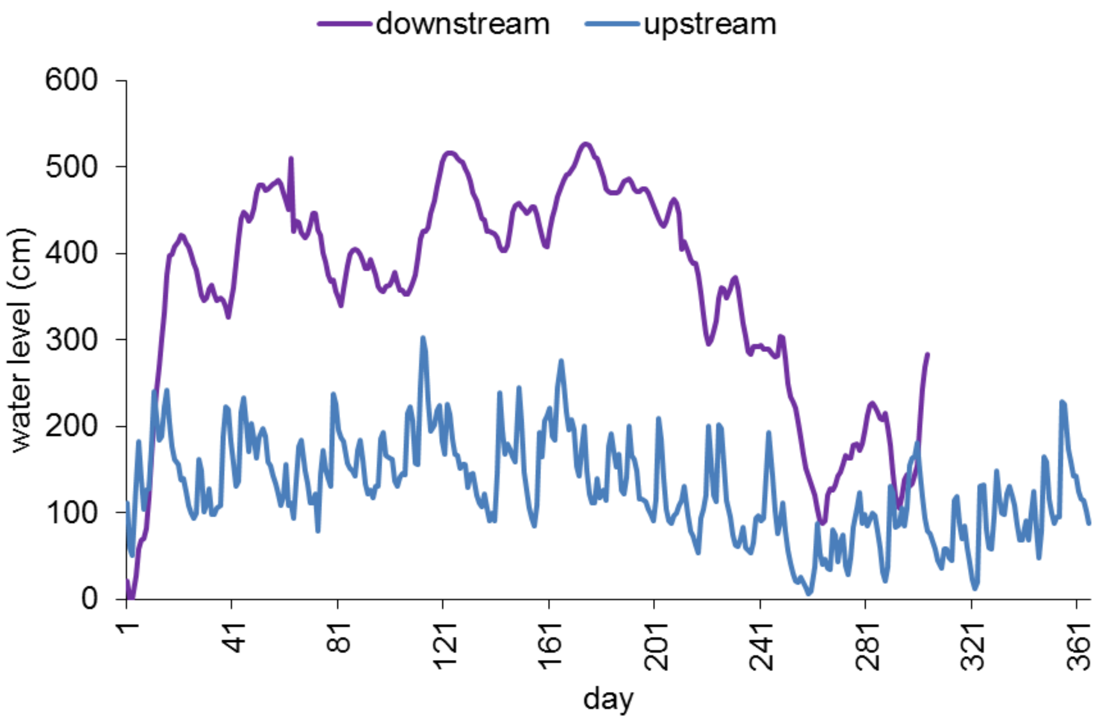


Figure 3.3. Daily water levels (year 2009) of the Napo River after the confluence with the Coca River in the foothills of the Andes ("upstream") and after the confluence with the Mazán River before the confluence of the Napo River with the Amazon ("downstream"), representing the boundaries of the current study. Data represent elevation above the minimum value observed in the observation period.

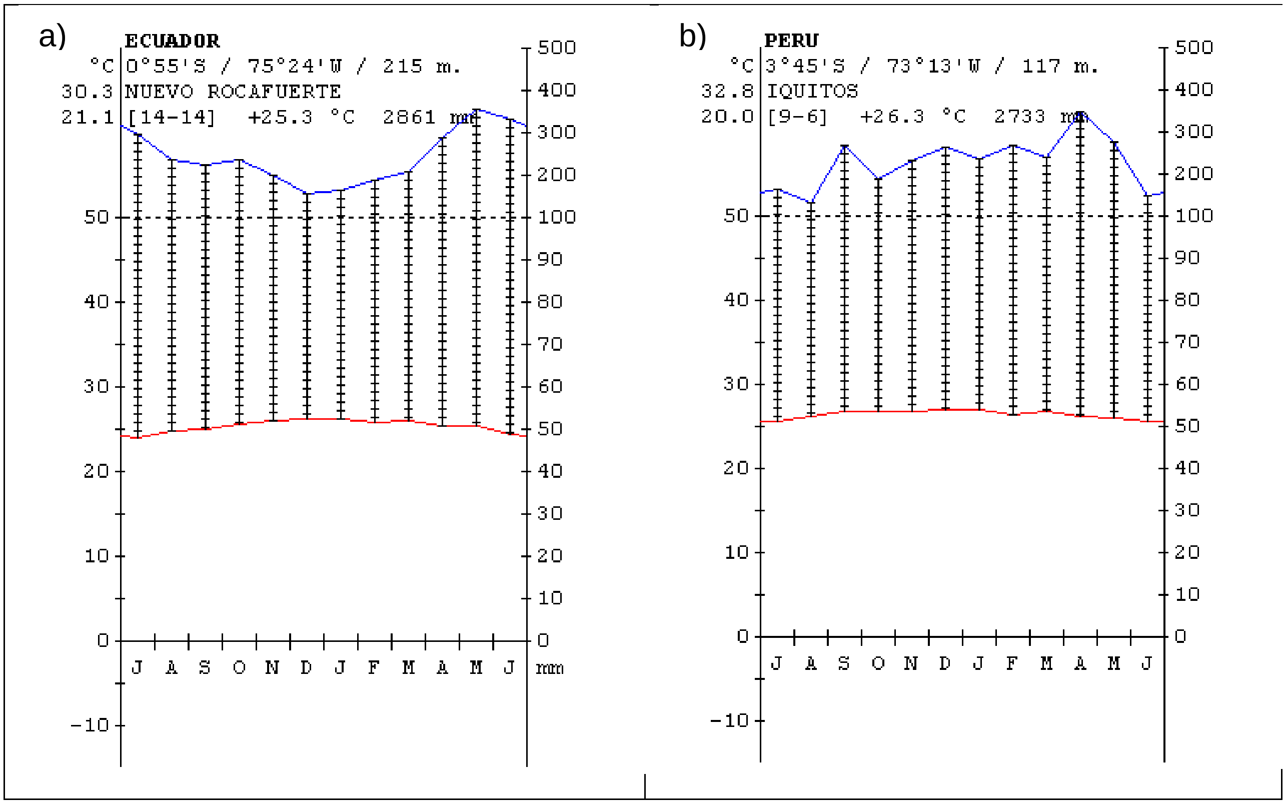


Figure 3.4. Mean monthly rainfall (mm) and temperature ºC of the Napo region: a) upstream (Nuevo Rocafuerte – Ecuador) and, b) downstream (Iquitos, near the confluence of the Napo with the Amazon). Diagrams from the Worldwide Bioclimatic Classification System, 1996–2009, S. Rivas-Martinez & S. Rivas-Saenz, Phytosociological Research Center, Spain (http://www.globalbioclimatics.org).

Along the relatively low gradient of the lowland Napo River, there are extensive presently active and relict floodplains that harbor many types of terrestrial and aquatic habitats, with different degrees of hydrologic connectivity with the river. Most of the region, including the wetlands, is forested and encompasses a continuum of plant communities or associations that are mainly controlled by soil/wetland hydrology and geomorphology (Kalliola et al. 1991, Toivonen et al. 2007). Among the most prevalent wetland communities are the *Mauritia flexuosa* palm swamps that occur on extensive and poorly drained areas along and behind the river levees or on elevated depressions of abandoned fluvial terraces. On areas surrounding lakes or creeks subject to frequent flooding other plant associations are common, often dominated by a few species including the palms *Astrocaryum, Bactris, and Mauritiella*. In areas subject to longer or permanent inundation, shrubs and herbaceous plants, including species of *Montrichardia* (Araceae), grasses and floating aquatic macrophytes are dominant. Along banks of lotic environments subject to flashier inundation, more diverse forests occur, with several kinds of emergent trees on levees and different canopy and understory palm species (e.g., *Phytelephas* (tagua-yarina), *Attalea* (palma real), *Bactris* (Chontilla), etc.) and herbaceous vegetation (e.g., *Cyclanthus*, etc.) in depressions behind those levees.

The region is drained by many types of lotic environments that vary widely in their chemistry, hydrology and ecological conditions. Among these are the very large Andean (e.g., main stem Napo, Coca, and Aguarico) and subandean (piedmont) (e.g., Tiputini, Curaray, etc.) rivers that carry large amounts of suspended sediments and higher concentrations of nutrients and ions; the lowland black-water rivers (e.g., Pañayacu, Yasuní, Aushiri, Santa María, Mazán, etc.); and lowland streams and creeks with tea-colored (DOC-rich) water and low concentrations of nutrients and major ions. Additionally, many lentic habitats occur on the floodplains, including lakes and permanent and seasonal ponds, adding to the diversity of aquatic environments of the region.

The Napo region has a low population density (<2 to 6 people per km^2) (INEC 2014, INEI 2014). Local inhabitants live mostly on the levees along the river, relying on the floodplains as well as the river for subsistence-level consumption of animal protein, medicinal products, etc., with limited agriculture on the levees and floodplains (Kvist and Nebel 2001). The region is being developed rapidly, especially towards the uppermost and lowermost reaches of the river, because of the expanding oil industry and regional infrastructure development (Finer et al. 2008, Finer and Jenkins 2012, Castello et al. 2013). Channel modifications including dredging and dam construction are presently under consideration, and these could alter the hydrology of the mainstem Napo River and its connectivity with the floodplains, with uncertain consequences to the floodplain ecosystems and the ecosystem services that these environments provide to local people.

Methods

Field measurements in the lowland Napo River region are constrained by the remoteness and limited accessibility of the floodplains. The approaches that I employed to assess hydrological regimes of aquatic environments across the Napo River floodplains consisted of a combination of direct and indirect methods to record water levels and sources of flood waters in the floodplains. I carried out nine field campaigns from 2007 to 2013, during different seasons, to deploy and retrieve equipment, collect water samples, and take direct measurements or observations of water chemistry, inundation, elevation, and vegetation across distal and proximal floodplains. I define a study site as proximal to the river when it was connected via permanent channels or within ~1 km of the river channel or its connected waters; all other sites are defined as distal to the river.

Water levels were measured using temperature sensors/data loggers (Thermochron iButtons – IBs) and pressure transducers (HOBO loggers – PTs). IBs were deployed for up to three years at different elevations above the soil or sediment surface at over 100 study sites in the Napo River and its floodplains (Figure 3.5). By recording the damping of the diel amplitude of temperature (DAT) during flooding events, these temperature records indirectly indicated water level fluctuation over time. PTs were deployed in 17 sites and directly recorded water level variation for up to five years (Figure 3.5). IBs provided a range of the depth of inundation versus PTs that recorded absolute depth values. In some cases, loggers placed along permanent water bodies were deployed above the normal low water levels at the time of deployment, thus in these situations inundation refers as overbank flooding. Details of this approach are described in Chapter 1.

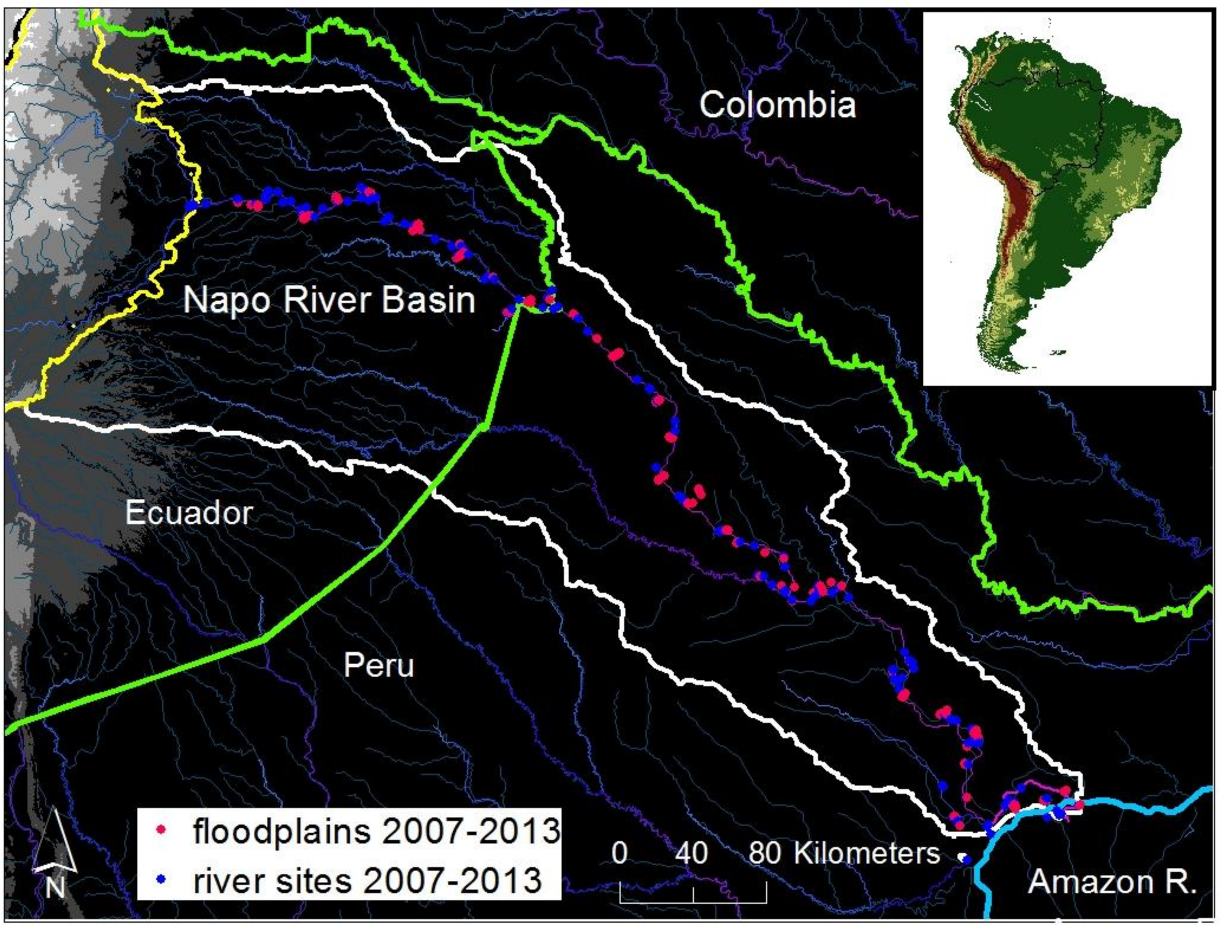


Figure 3.5. Study area showing open water and floodplain sites sampled from 2007 to 2013, depending on the site.

Sources of flooding (river overflow vs. local rain and runoff) were assessed from the major solute chemistry of water samples collected during the field trips or using Rising Stage Samplers (RSSs) placed at different elevations at sites across the floodplains. Major solute concentrations were compared to the chemistry of different water bodies of the region obtained over more than five years of sampling. In Chapter 2, I describe the optimal combination of solutes used to assess water sources as well as the details of the RSS design. These were co-located with IBs and also provided a snapshot of the magnitude of previous flooding events.

The main components of the flood regime that I assessed were the magnitude, duration, frequency, and predictability of inundation. These components were evaluated for each study site on an annual basis and compared over time to have a measure of temporal variability.

