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Amazon floodplain hydrology and implications for aquatic conservation

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Abstract

1. The amplitude, duration, frequency, and predictability of runoff and inundation of aquatic habitats are key hydrological characteristics linked to aquatic ecosystem functioning and biodiversity, but they are seldom integrated into analyses of Amazon floodplain ecology. Remote sensing approaches, measurements and modelling of floodplain hydrology provide a basis for this integration.
2. Effective legislation to protect floodplains and other wetlands depends on operational definitions that require application of hydrological data.
3. Extent and changes of flooded areas are linked to fish diversity and to presence and growth of flooded forests and floating plants.
4. Dam construction reduces river system connectivity and modifies the flood pulse, with major negative implications for floodplain ecosystems adapted to and dependent on a natural flood regime.
5. Trends and variability in climate plus deforestation are altering the Amazon's hydrological cycle, causing changes in discharge and flooded area with concomitant ecological impacts.

KEYWORDS

drought, fish, hydroecology, hydropower, lake, modelling, vegetation, wetland

1 | INTRODUCTION

Aquatic ecosystems of the Amazon basin vary from small streams to massive rivers often bordered by narrow riparian zones or immense floodplains with vast areas of seasonally flooded forests and lakes (Figure 1). Hydrological conditions are central to the existence, biodiversity, and ecological functioning of all these aquatic ecosystems. Topographic, climatic, and landscape features range from Andean highlands in the west to lowlands across the central and eastern basin, and these features strongly modulate hydrological conditions (Junk & Piedade, 2005). As human activities increasingly modify the hydrology of Amazon aquatic ecosystems, there is a critical need to improve understanding of how changes in the hydrology of the Amazon basin manifest in aquatic ecosystems across the basin.

Biodiversity encompasses species, biological communities and ecosystems, and, in aquatic habitats, is strongly linked to temporal and

spatial variations in hydrological conditions. For example, analyses of large rivers in the Neotropics and tropical Australia revealed that systems with rhythmic annual floods have higher fish species richness, more stable avian populations, and elevated rates of riparian forest production than those with arrhythmic flood pulses (Jardine et al., 2015). Many species in the Amazon are adapted to and depend on floodplains and associated wetlands (Junk, 1997). Furthermore, the geomorphology of the floodplains is influenced by and determines the flooding patterns (Park & Latrubesse, 2017), which contribute to aquatic biodiversity (Hamilton, Kellndorfer, Lehner, & Tobler, 2007).

Castello and Macedo (2016) emphasized hydrological connectivity as a key aspect of the integrity of Amazonian freshwater ecosystems. Junk et al. (2011) delineated 14 major types of naturally occurring wetlands in the lowland Amazon for which the amplitude, duration, frequency, and predictability of inundation are key characteristics. Human activities, such as deforestation, construction of



FIGURE 1 Flooded forest in the Anavilhanas archipelago, lower Negro River as river level is beginning to decline. Trees in flooded forests, the largest habitat on Amazon floodplains, vary in growth as waters rise and fall. When flooded, they offer food and cover for many fishes. Interactions of hydrological conditions with the ecology of flooded forests are discussed in the text

dams, reductions in runoff due to water extractions, altered discharge, and urban development, as well as intensification of the hydrological variability by climate change, are perturbing the natural hydrology of the Amazon basin on increasing scales.

Although ecological, social, and economic impacts of these hydrological alterations have been investigated, to date, understanding and measurements of hydrological fluxes and processes have not been adequately incorporated into most ecological and conservation analyses of the diverse aquatic ecosystems of the Amazon basin. Missing in the conservation literature is sufficient consideration of recent advances in hydrological modelling and remote sensing, which provide a sound basis for linking changes in hydrology to the integrity and conservation of Amazon lakes, rivers, and wetlands.