To conduct spatial comparisons among the different sites I estimated single metrics for each of the main components of the flood regime. The maximum depth of inundation (magnitude of flooding) was either measured directly with PTs or ascertained from IB temperature records or the presence of water in RSSs. Duration of inundation was estimated as the total number of days of flooding above the lowermost IB. Frequency of inundation was estimated as the number of distinct inundation events recorded with the lowermost IB. Predictability was assessed using the R-B index of "flashiness"—based on the day-to-day changes in water levels (Baker et al. 2004)—for the limited number of sites with longer hydrograph records (PTs and governmental hydrological stations). The median and mean depth (or depth range) of inundation and the median and average duration of single flooding events were also estimated as additional measures of magnitude and duration of inundation, respectively.

To facilitate the description of the hydrological features of the study sites, they were pre-classified into either lotic systems (here referred to, in order from smaller to larger, as creeks, streams and rivers), lentic systems (lakes and ponds), seasonally flooded forests, or permanently or nearly permanently flooded swamps. Most of these environments were proximal to the river, except for some of the swamps and flooded forests that were distal.

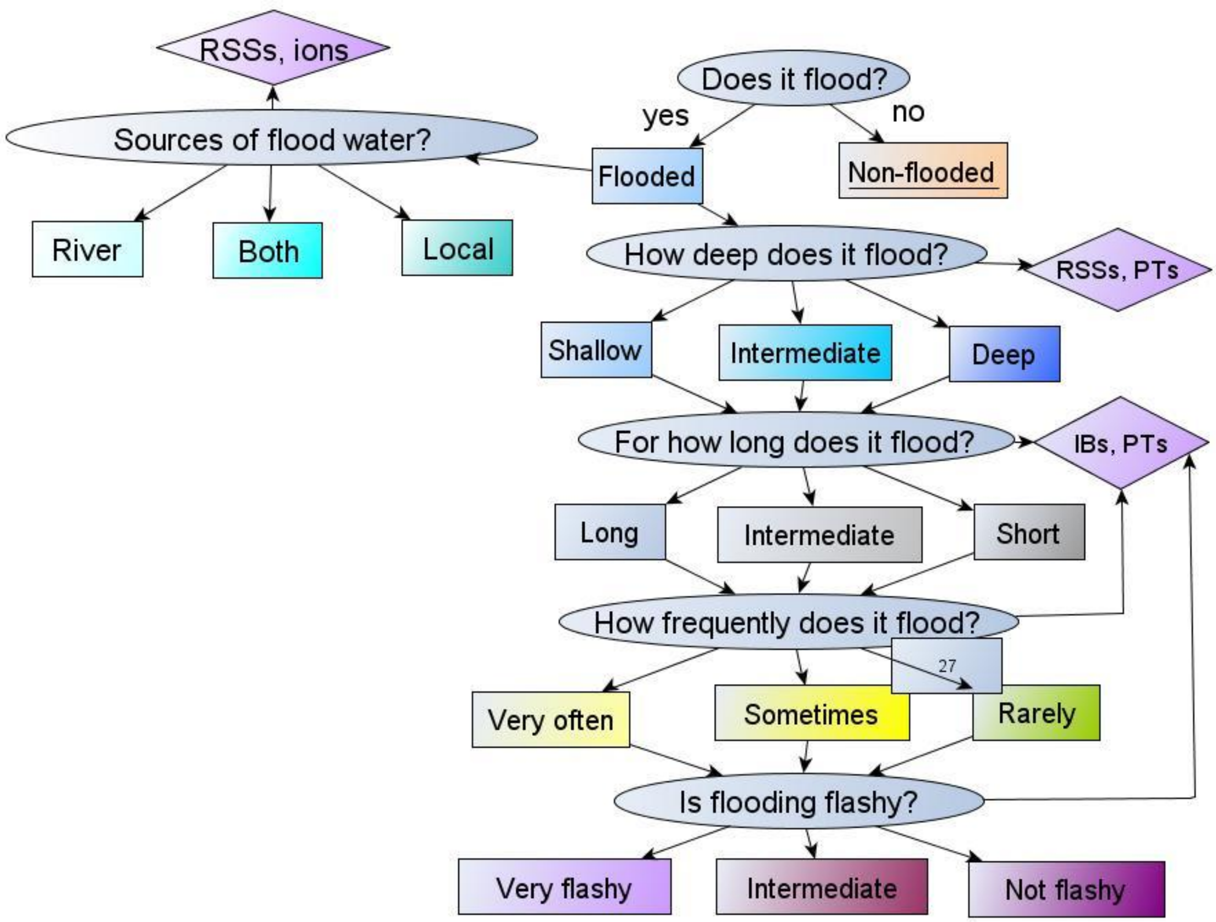


Figure 3.6. Schematic categorization of aquatic ecosystems based on the main components of the flood regime analyzed in this study: magnitude, duration, frequency and flashiness.

A flow chart summarizes how the various sources of information on floodplain hydrology were integrated to characterize the flood regimes of the floodplain study sites, including water sources and flood magnitude, duration, frequency and flashiness (Figure 3.6). In addition I looked at the relationship between PT-based hydrographs of the floodplain sites and those of the nearest river site using cross-correlation analyses to look for time lags in the riverine influence on these systems (i.e., delayed filling and drainage of the floodplains). Finally, based on these records and those of the chemistry of the waters measured over time I categorized each floodplain site by the degree of river influence, spanning a gradient from direct and permanent hydrologic connectivity to indirect and sporadic flooding without significant river control. I compared the solute chemistry of each floodplain site with that of the nearest river sites and estimated a degree of river influence based on a linear mixing model for select solutes based on their concentrations in river water vs. local waters. Five categories ranging from 0 to 100% degree of river influenced were defined through this analysis.

Outcomes of the flood regime analysis were categorized according to the procedure described in Figure 3.6 and mapped out over a watershed DEM-based model (Hydrosheds) to assess the spatial distribution of the different hydrological habitats associated with the river. Nonparametric Kruskal-Wallis (H) tests were performed to assess longitudinal variation for the main components of the flood regime along three river reaches (upper, middle and lower), and Mann-Whitney (U) tests were performed to compare proximal and distal floodplains.

Results

Characterization of flood regimes

Magnitude of inundation

The mean of the maximum depth of inundation of all the study sites recorded with RSSs during the period of study was 98.8 ±109.4 cm. Water levels of lotic systems (creeks, streams, and rivers) varied more than those of other environments as shown by their rank distribution (Figure 3.7a) and their median and range, 214 and 145.9 cm respectively (Figure 3.7b). Medians and ranges of depths of lakes and ponds (64 and 100.4 cm) were higher than those of seasonally flooded forests, including distal and proximal flooded forest (29 and 139 cm respectively) and permanently flooded distal and proximal swamps (18.8 and 128 cm) (Figure 3.7). Depth of inundation was higher in environments proximal to the river, including lotic and lentic systems. Also, seasonally flooded forests were often proximal to lotic systems and had higher inundation depths (median = 34 cm, range = 80.8 cm) than proximal (20 and 197.3 cm) and distal swamps (17.5 and 58.7 cm), although depth range was higher in proximal swamps (Figure 3.7).

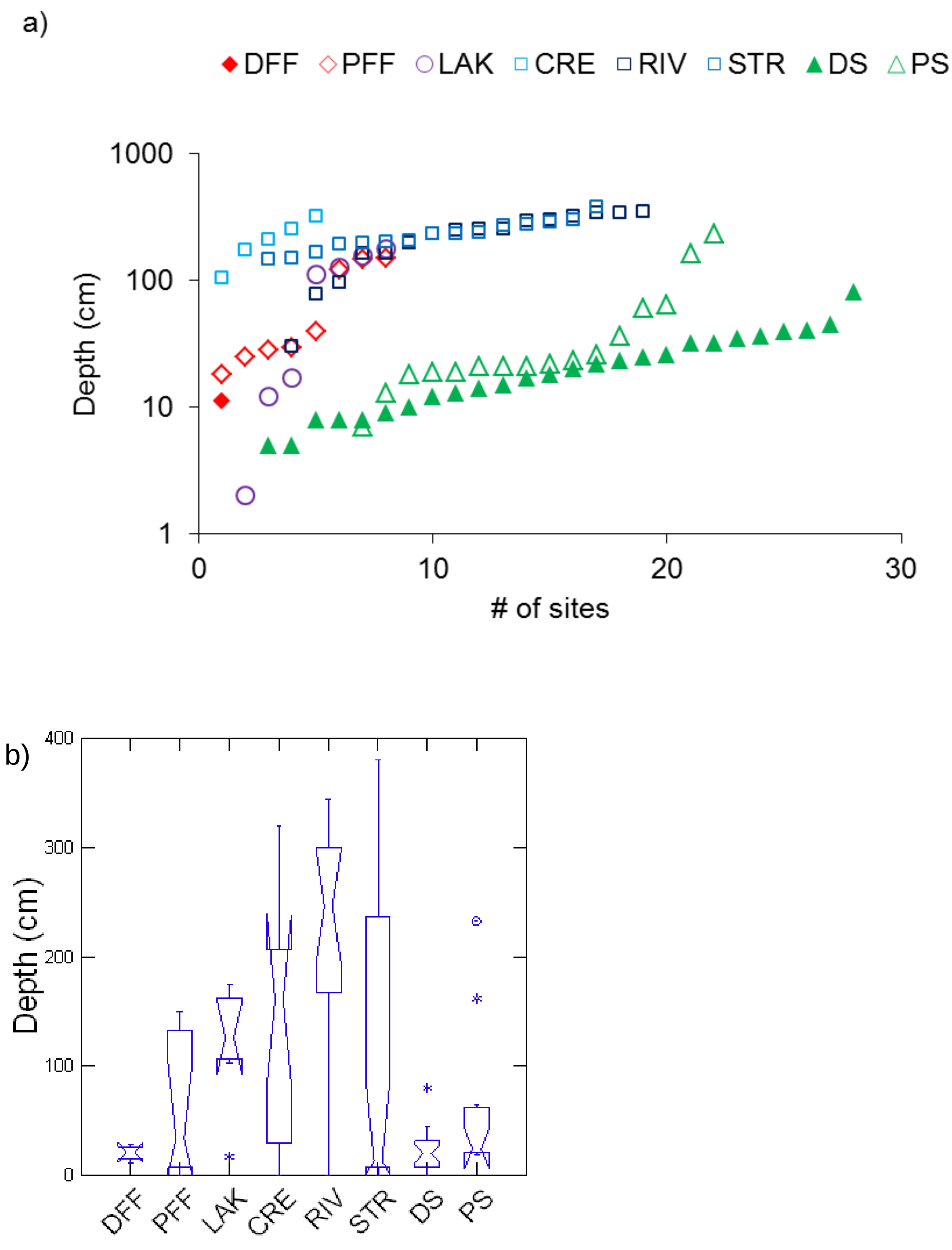


Figure 3.7. Rank abundance curves (a) and notched box plots (b) of the maximum range of water level variation (depth) of different aquatic environments (n=107) associated with the Napo River during the 2007-2010 period of study: distal flooded forests (DFF), proximal flooded forests (PFF), lakes (LAK), creeks (CRE), rivers (RIV), streams (STR), distal swamps (DS) and proximal swamps (PS). The notches provide an approximate indication of statistical significance of the difference in medians; if the notches in two plots do not overlap their medians are likely to differ.

Duration of inundation

The median duration of inundation of all sites, as recorded with the lowermost IB during the period of study, was 27 days per year, although it ranged from 272 days in one of the river sites to one day in few locations (Figure 3.8). In general, as shown by their medians and ranges, lotic systems (median=101 days/yr., range=232 days/yr.) and lakes (86 days/yr., 255 days/yr.) had the longest and most variable hydroperiods compared to swamps and flooded forests that varied from 11 and 133 to 24 and 173 days/yr., respectively. Overall, permanently flooded distal swamps appear to have longer hydroperiods (16.5 and 168.9 days/yr.) than proximal sites (13.7 and 183.1 days/yr.), although the latter showed more variability (Figure 3.8).

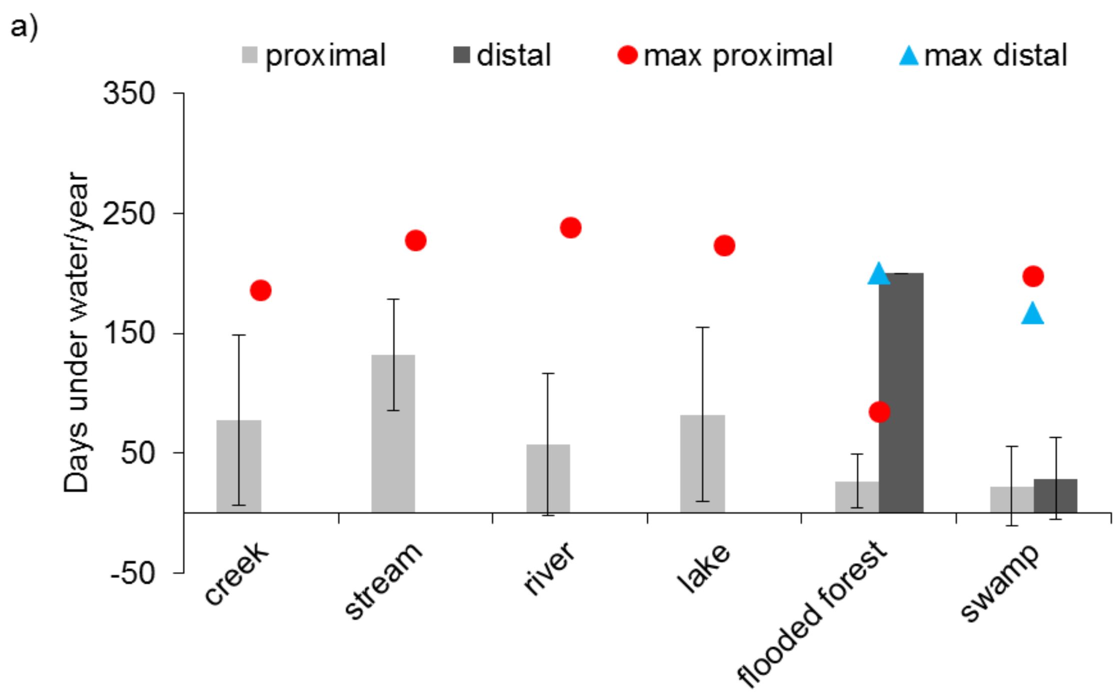
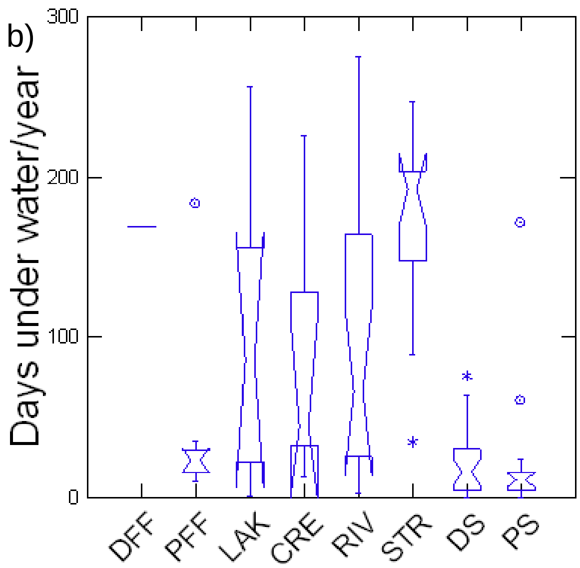


Figure 3.8. Mean (±SD) and maximum hydroperiods (a) and box plots (b) showing the duration of inundation (in number of days per year) of different aquatic environments (n=107) associated

Figure 3.8. (cont'd)

with the Napo River during the 2007-2010 period of study: distal flooded forests (DFF), proximal flooded forests (PFF), lakes (LAK), creeks (CRE), rivers (RIV), streams (STR), distal swamps (DS) and proximal swamps (PS).



Based on the duration of flooding of the lowermost IB and the maximum range of water level variation recorded with RSSs, without considering the proximity of floodplain sites to the river and their potential connectivity, I identified five main types of flood regimes, ranging from long-lasting and deep to short and shallow inundation (Figure 3.9). Forty-five percent of the floodplain sites had intermediate levels of inundation in relation to both magnitude and duration (relative to the heights of measurement) (n=26 out of 58), whereas 40% were shallow (n=23), and the remaining 15% had longer (independent of the depth) and/or deeper (independent of the duration) inundation. When I accounted for the proximity of the environments to the river, most of the distal floodplain sites where shallower than the proximal ones and had relatively shorter inundation, although both types of environments had a large range of depth and duration of inundation (Figure 3.10). Distal sites represented 43% of the floodplain study sites.

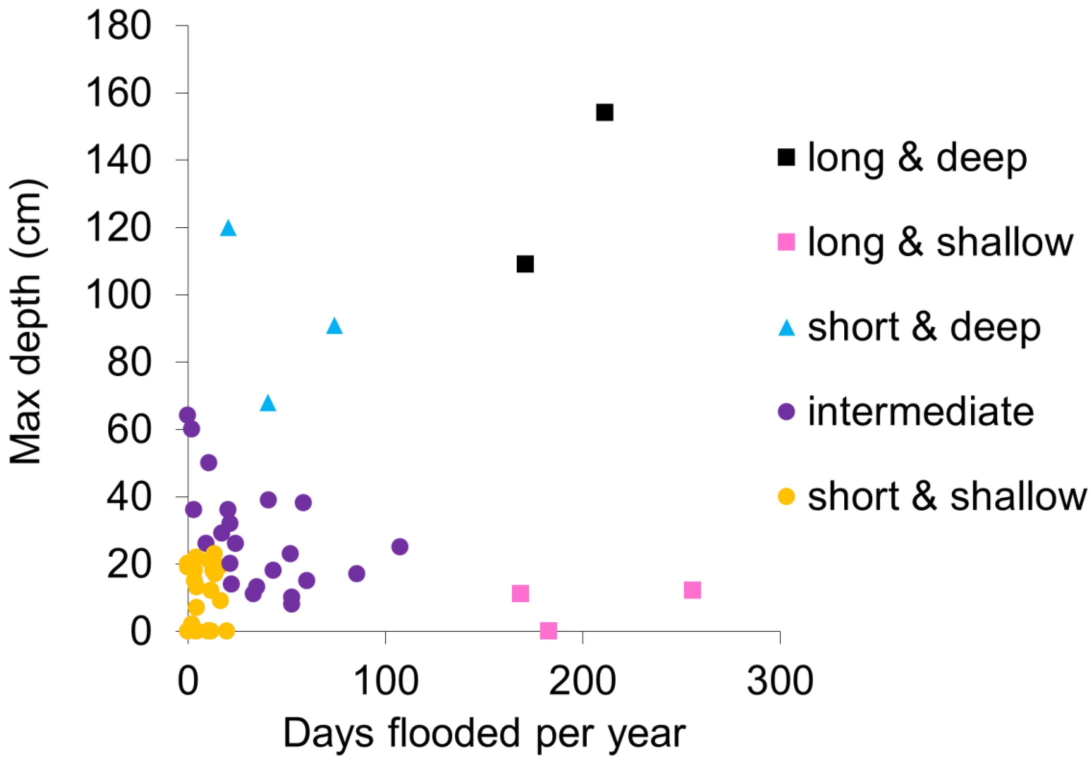


Figure 3.9. Categorization of floodplain environments (n=58) along the Napo River based on their maximum depth (recorded with RSSs) and duration of inundation (recorded with the lowermost IB). Distal and proximal sites are combined here and shown separately in Figure 3.10.

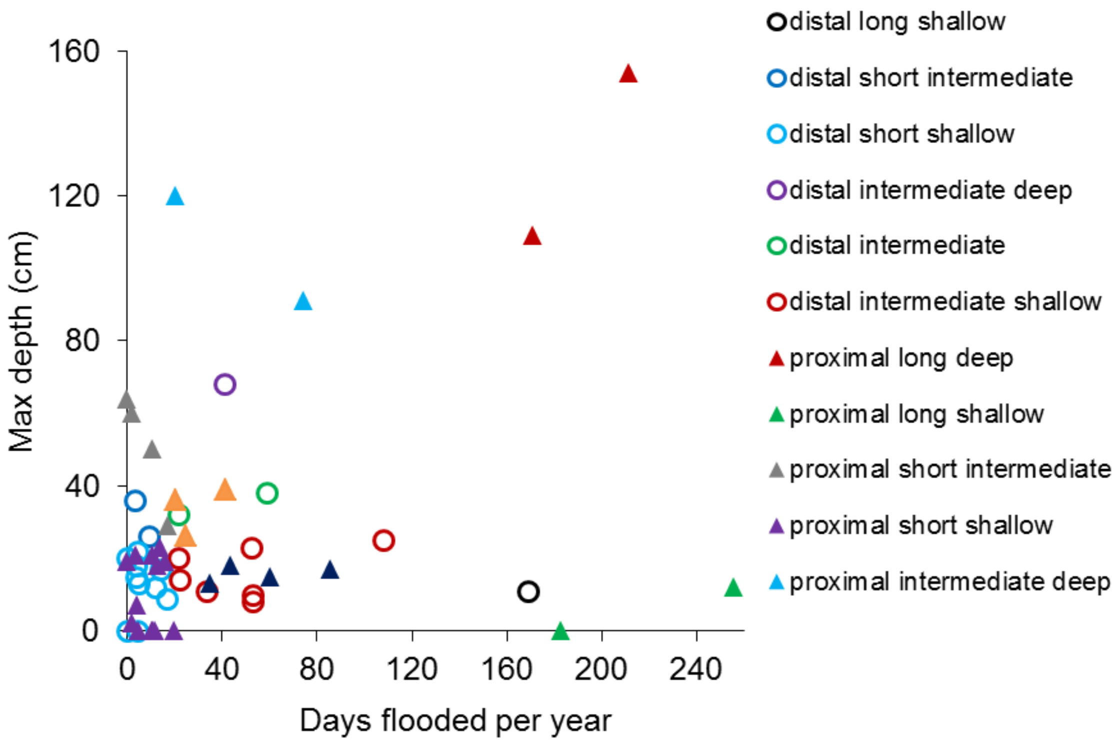


Figure 3.10. Comparison of proximal and distal floodplain environments (n=58) along the Napo River based on their maximum depth (recorded with RSS) and duration of inundation (recorded at the lowermost IB).

Frequency of inundation

The median number of flooding events per year was 13 and ranged from 0 to 57 depending on the floodplain site. These events varied from one year to another and showed a non-linear significant relationship with the duration of inundation (t_{2009}= 9.42, df=88, p=<0.0001; t_{2008}=4.13, df=34, p=<0.0001) (Figure 3.11). As the duration of inundation increased the number of flooding events also increased; however, this trend was reversed when inundation occurred for nearly all year (Figure 3.11).

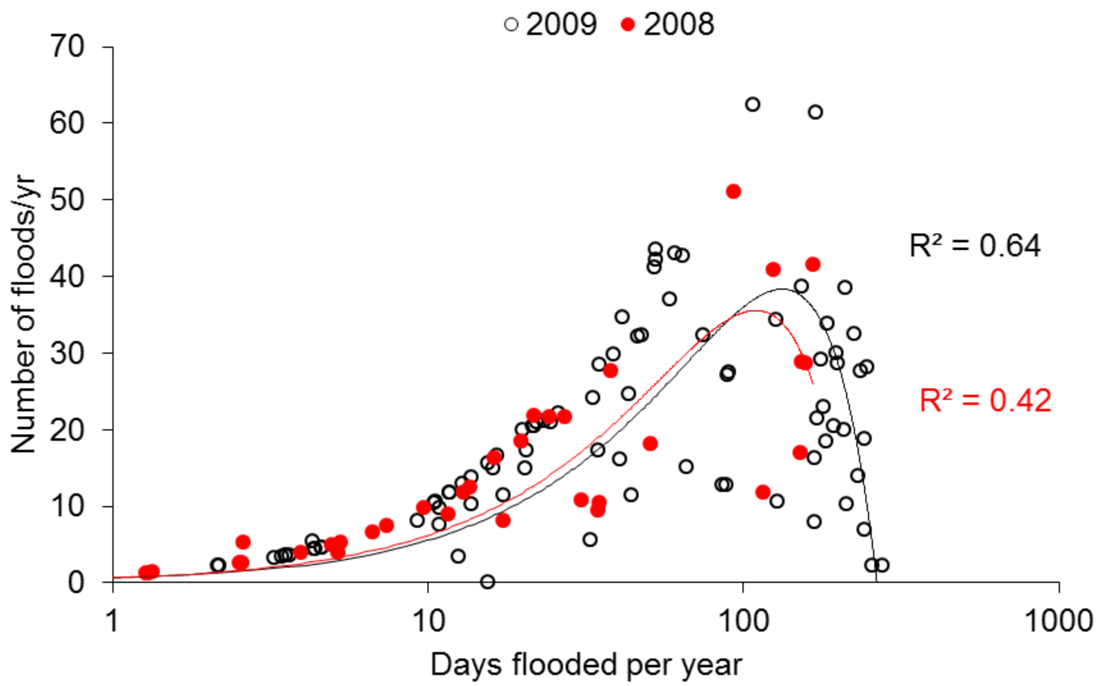
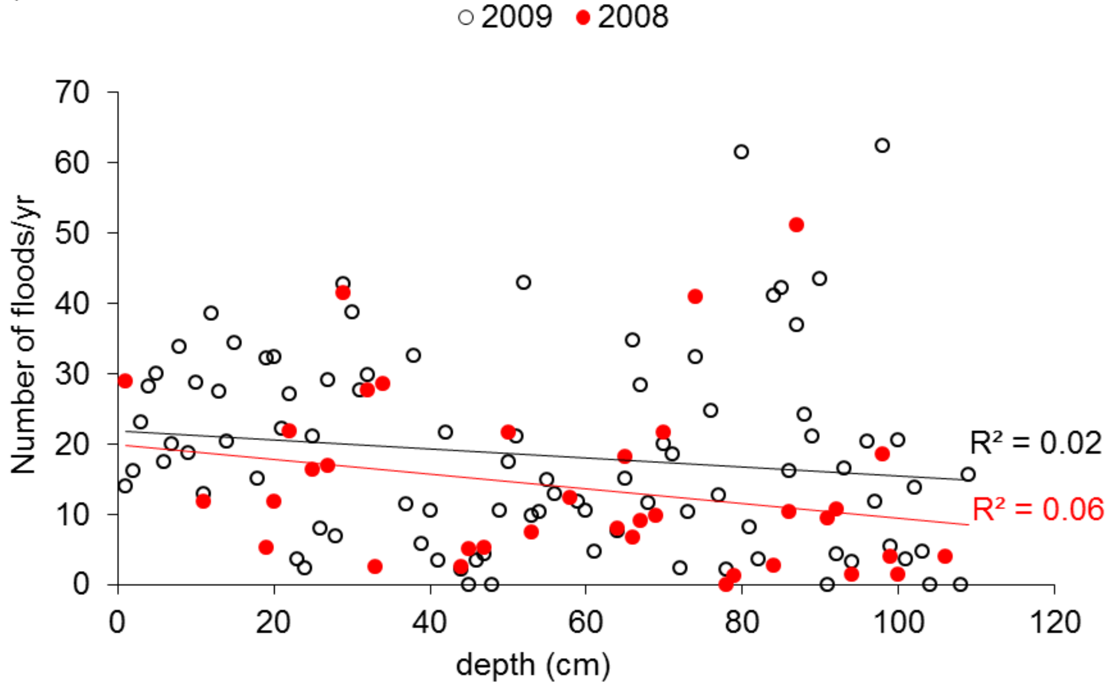


Figure 3.11. Frequency and duration of flooding events in the Napo floodplains recorded during 2008 and 2009.

Overall, the relative increase in depth of inundation (of the lowermost and uppermost sensors) was associated with decreased frequency of inundation, indicating that deeper flooding events were less frequent than the shallower events (Figure 3.12a-b). However, an opposite relationship between the number of flooding events and the mean depth of inundation suggests that deeper sites tend to be flooded more frequently, independent of the duration of those events (Figure 3.12c). These trends were only significant for year 2009.

a)



b)