Here, hydrological perspectives on conservation of aquatic ecosystems are provided, with a focus on lowland floodplains, the largest aquatic system in the Amazon basin. First, relevant aspects of Amazon hydrology with a focus on inundation hydrology of floodplains are discussed to frame the context for ecological functions and biodiversity conservation. Second, extant hydrological conditions and likely hydrological changes and their implications for aquatic conservation are presented and discussed.

2 | HYDROLOGY OF THE AMAZON BASIN

2.1 | Rivers, streams, and inundated areas

The Amazon River and its major tributaries have annual monomodal hydrographs with amplitudes from 2–18 m depending on location and year (Richey et al., 1986). A several-year cycle of interannual variation in discharge correlates with the El Niño–Southern Oscillation (ENSO; Richey, Nobre, & Deser, 1989). Analyses of rainfall reveal an interannual mode in variance about every 5 years in the northern Amazon basin and decadal scales of variability in northern and southern regions (Marengo, 2004). Anomalously large or small amounts of

rainfall, leading to especially high or low water level in rivers and lakes, have been linked to intense ENSO events and strong warming of surface waters in the tropical North Atlantic (Marengo et al., 2008). Rainfall rates are often intense and associated with convective clouds (Figures 2 and 3).

The $\sim 4 \times 10^6$ km of streams throughout the Amazon basin (Beighley & Gummadi, 2011) harbour a diversity of aquatic organisms and depend on runoff from their catchments. Few measurements of the hydrology of these streams are available, as summarized in Tomasella, Neill, Figueriedo, and Nobre (2009). Modelling of hydrological processes and runoff at the catchment scale provides further understanding and information on streams. For example, Niu, Shen, Chambers, Melack, and Riley (2017) applied a process-based hydrological model to examine the sensitivity of hydrological budgets and stream discharge to annual precipitation in an upland Amazon catchment. They found that annual precipitation was the major control of surface runoff, whereas evapotranspiration variability was less important.

Linked to changes in river and stream stage are large seasonal and interannual variations in extent of inundation of thousands of lakes and associated wetlands and riparian zones (Hess et al., 2015; Sippel, Hamilton, & Melack, 1991). To estimate the area of the aquatic habitats is quite a challenge given the large size of the Amazon basin



FIGURE 2 View across a floodplain lake in the Anavilhanas archipelago (Negro River) in an afternoon rainstorm illustrating an intense deluge typical of convective clouds throughout the Amazon



FIGURE 3 Intense rain falling in a flooded forest of the Anavilhanas archipelago (Negro River)

and the wide range of aquatic environments from headwater streams (<1 m across) to floodplains fringing major rivers (tens of kilometres wide). Beighley and Gummadi (2011) combined hydraulic geometry with a high-resolution drainage network and estimated, for drainage areas from 1 to 431,000 km² and channels >2 m in width, that the Amazon basin contains 4.4×10^6 km of channels with a combined area of about 60,000 km². Hess et al. (2015) used synthetic aperture radar (SAR) data with 100 m resolution to estimate that the lowland Amazon basin (the region <500 m asl) has total floodable area of ~800,000 km² with about three-quarters covered by periodically inundated forests (Figure 1). Riparian zones along streams are intermittently flooded and further increase wetland area.

2.2 | Floodplain hydrology

Floodplains border most rivers and streams throughout the Amazon basin and represent the most extensive aquatic habitats, harbour a diverse biota, and are important economically. The hydrology of floodplains is complex because it combines local catchment inputs with regional-scale fluvial fluxes, both modulated by climate conditions. Measurements and modelling of these integrated processes is challenging and difficult, yet essential for understanding the ecological conditions and functions of the Amazon basin.

Mertes (1997) examined hydrological aspects of inundation dynamics of floodplain systems and introduced the concept of the perirheic zone, the mixing zone of waters with different characteristics. Junk, Bayley, and Sparks (1989) emphasized the flood pulse and defined floodplains in terms of river stage, associated physical and chemical conditions, and adaptations of organisms to these conditions; Junk (1997) elaborated these concepts for the central Amazon. However, hydrological processes and fluxes have seldom been integrated into analyses of the flood pulse and its connection to Amazon floodplain ecology. As measurements and modelling of floodplain hydrology have developed, their inclusion in the study of aquatic habitats in Amazon floodplains is a critical need. Hence, we review the current understanding of relevant floodplain hydrology in the Amazon basin to stimulate its incorporation into ecological, management, and conservation research.