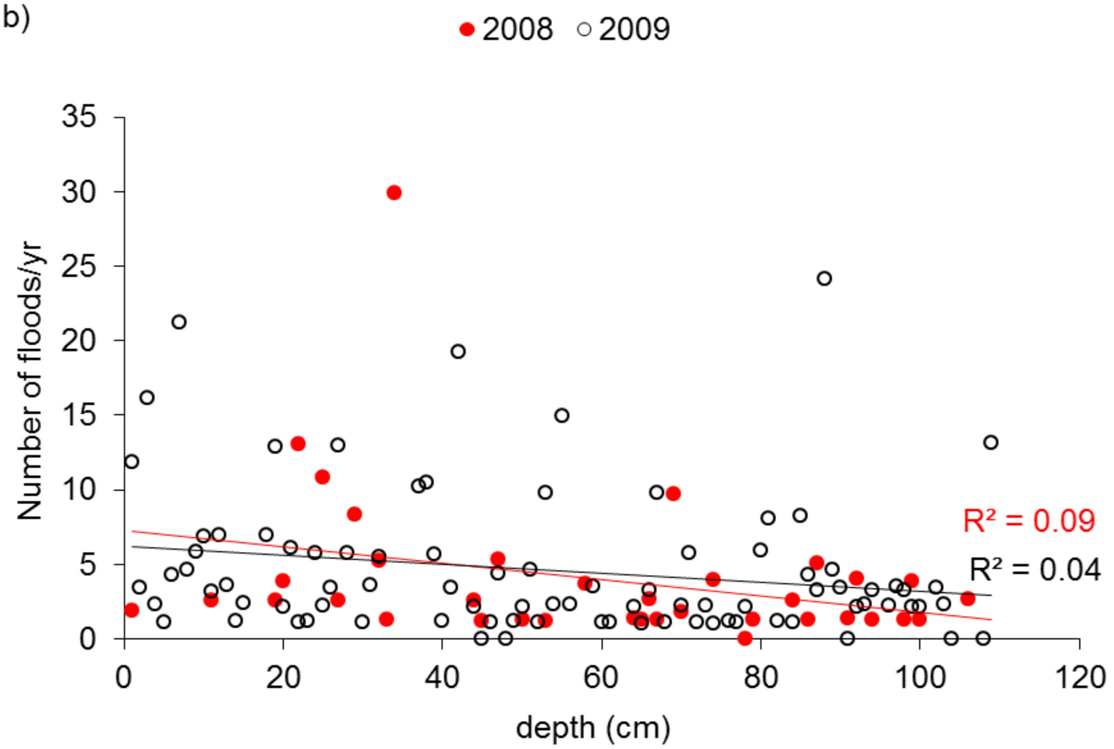
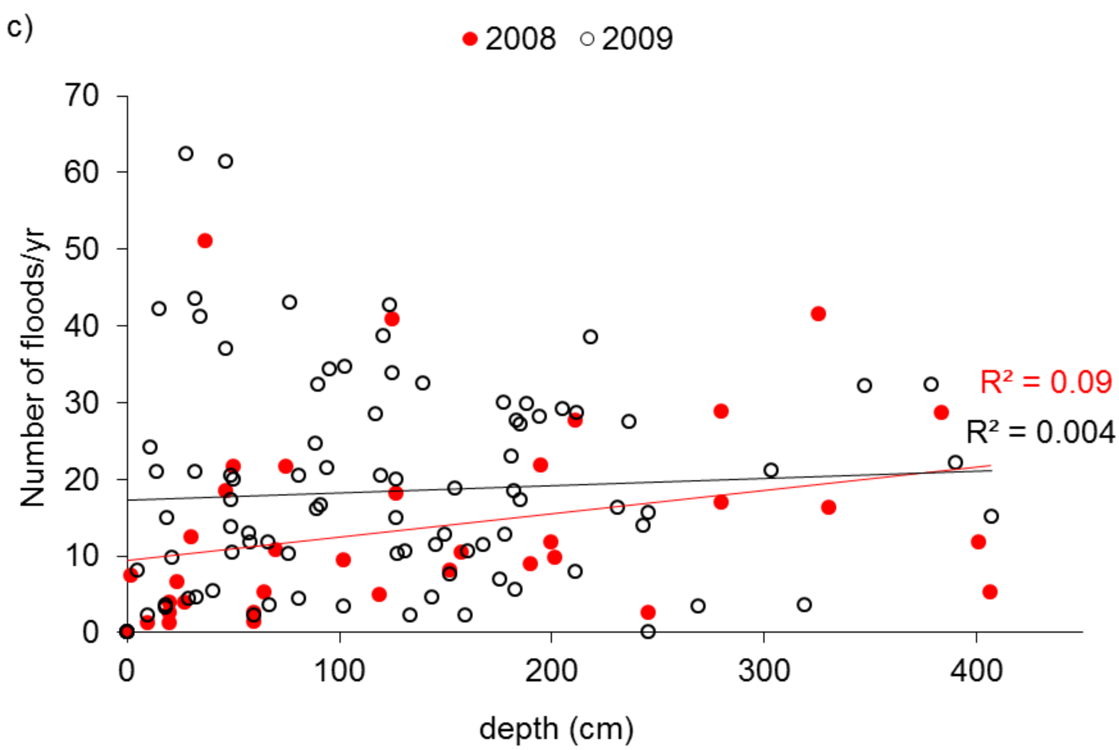


Figure 3.12. Frequency of flooding events in the Napo floodplains recorded in 2008 and 2009 in relation to depth (cm) of inundation: a) depth recorded with lowermost sensors (t_{2009}= 2.345, df=88, p=0.001), b) depth recorded with uppermost sensors (t_{2009}= 2.941, df=88, p=0.002), and

Figure 3.12. (cont'd)

c) mean depth of inundation (t_{2009}= 2.943, df=88, p=0.002).



Flashiness

Overall, with the exception of few sectors in the mid reaches, there was a decreasing trend in flashiness in the downriver direction. Flashiness, which is indicated by the ratio of the sum of the absolute day-to-day water level fluctuations to the sum of water levels during the period of study (R-B Index), and ranged on average from 0.14 in study sites in the upper reaches to 0.08 in the lower reaches, with a mean of 0.13 ± 0.03. As expected based on the larger absolute day-to-day changes in water level of the river sites (5.12±11.26cm), these had the largest R-B flashiness indices (0.17±0.04) compared to the proximal (0.11±0.03) and the distal swamps (0.10±0.05), which had an average day-to-day water level change of 0.01±0.00 cm and 0.04±0.05 cm, respectively. In Figure 3.13 this pattern is shown for three river reaches.

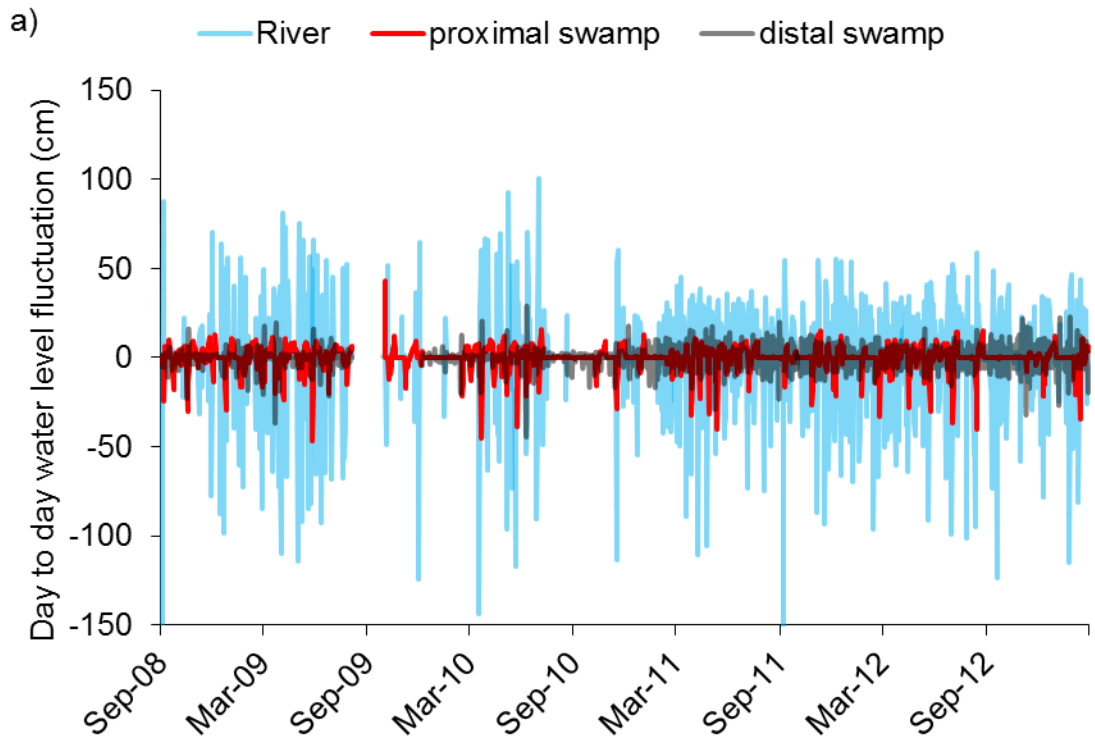
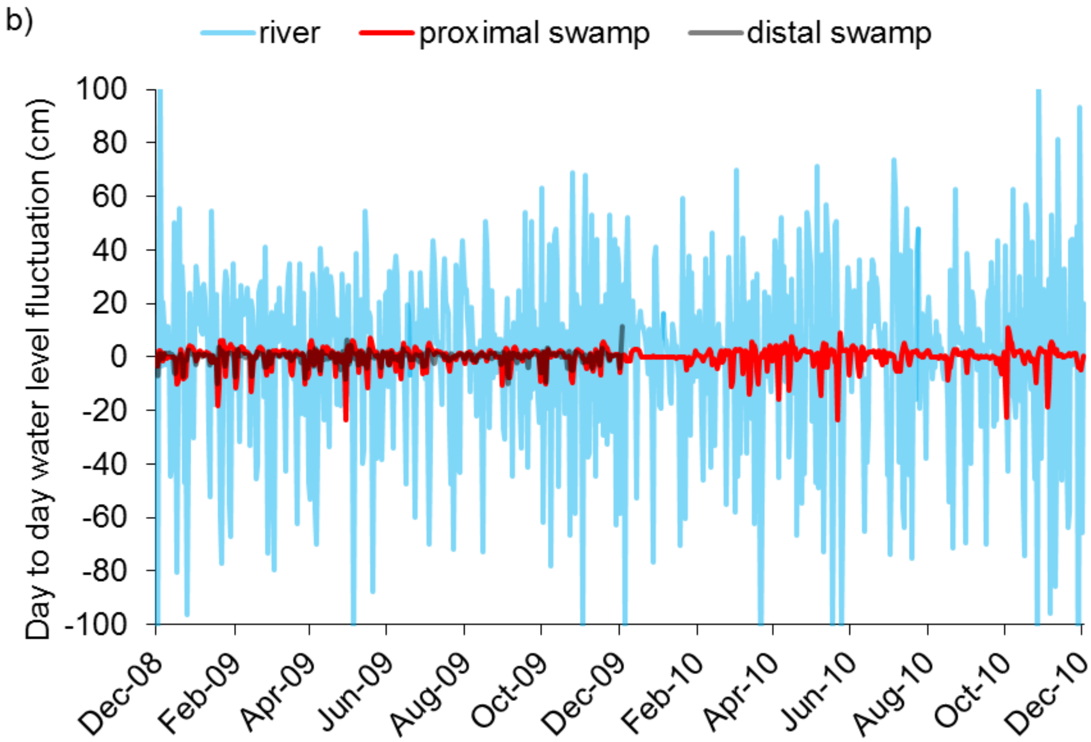
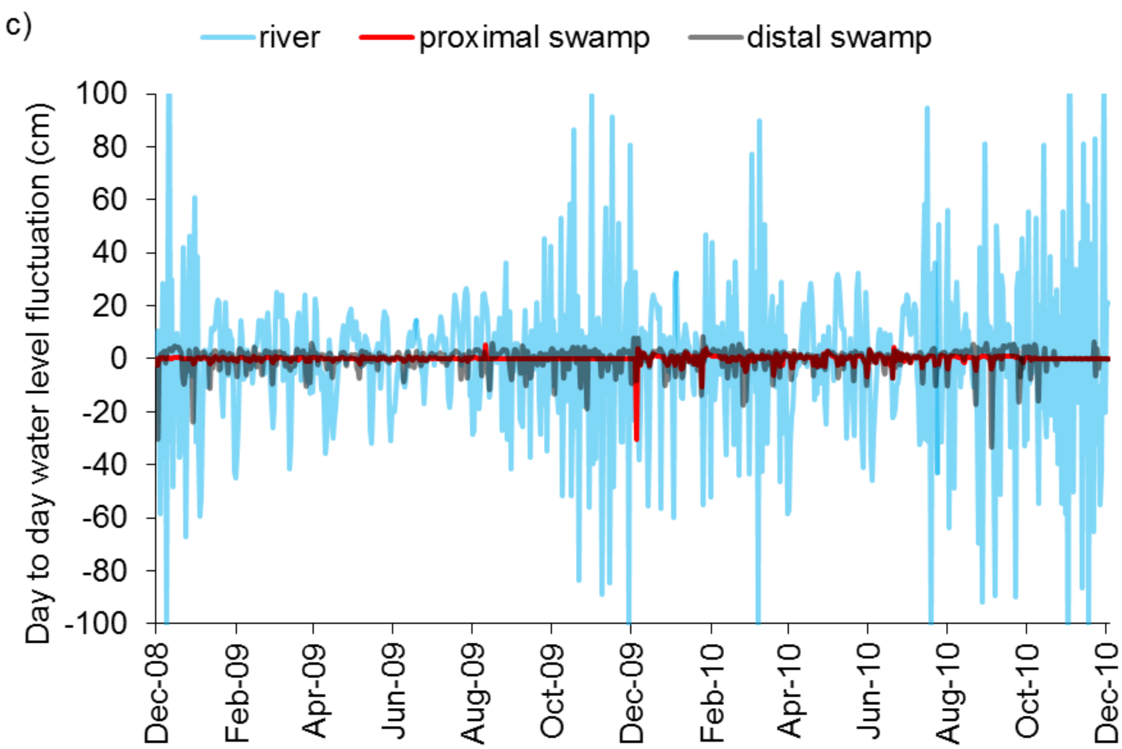


Figure 3.13. Day-to-day fluctuation of water levels of proximal and distal floodplains in relation to the river in a) the upper reaches (Huiririma community), b) middle reaches (Campo Serio community) and c) lower reaches (Huamán community) of the lowland Napo River in Ecuador and Peru.

Figure 3.13. (cont'd)





Source of flooding

Based on the major solute chemistry of the waters I found that 98% of the floodplain sites were influenced by local rainfall and runoff from black water swamps and streams, however 74.1% of the sites also had some degree of river influence (Figure 3.14a). Out of these, 25.9% and 1.9% were solely controlled by local and river waters, respectively. Overall, floodplains that were mostly flooded by local waters (50 to 100%) were more common (64.8%) than floodplains that were mostly influenced by river waters (16.7%). However, 18.5% of the floodplain sites were significantly influenced by both types of waters (Figure 3.14a).

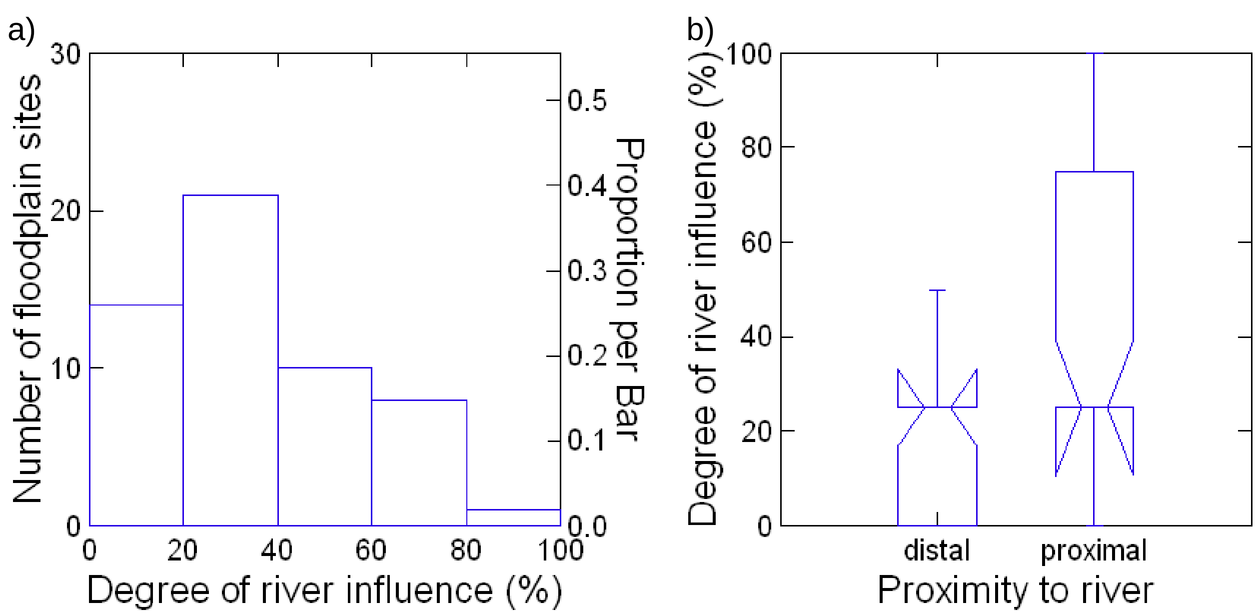


Figure 3.14. Number of floodplain sites by degree of river influence based on the major solute chemistry of the waters (a) and distribution of proximal (N = 30) and distal (N = 24) floodplain sites by degree of river influence (b).

Overall, sites that were proximal to the river had a greater range in the degree of river influence than distal sites, although the difference between the medians was only marginally significant

(U=255, df=1, p=0.056) (Figure 3.14b). Similarly depth and duration of inundation were more variable in the proximal sites than in the distal ones, but the medians were not different (Figure 3.15). In addition, sites that had higher degree of influence by the river, except for one site that was fully controlled by the river, had larger ranges in depth and duration of inundation (Figure 3.16).

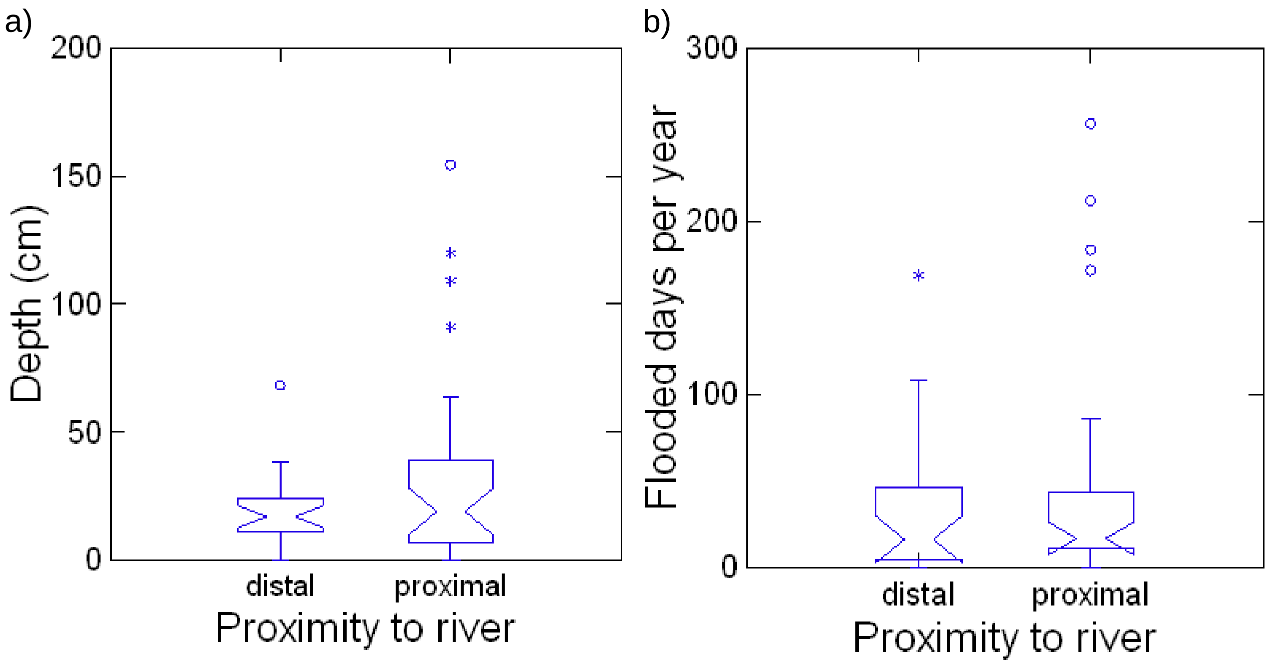


Figure 3.15. Variability in depth (a) and duration (b) of inundation of floodplain sites in relation to their proximity to the river.

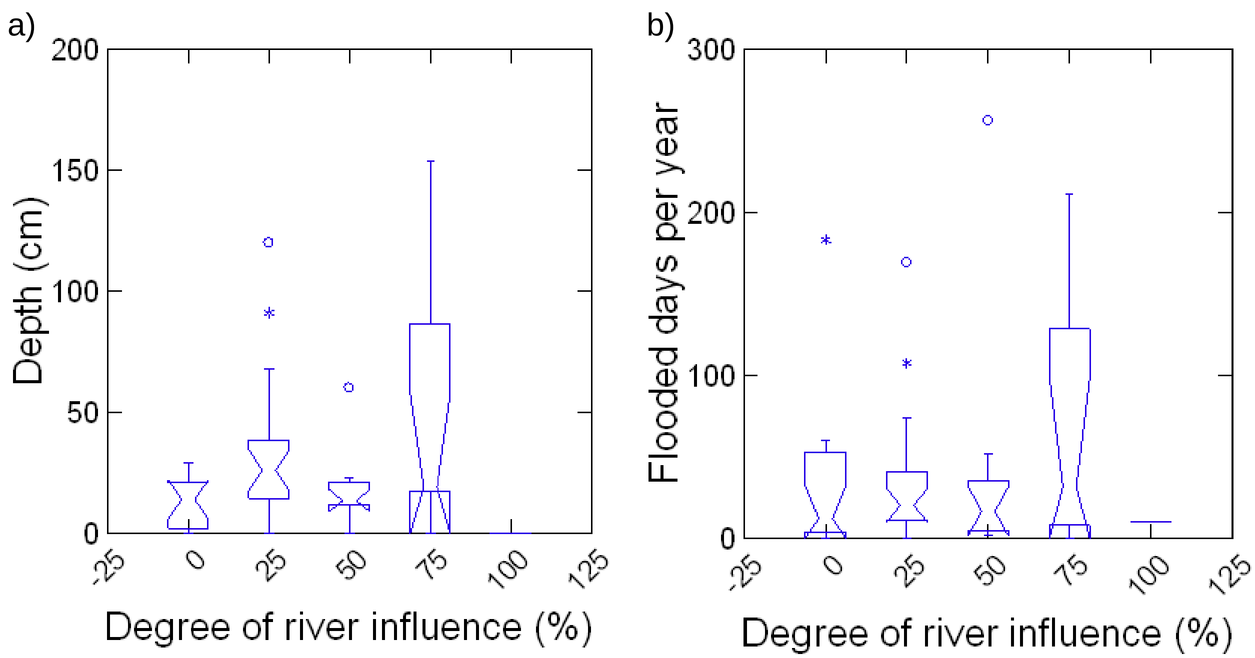


Figure 3.16. Variability in depth (a) and duration (b) of inundation of floodplain sites in relation to their degree of river influence. Number of sites in each category: 0-25% = 14, 25-50% = 21, 50-75% = 10, 75-100% = 9.

Spatial distribution of flood regimes

I found large spatial variability in the flood regimes of the Napo River floodplains. However, contrary to what was expected, inundation tended to be deeper in the floodplains of the upper reaches of the Napo (median = 38 cm) than in the floodplains of the middle and lower reaches (15 and 19 cm, respectively) (Figures 3.17and 3.18). However, the range of water level variability was larger in the lower reaches (154 cm) than in the upper (120 cm) and middle (26 cm) reaches (Figures 3.17 and 3.18). Similarly, the median duration of inundation was longer in floodplains along the upper reaches (41 days) compared to the middle and lower reaches (22 and 33 days, respectively) (Figures 3.17 and 3.18); however, the floodplains along the upper reaches spanned a narrower range (108 days) of inundation duration than the floodplains of the middle and lower reaches (169 and 256 days, respectively) (Figures 3.17 and 3.18).

These patterns were only significantly different for the depth of inundation based on the Kruskal-Wallis test (depth: H=7.50, df=2, p =0.02; duration: H=0.93, df=2, p=0.63). Figures 3.19 and 3.20 depict these depth and duration of inundation patterns of the floodplains along the upper, middle and lower reaches of the Napo River, and in combination these characteristics define at least 7 different types of flood regimes (Figure 3.21).

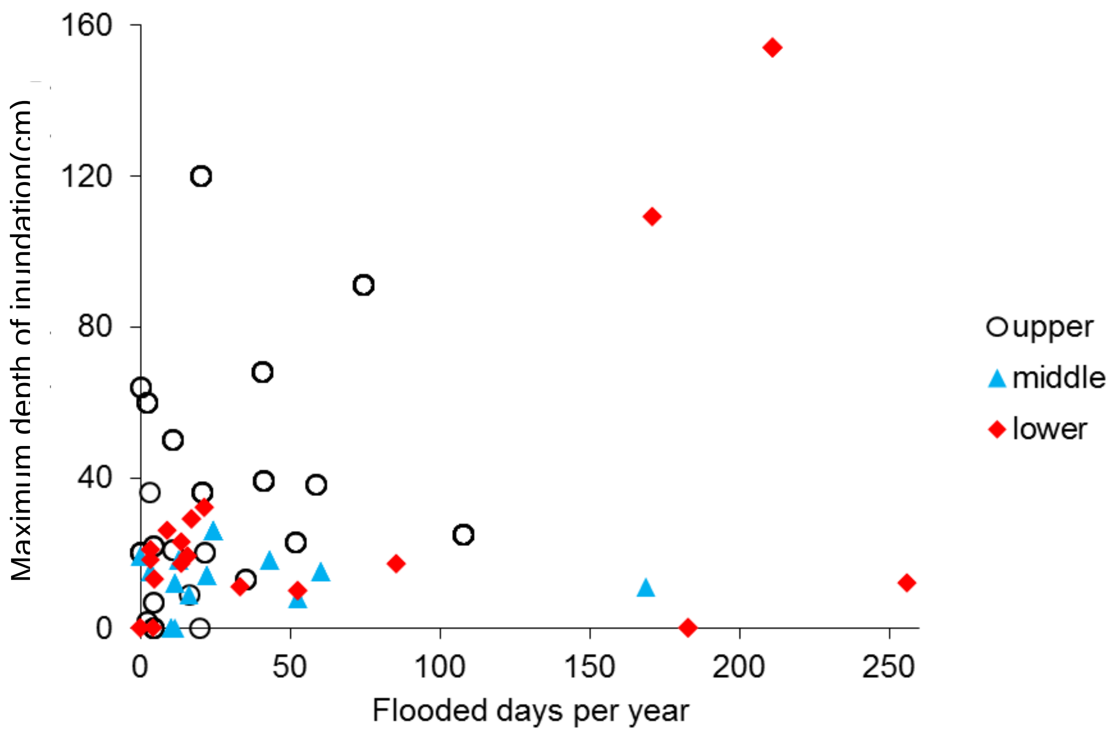


Figure 3.17. Duration and maximum depth of inundation of the Napo River floodplains in the upper, middle and lower reaches.

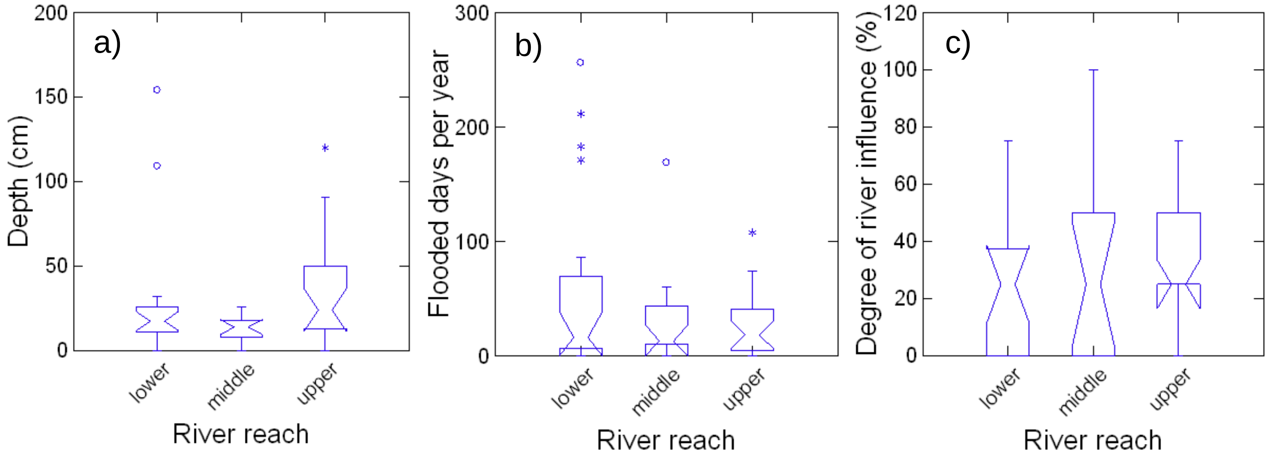


Figure 3.18. Depth and duration of floodplain inundation and degree of river influence by reach of the Napo River.

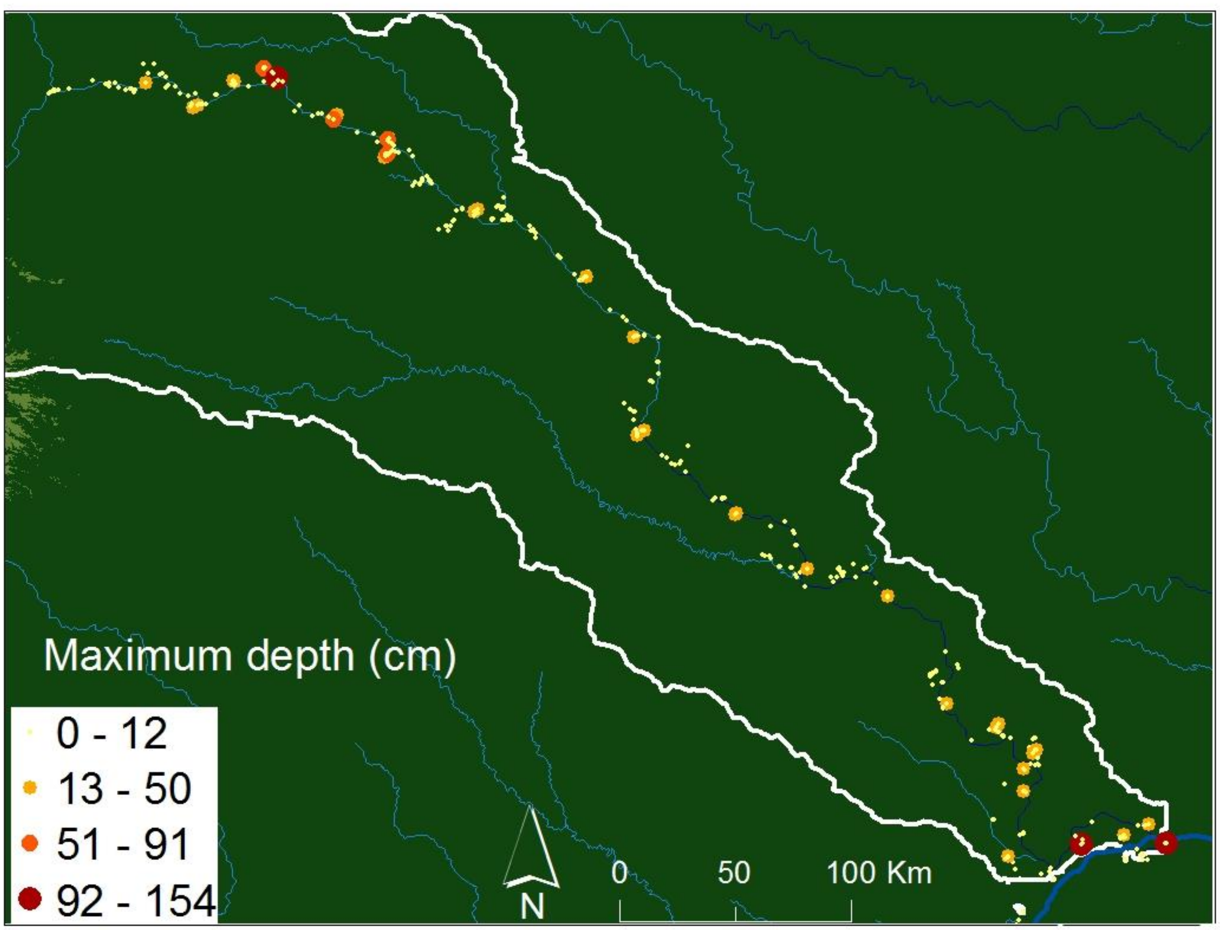


Figure 3.19. Maximum depth of inundation (cm) of floodplains along the upper reaches of the Napo River (from its headwaters to its confluence with the main northern Andean tributary, the

Figure 3.19. (cont'd)

Aguarico River), the middle reaches (from its joint with the Aguarico until its confluence with the main lowland and southern tributary, the Curaray River), and lower reaches (from the Curaray to its confluence with the Amazon River).