The hydrology and hydroecology of Amazon floodplains can be characterized by (i) the flood pulse (i.e. the amplitude, duration, frequency, and predictability of inundation), (ii) the sources of water causing inundation, (iii) connectivity of the rivers and floodplain habitats, (iv) residence times of organisms, materials, and water within the floodplain, and (v) a seasonally flooded ecotone called the aquatic–terrestrial transition zone (ATTZ). As noted by Park and Latrubesse (2017), the extent and inundation of the ATTZ depends on the spatial and temporal connectivity among different geomorphological units. These factors are explicit and/or implicit in the measurements and models of hydrological processes in the Amazon basin. A general water balance equation, which can be applied at multiple spatial scales from specific lake–floodplain systems to whole reaches of major rivers, is presented first and is followed by examples of

measurements of its terms. The present status of inundation models and applications of remote sensing to floodplains are then discussed.

2.2.1 | Analyses of water balances

The water balance of a floodplain can be expressed by the equation

$$\Delta S = P + R \pm L \pm H \pm G - E$$

where ΔS is the change in volume of water, P is rainfall onto water surfaces, R is inflowing upland runoff, L is exchange of water in either direction to adjacent floodplains, H is exchange of water in either direction to an adjacent river, G is exchange with groundwater, and E is evaporation.

Each of the terms varies on multiple temporal and spatial scales. A typical water year can be divided into four hydrological phases: low, rising, high, and falling water levels. The sources and movements of water to, through, and from the floodplain during these phases changes through the seasons and varies among different lakes. Determination of a water balance for a floodplain requires bathymetry of the basin and measurements or calculations of all the processes. However, bathymetric data are available for very few Amazon lakes and floodplains, and appropriate meteorological and hydrological measurements have rarely been made. Only three hydrological analyses that combine local data with calculations for specific floodplains are available, and they illustrate the complexity of these environments. Figure 4 illustrates how the proportion of water from different sources varies over a hydrological cycle and contrasts the relative importance of local runoff versus mainstem river inputs. The simplified diagram is derived from studies of Lake Calado and the Curuaí floodplain.

The first analysis of a floodplain water balance was performed at Lake Calado, located in the central Amazon (3.15°S, 60.34°W;

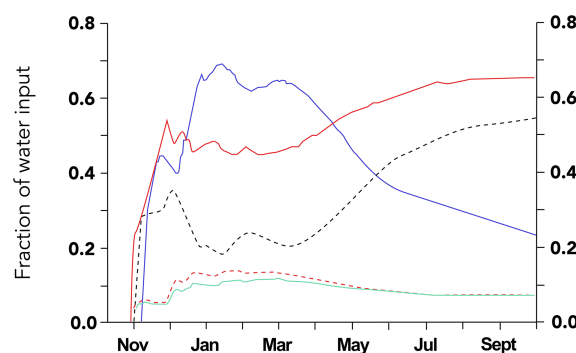


FIGURE 4 Fraction of water contributed from major inputs to floodplain systems. Patterns are derived from data summarized in the text from lakes Calado (data shown for 1983–1984; Lesack & Melack, 1995) and Curuaí (data from 2001–2002; Bonnet et al., 2008). Key to lines: Solimões River input to Calado (solid blue); upland catchment runoff to Calado (dashed black); Amazon River input to Curuaí (solid red); upland catchment input to Curuaí (solid green); aquatic–terrestrial transition zone catchment input to Curuaí (dashed red). Minor inputs from seepage and direct rainfall are not shown