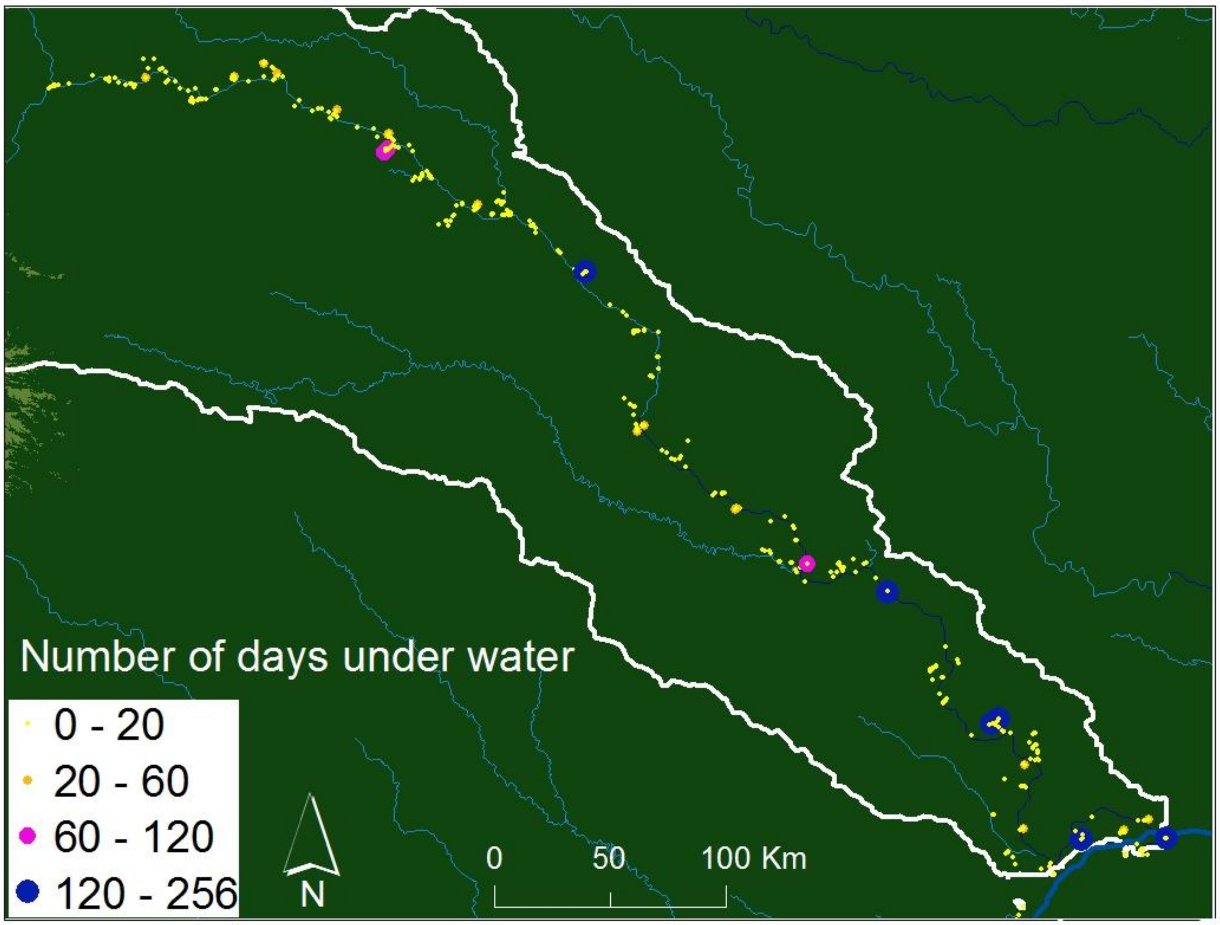


Figure 3.20. Duration of inundation, in number of flooded days per year, of floodplains along the upper, middle and lower reaches of the Napo River.

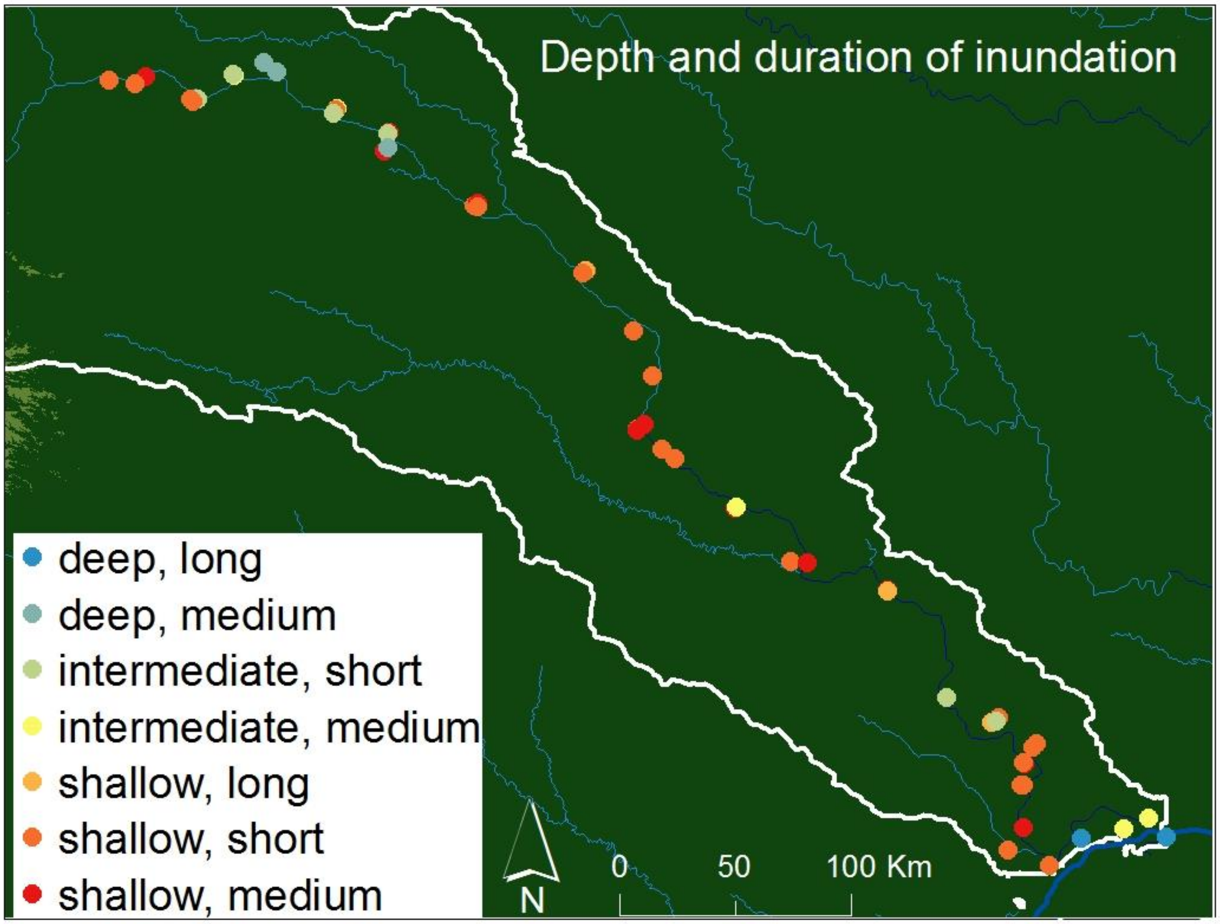


Figure 3.21. Flood regimes of the Napo River floodplains based on depth and duration of inundation. Depth categories are: shallow (0 to <40 cm), intermediate (40 to 80 cm) and deep (>80 cm). Duration of inundation categories are: short (0 to <50 days), medium (50 to 150 days) and long (>150 days).

In contrast to some of the patterns described above, the degree of river influence on the floodplains, defined based on the major solute chemistry of the waters, showed no consistent longitudinal pattern along the river (H=2.20, df=2, p=0.33) (Figure 3.22). However, results of the cross-correlation analyses between hydrographs of river sites, proximal and distal floodplains indicated that sites along the middle reaches had a stronger relationship with each other (median r=0.58) than sites in the upper (median r=0.39) and lower (median r=0.26) reaches (H=5.79, df=2, p=0.06) (Table 3.1). Independent of the river reach, water levels in the river had a stronger relationship with the proximal floodplains (median r=0.55) than the distal floodplains (median r=0.35), but the distal floodplains had a stronger relationship with the proximal floodplains (median r=0.43) (Table 3.1). . These results were consistent with the cross-correlation lags in number of days between hydrographs, as indicated by the median lags for the maximal correlations (one day between the river and proximal floodplains, three days between the river and the distal floodplains, and four days between distal and proximal floodplains).

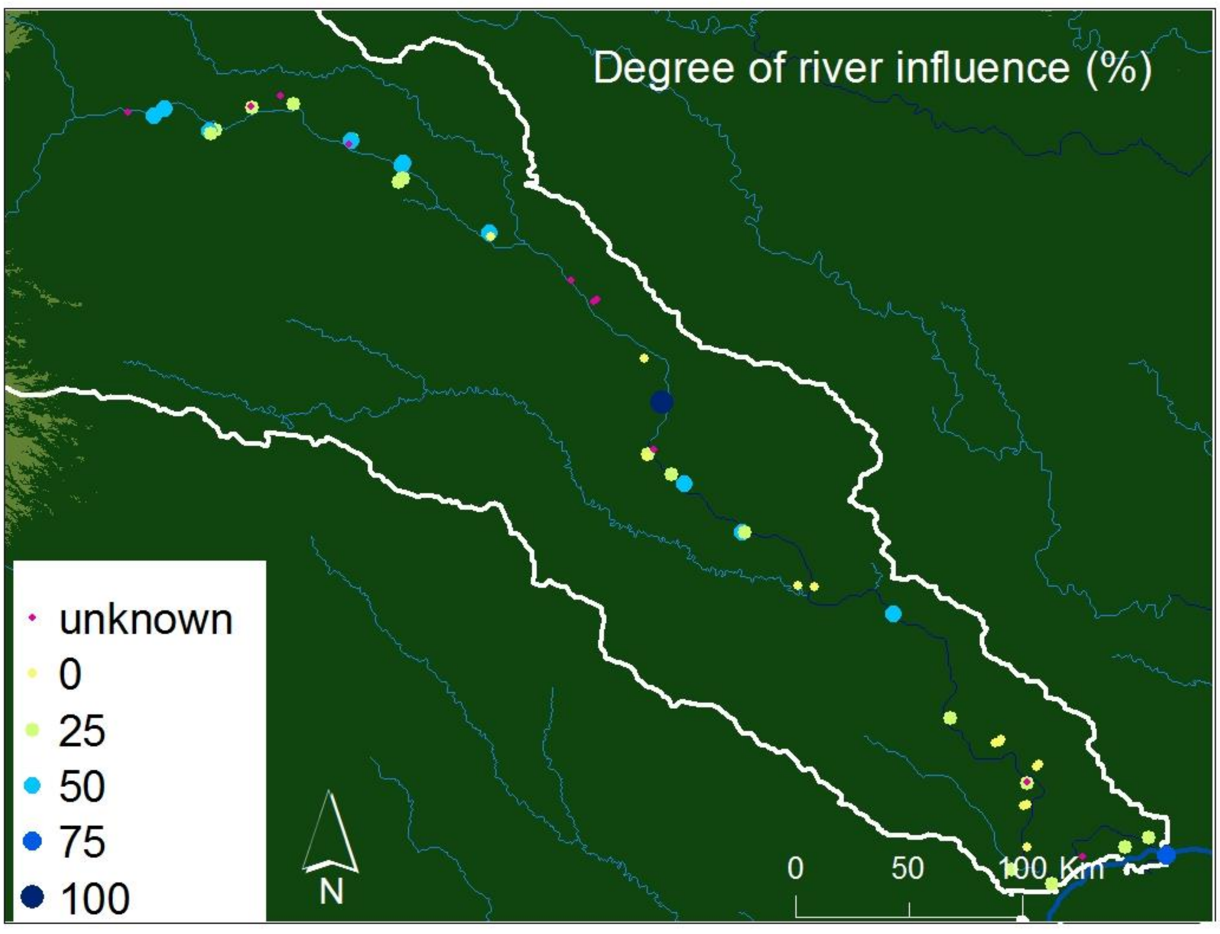


Figure 3.22. Degree of river water influence of floodplain sites along the Napo River grouped by class: 0 = 0% 25 = <0-25%, 50 = <25-50%, 75 = <50-75%, and 100 = <75-100%.

Table 3.1. Median of maximal cross-correlation coefficients of lagged hydrographs between river sites and distal and proximal floodplains along the three reaches of the Napo River (N_{lower}=3, N_{middle}=4, N_{upper}=3). Median number of lag days is included, and maximal of comparisons by environment are included.

Reach	Comparison	Maximal median r	median lag days
upper	all environments	0.43	2
middle	all environments	0.58	2.5
lower	all environments	0.24	25
all reaches	river vs proximal floodplains	0.55	1
all reaches	river vs distal floodplains	0.35	3
all reaches	proximal vs distal floodplains	0.43	4

Combining these three components of the flood regime—magnitude, duration, and the sources of the flood waters—I found a continuum of 15 flooding conditions spanning from short-lasting shallow inundation not controlled by the river to long-lasting, deep and river-controlled inundation (Figure 3.23). Six percent of the sites had anomalously high ion concentrations that could not be explained by mixing between the water sources and may be due to high evapoconcentration in shallow isolated open waters, and/or mineral weathering of recently deposited river-borne sediments. They are labeled as "unknown" river influence in Figures 3.22 and 3.23 and were excluded from further data analyses. If I consider the frequency and flashiness of flooding events the picture is even more diverse.

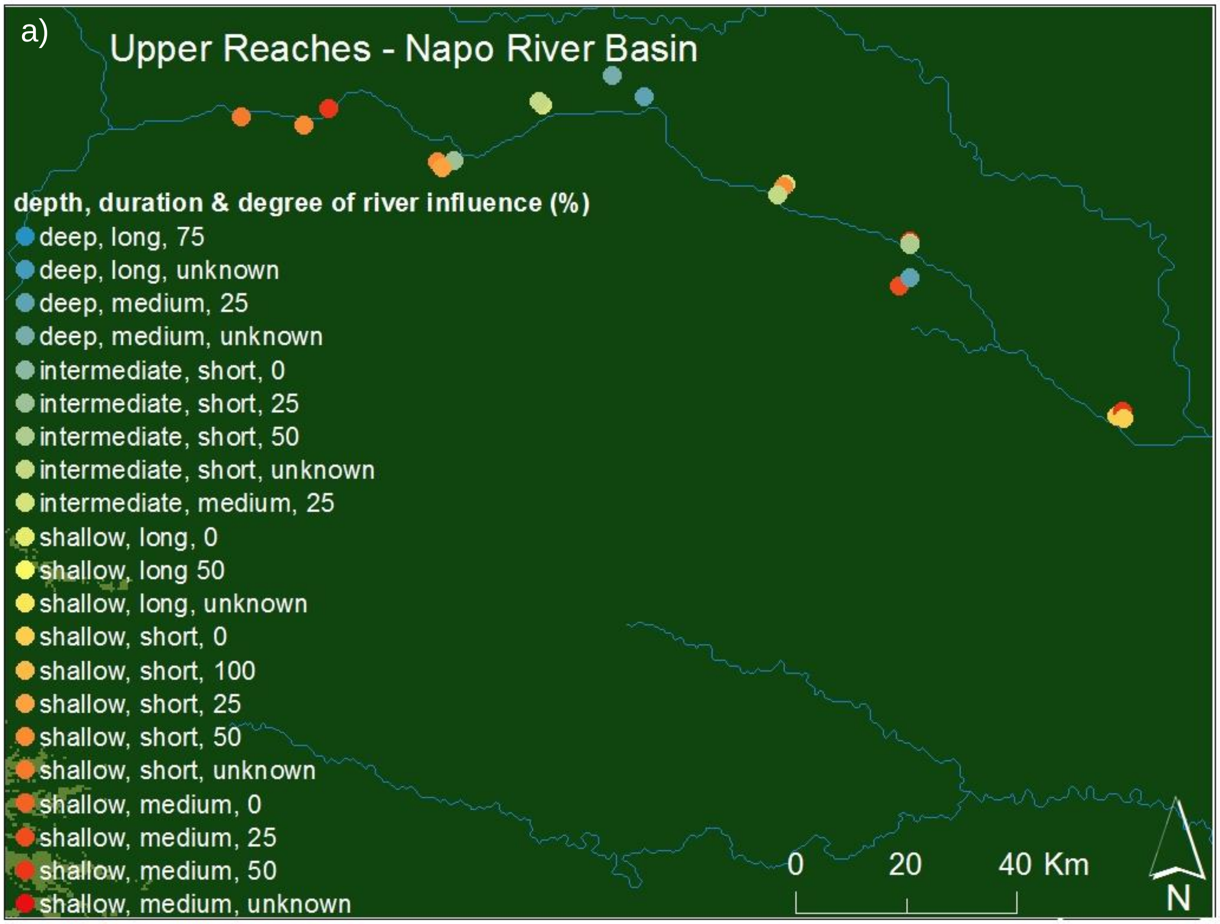


Figure 3.23. Characterization of flood regimes of the floodplains along the a) upper, b) middle, and c) lower reaches of the Napo River. Degree of river influence was grouped by class: 0 = 0% 25 = <0-25%, 50 = <25-50%, 75 = <50-75%, and 100 = <75-100%.

Figure 3.23. (cont'd)

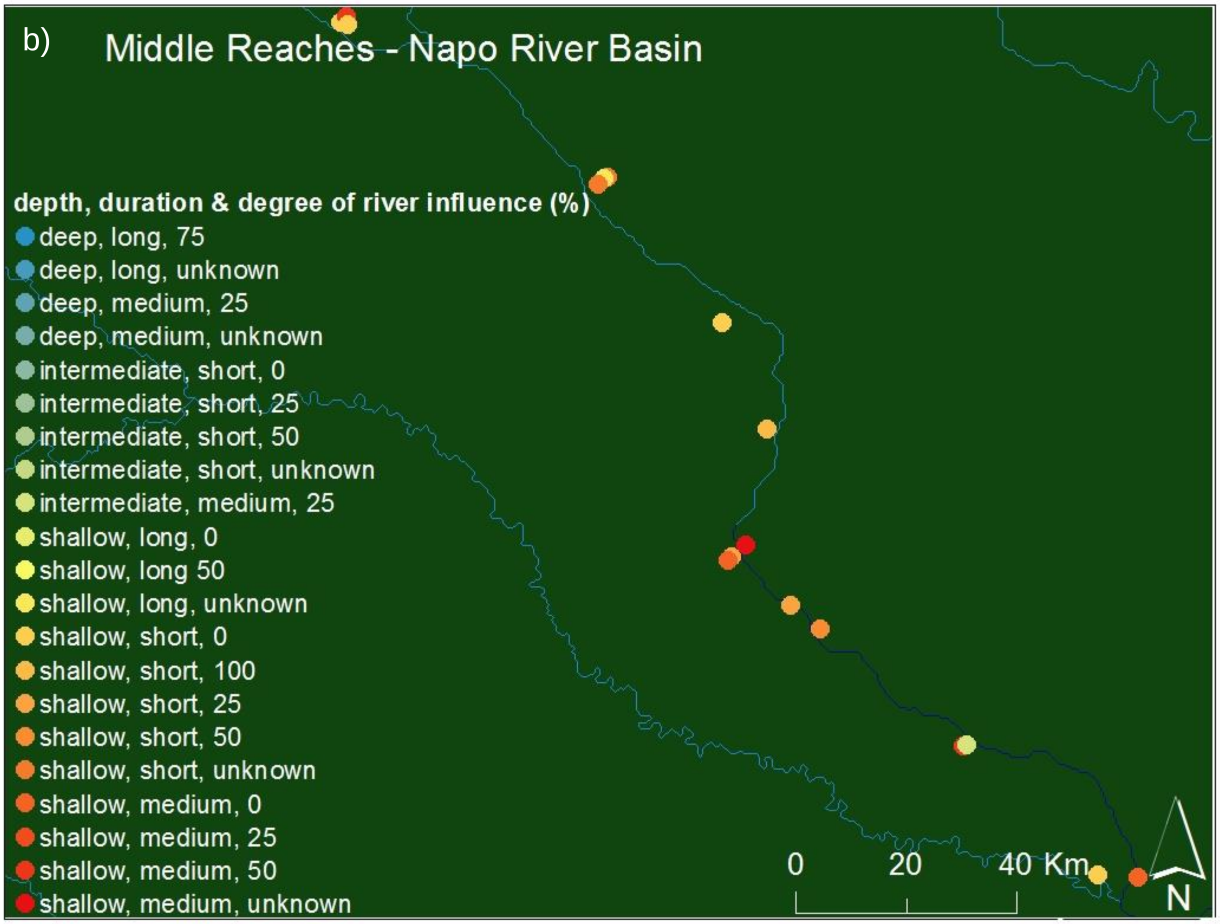
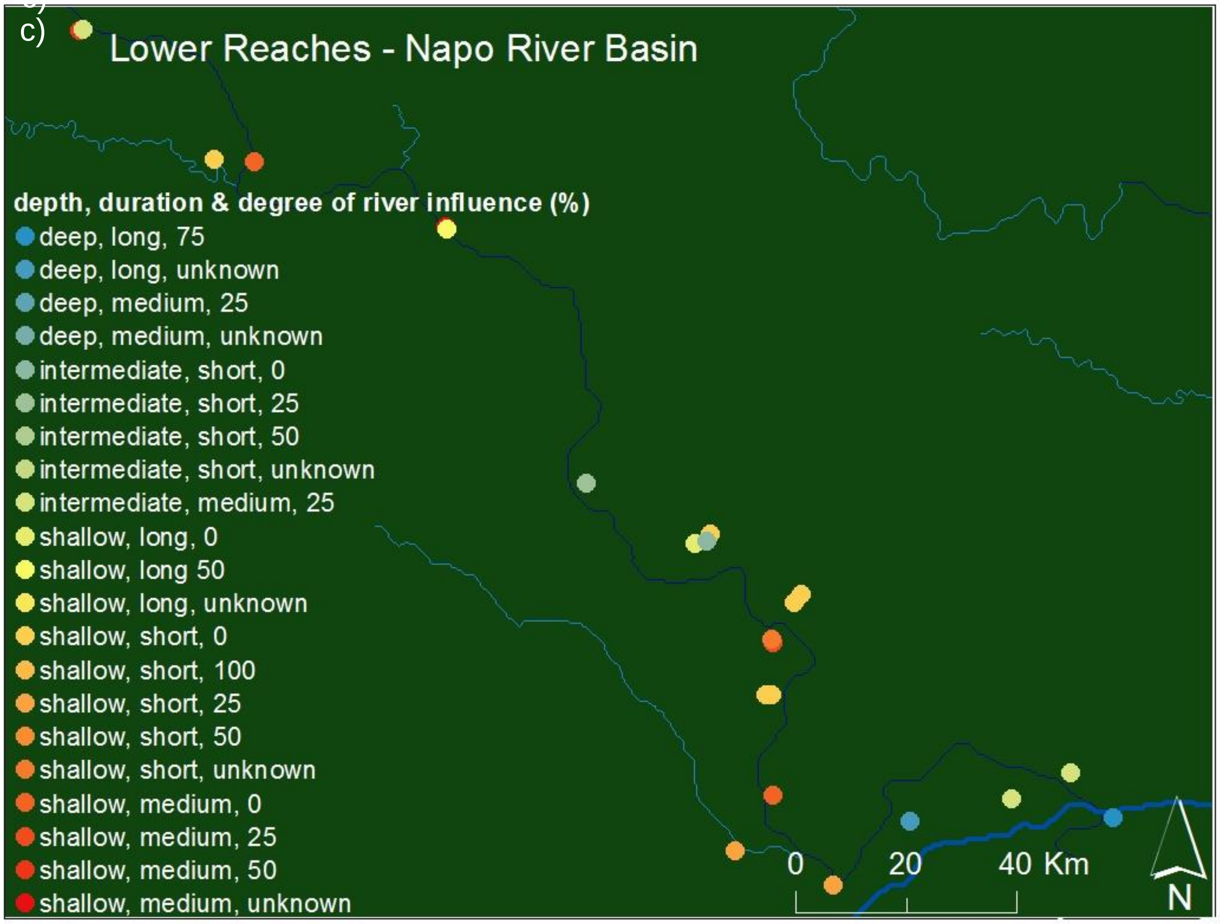


Figure 3.23. (cont'd)



Discussion

Flood regimes of the Napo River floodplains

Overall our findings suggest an important role of the Napo River in controlling the hydrology of floodplains in the region, although there were also many floodplain sites that were flooded primarily by locally derived precipitation and runoff (Figure 3.22). Based on the chemistry of the standing waters, approximately 75% of the floodplain sites were directly influenced by river water to at least some degree. Approximately a fifth of the floodplain sites was primarily flooded by river water while a fourth was primarily flooded by local waters. A potential explanation for these locally flooded floodplains is that they are relict floodplains on fluvial terraces perched above the reach of the river, although they may be flooded by river water during exceptional flood events (which I did not observe over the study period). Personal communication with local inhabitants and examination of historical hydrological records indicate past discharge episodes of larger magnitude and duration (e.g. Figure 3.24), with potential implications for the productivity and biodiversity of the ecosystems. Unfortunately I lack reliable elevation data with the necessary vertical resolution for most of the Napo floodplains to determine the elevation of floodplain sites relative to the range in river levels.

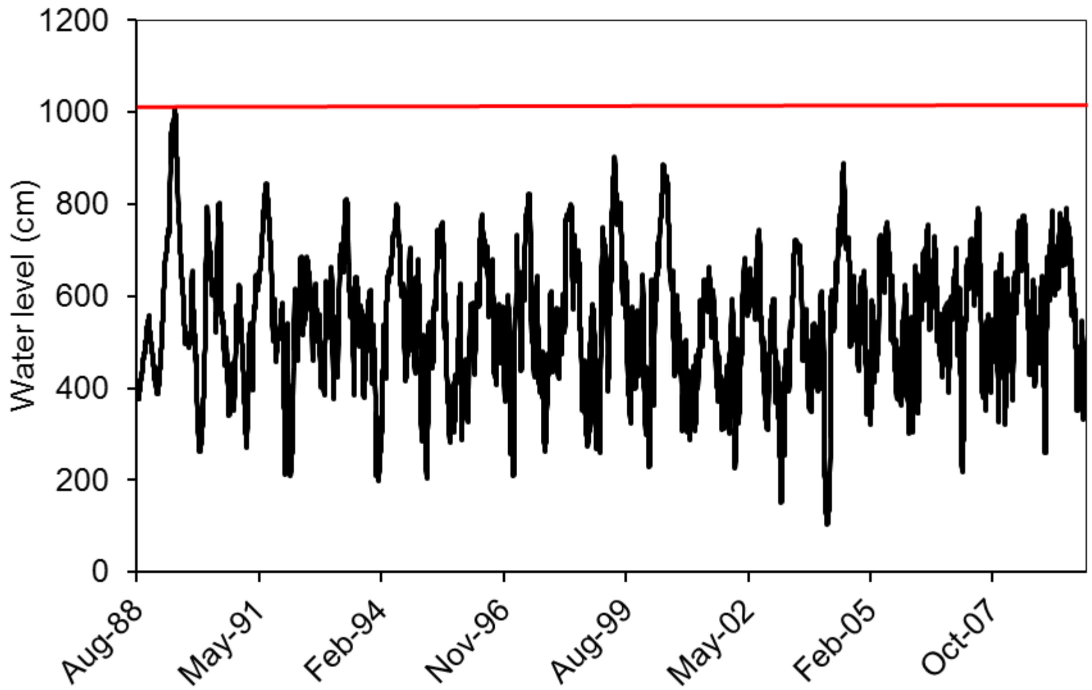


Figure 3.24. Napo River hydrograph near the confluence with the Amazon River (Mazán area) recorded by SENAMHI-PERU from 1988 to 2009. The red line marks the highest flood peak recorded in this station and that event is recalled in the oral tradition of local communities as a particularly deep and long-lasting flooding event.

Contrary to what I expected, I did not find a consistent longitudinal change in the degree of river influence on the floodplains along the river. This lack of clear pattern is interesting as I expected higher hydrological connectivity and overbank flooding towards the lowland reaches due to the larger amplitude of the river hydrograph there and the overall lower elevation of the terrain. Tributary inputs of large Andean and piedmont rivers (e.g., the Aguarico (Andean) or the Curaray (piedmont) rivers) could have accentuated the effects of Andean waters on the hydrology of the floodplains downstream from their confluence with the Napo River (Figure 3.22).

Based on the depth of inundation, the floodplains in the upper reaches seem to have a closer relationship with river hydrology than in the other two downstream reaches (Figures 3.19 and 3.23a). This suggests that these systems were indirectly controlled by backwater effects of local waters by the more frequent and flashier floods of the upper reach of the Napo River. The positive relationship between depth of inundation and frequency of flooding events supports this hypothesis, although the relationship is very weak (Figure 3.12c). On the other hand, outcomes of the cross-correlation analyses suggest that hydrographs of floodplains in the middle reach had a stronger relationship with river hydrology (Table 3.1), although floods in this reach had a longer lag to the river hydrograph than in the upper reach.

The spatial distribution of flood regimes in floodplains along the river was very heterogeneous, and the continuum of flooding conditions was found within all three main reaches of the river (Figure 3.23). When looking at the temporal variability of flooding, based on the decoupling of precipitation with river flooding in the lower reaches (Figure 3.2b) and on personal observations I believe that the same sites could potentially be flooded by different water sources during different periods of the year. In contrast, closer correspondence in timing of precipitation with high water levels of the river in the upper reaches (Figure 3.2a) would enhance backwater effects of local waters, as observed often in floodplains along this river reach that were directly connected to the river via tie channels.

Proximity to the river accounts largely for the variability in flooding conditions of floodplains proximal to the river, although median depth and duration of inundation were relatively similar in both proximal and distal floodplains (Figure 3.15). Overall, based on the chemistry of the waters floodplains proximal to the river had a larger degree of river influence than distal floodplains (Figure 3.14b). These results were statistically significant based on the Mann-Whitney test. However, when looking at this pattern in each of the river reaches I only found significant differences, based on the Kruskal-Wallis test, in the depth of inundation, which was larger in the upper reaches. Since depth of inundation was in general larger in both distal (less river-controlled) and proximal (more river-controlled) floodplains along this river reach (Figure 3.18a), I suspect that a combination of lower-lying floodplains in this formerly tide-dominated estuary due to neotectonics or lower sedimentation (Shanmugam et al. 2000, de Berc et al. 2005) might accentuate the effects of the more frequent flooding events of the upper reach of the river .

The apparent longer duration of inundation in the floodplains of the upper reaches of the Napo seems to be largely explained by cumulative inundation by frequent and flashier flooding events (Figures 3.11 and 3.13a), rather than by constant long-lasting inundation. The latter condition seems to be more prevalent in the less flashy lower reaches of the Napo; stronger seasonality (Figure 3.2b) and lower frequency of flooding (Figure 3.13c) limited the total duration of inundation in the lower reaches.

Ecological implications of flood regimes

These diverse flooding and connectivity patterns found across the Napo floodplains have profound implications for the ecology of these environments, and probably help explain the high levels of biodiversity of the Western Amazon. Paleo-ecological and geological evidence suggests that uplift of the Andes and subsequent complex drainage patterns and sedimentary dynamics created dynamic environmental conditions that enhanced the sympatric evolution of species in the region (Toivonen et al. 2007, Hoorn et al. 2010, Rossetti et al. 2012). Current diverse hydrological conditions seem to be the result of these geomorphological dynamics that occurred in the past and that are still maintained by the very active erosional and sedimentary processes of the Andean Amazon (Salo et al. 1986, Laraque et al. 2009a, Bernal et al. 2012, Bernal et al. 2013).

High predictability in the timing and magnitude of flooding in large river systems with monomodal flood regimes, like the Central Amazon or the Orinoco, has favored species with traits that help them benefit from inundation (Junk and da Silva 1997, Lewis et al. 2000, De Simone et al. 2002). In contrast, in highly unpredictable environments, like ephemeral pools or riparian zones along smaller streams and rivers, species develop spatial and opportunistic niche differentiation that allows them to be “always ready” rather than developing long-term life histories tuned to flood regimes (Barrat-Segretain and Bornette 2000, Poiani 2006, Wang et al. 2012). The higher flashiness and more frequent occurrences of flooding in the upper reach of the Napo River (Figure 3.13a) compared to its lower reaches (Figure 3.13c) and to other systems with monomodal flood regimes make floodplain environments along this reach of the river less stable and may thus impede adaptation by aquatic species to a predictable flood pulse. At the same time these features of the flood regime do not act as such a strong filter to the terrestrial biota. Thus, these flooding patterns may support the coexistence of more species with different life-histories and the maintenance of more complex food webs and species dynamics in the floodplains of the Napo River and similar rivers of the western Amazon compared to floodplains such as the Central Amazon with long-lasting, predictable, monomodal inundation.

The lower stress for the terrestrial biota in floodplains along the Napo River due to shorter duration and shallower depth of flooding compared to floodplains like the Central Amazon, allows the development of extensive forested floodplains along the river. These systems are light-limited because of their canopy and thus might have lower aquatic productivity levels than un-canopied floodplains, like those found in the Central Amazon or Orinoco Rivers (Furch and Junk 1993, Junk and Piedade 1993, Lewis et al. 2001). However, the proximity of these ecosystems to higher-nutrient river water from the Andes might partially compensate for the effects of limited light availability on productivity of aquatic water bodies (Hoorn et al. 2010). Also accumulation of organic matter in these forested environments might be higher than in un-canopied systems and might be partially responsible for the formation of peatlands (Lahteenoja et al. 2013), with implications for the carbon budget and emission of greenhouse gases from the region (Wright et al. 2013).

The more frequent flood peaks and deeper floodplain inundation of the upper reaches (Figures 3.3 and 3.18a) might also mitigate the effects of droughts on aquatic biota and might support the large upstream migration of many different species of fish maintaining spawning habitats during the low water level periods of the year.

The Napo River floodplains compared to other floodplains

Our observations from the Napo River indicate that its floodplains have more unpredictable, shallower, and shorter inundation than floodplains of large rivers with monomodal flood regimes such as the Amazon, Congo and Mekong Rivers, where inundation is relatively predictable, deeper and longer-lasting (Figure 3.25). In terms of the flashiness and unpredictability of flood regimes, the Napo River system is comparable to the flood regimes of river systems in the wet-dry tropics, such as those of tropical Australia (Warfe et al. 2011), with the difference that precipitation seasonality in the western Amazon is not nearly as marked as in Australia, and consequently there is much lower drought stress on biota in between floods (Figure 3.25).

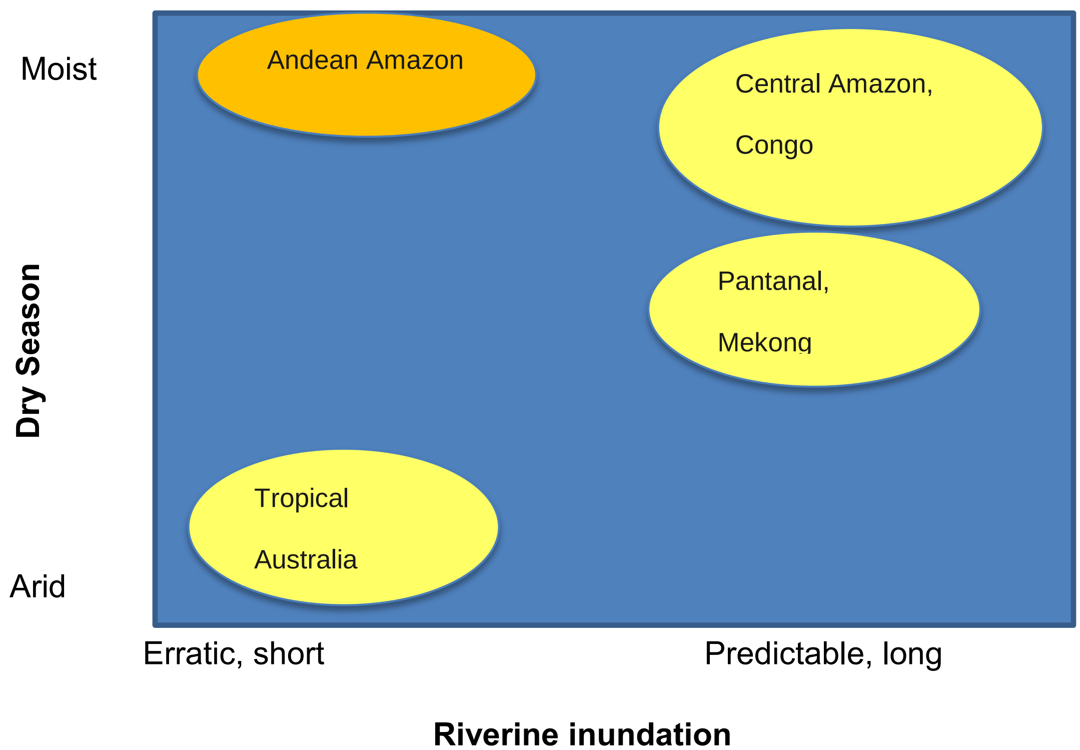


Figure 3.25. Floodplains of the Andean Amazon compared to floodplains of other tropical river systems in terms of the predictability and duration of inundation and the length of the dry season.

The very high levels of biodiversity of the Napo River region are the result of large spatial and temporal variability of climatic and geologic conditions, but also of the effects of diverse past and present hydrological conditions and geomorphological dynamics (Hoorn et al. 2010). Thus, maintenance of these hydrological patterns and of the processes that controls them is crucial for the maintenance of biodiversity in the region.

Implications for management and conservation

The Napo River Basin is increasingly affected by human activities and current development plans (Celi 2005, Finer et al. 2008, Finer and Jenkins 2012). Modification and dredging of the main stem of the Napo River are being considered to facilitate industrial navigation from its confluence with the Coca River, in Ecuador, to its mouth at the Amazon River in Peru (Serman and CSI 2010). Transformation of the Napo River into an industrial barge channel would require substantial interventions to increase and stabilize its channel depth. Changes in the water-level regime of the river could have tremendous consequences for the hydrologic connectivity of the river with the floodplains, with potential effects on floodplain water levels and the extent of inundation. Alterations of the hydrology of these environments could have severe and long-lasting effects on the ecology and biodiversity of these systems.

Development of the river system upstream of the lowland reaches can also affect floodplain ecohydrology. For example, a large hydroelectric project (Coca-Codo Sinclair) (GDE 2014) is being developed in the Andean portion of the Napo (Coca River) in Ecuador, and it may alter the timing of the multiple and less predictable flooding events of the upstream reach of the lowland Napo River, with potential implications for the timing of floodplain inundation. Mitigation of some of these impacts to the ecohydrology of these systems would depend on the maintenance of the flow and flood regimes of the southern headwaters of the Napo (named the Napo River) which are also being altered by the fastest rate of hydropower and road development and land cover change of the Upper Napo River Basin (Celi 2005).

Perhaps the most severe impacts to the hydrology and ecology of the lower Napo River would be the development of the Mazán hydropower project (GRL 2013), located ~80 km from the confluence of the Napo River with the Amazon River. This project plans to divert approximately 85% of the Napo River flow to the Amazon River through a diversion channel leading to a hydroelectric facility, building a dam across the mainstem of the Napo downstream of its confluence with the Mazán River. Environmental impacts of the project have yet to be comprehensively assessed, but the proposed works would be expected to substantially lower the water levels of the river and floodplains downstream of the canal and the dam, with subsequent changes in the hydrology and ecology of aquatic habitats. Impacts of the damming would extend upstream and permanently flood habitats that are only flooded part of the year now, but the area of influence has yet to be determined.

In addition to direct impacts of the Mazán Dam on local hydrology, the blockage of the river by the dam and the dramatic change in water levels above and below the dam may seriously affect many species of migratory fishes and aquatic mammals that depend on habitats on the upstream reaches for spawning and downstream reaches for growth. Some of these fishes (e.g. *Prochilodus* spp., *Brycon* spp.) travel long distances, in some cases across the entire Amazon River (e.g., *Brachyplatystoma* spp.) to spawn in habitats associated with the river reaches near the Andean foothills (Stewart et al. 2002, Galacatos et al. 2004, Junk et al. 2007). They link complex food webs in the estuary and central part of the Amazon with diverse networks in the foothills of the

Andes, and indicate that they are dependent on the hydrological connectivity of diverse aquatic ecosystems across the basin (McClain and Naiman 2008). Disruption of migratory fish life histories could impact food webs throughout the basin, including people living along the Amazon River who are highly dependent on the local fisheries (Junk et al. 2007).

Unfortunately, this development pattern is being replicated in most of the Western Amazon (Finer and Jenkins 2012, Kareiva 2012), threatening to impound the last free-flowing rivers and potentially degrade the ecological integrity of some of these environments and the ecosystem services that they provide. Since we know relatively little about the ecohydrology of these ecosystems, it is imperative to conduct more ecohydrological research in the region. In that sense, this study improves our understanding of floodplain ecosystems of the Western Amazon and provides fundamental information to improve management and promote conservation in the region.

Conclusions

Overall our data show that there is a continuum of floodplain hydrology along the Napo River ranging from control mainly by river flooding to control by local rainfall and runoff with little or no influence of the river, and that this diversity occurs along the entire length of the lowland river corridor. River water was at least a partial source of flooding in at least 75% of the floodplain sites during the years of this study, and may be more important during higher flood events. The variable degree of river influence was related to proximity to the river, and presumably to floodplain geomorphology, although the available elevation data are inadequate to discern whether a particular location is potentially within reach of river flooding. This continuum of ecohydrological conditions is likely to be one factor that explains the high levels of biodiversity of the region. Protection and management of these floodplain ecosystems should consider their variable hydrology, and in particular the relative importance of the river vs. local water. Further research is needed to understand the ecological implications of the hydrological variability I have documented here, and how hydrological alterations associated with proposed large-scale development projects may affect floodplain ecosystems, the biodiversity they support, and the services they provide to people.

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CONCLUSIONS

This dissertation on the ecohydrology of floodplains of the Napo River has increased our understanding of the extent and diversity of aquatic habitats in the Napo River region, and of the role that the river and local rain and runoff play in the hydrology of these ecosystems. To date this is the most comprehensive field study of tropical floodplain ecohydrology of the Western Amazon, and provides important understanding of the hydrology of these environments that should be applicable to the broader region.

The Napo River floodplains span a continuum of hydrological regimes ranging from deep and long-lasting to shallow and short-lasting inundation. These floodplains have different degrees of river influence, from river-controlled hydrology to areas only flooded by local waters. Approximately 75% of the floodplains have some degree of direct river influence as indicated by the chemistry of their flood waters, however, based on historical hydrological records and personal communications with the local inhabitants I expect a greater area of floodplain may be directly influenced by the river during the largest flood events. Among the 25% of the floodplains flooded only by local waters, some are indirectly influenced by backwater effects during high river levels and others are probably relict floodplains perched above the river that are not currently reached by the highest water levels of the river. Unfortunately I lack elevation data for most of the floodplain sites to determine with more certainty the degree of connectivity between the river and these floodplain ecosystems.

Andean river water was diluted by local water inputs along the length of the river, which is indicative of the contribution of local waters to the total discharge of the river. This pattern was consistent through the seasons, suggesting that local rain and runoff have an attenuating effect on the chemistry of rivers originating from the Andes.

Fifteen hydrological regimes were identified in the Napo River floodplains, and this variability may help explain the high levels of biodiversity of the Western Amazon. Compared to the floodplains of larger and more predictable rivers, like the Central Amazon or the Orinoco, the Napo River floodplains have more episodic, shallower and shorter inundation. Thus, floodplains along the Napo are more densely forested than floodplains of the Central Amazon, and likely support more plant and animal species that tolerate changing hydrological conditions rather than being adapted to benefit from inundation, the latter being common in the more predictable flooded systems. In this sense, floodplains along the Napo are similar to floodplains in the wet-dry tropics of northern Australia, with the difference that seasonality in rainfall is far more even throughout the year, which favors dense and diverse forests.

Outcomes of this study have allowed us to improve our ability to measure inundation of extensive and remote floodplains using novel and inexpensive approaches that could be applied in similar settings elsewhere. This study has increased our knowledge of floodplain ecosystems of the Western Amazon, and it informs the management and conservation of these ecosystems. Also, this improved understanding of floodplain hydrology is fundamental for the assessment of the potential environmental impacts to river and floodplain ecosystems of the region by hydrological modifications such as hydroelectric projects and waterways.

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