Lesack, 1993, 1995; Lesack & Melack, 1995). Over the course of a water year, water level changed 10 m, and local runoff contributed 57% of the total water input, river inflow 21%, rainfall directly onto the lake 11%, inflow from an adjacent lake 6%, and seepage 4%. Bonnet et al. (2008) examined the inundation hydrology of the Curuaí floodplain (2.2°S, 55.5°W), located in the eastern Amazon, and found that the Amazon River dominated the inputs of water year-round, accounting for about 77% of the annual total, on average. Rainfall and runoff accounted for about 9% and 10% respectively, and seepage accounted for 4%. Bonnet et al. (2017) combined measurements and a simple hydrological model complemented by electrical conductivity data to the Janauacá floodplain (3.38°S, 60.3°W; Figure 5) and found that the Solimões River was the main input, accounting for 93%, on average; direct precipitation and runoff from uplands contributed $\leq 5\%$ and $\leq 10\%$ respectively, and seepage was estimated to be $< 1\%$. The differences among Calado, Curuaí, and Janauacá in the relative contribution of the mainstem river versus local inputs reflect, in part, differences in local catchment area (CA) relative to floodable area (FA): Calado, CA/FA = 7; Curuaí, CA/FA = 2; and Janauacá, CA/FA = 2. The different water sources often have large differences in dissolved and suspended components that influence ecological conditions, as described in numerous publications and summarized in several (Melack, 2016; Melack & Forsberg, 2001; Richey, Mertes et al., 1989).

2.2.2 | Modelling of inundation

Models of inundation have been developed for three spatial scales. The nature of the processes that are included, the data requirements, and the computational intensity vary among the models. Their potential application to issues related to aquatic conservation will depend on the site specificity and timescale of the questions.

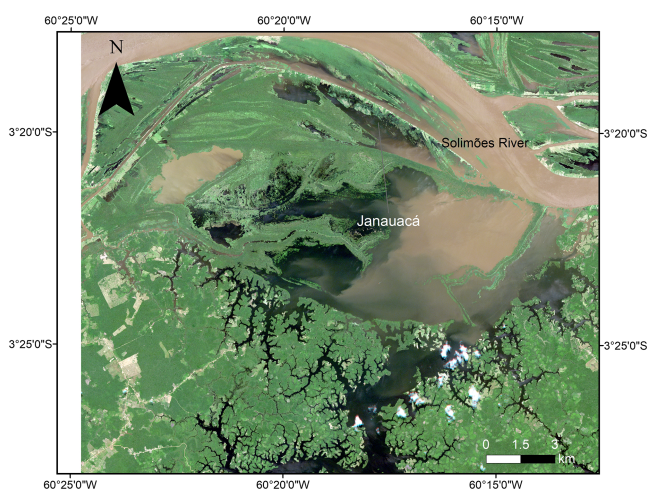


FIGURE 5 Janauacá floodplain in the central Amazon basin. Rising-water image (Planet® RapidEye-L3A, 5 m resolution, March 2015) showing inflows of sediment-laden water from the Solimões River mixing with local runoff and lake water. The portion of water from different sources varies seasonally, as calculated and modelled by Bonnet et al. (2017)

Ji et al. (2019) adapted a process-based hydrological model with surface and subsurface components to examine the particular hydrological characteristics of the Calado floodplain and lake. The model, the Adaptive Watershed Simulator coupled with the Community Land Model (PAWS+CLM), represents hydrological, energy, elemental cycles, and vegetation dynamics based on physically based equations (Shen, Niu, & Phanikumar, 2013). With the model, Ji et al. (2019) were able to assess the fraction of water in the Calado lake that came from the Solimões River for a range of hydrological conditions and the relative importance of the local basin, rainfall distribution in time, and inter-annual variability in rainfall and river stage for water sources in the lake.

Hydraulic models of flooding have been applied at mesoscales to Amazon floodplains. In the first application of a two-dimensional hydraulic model (LISFLOOD-FP), Wilson et al. (2007) found that more than 40% of river flow was routed through the floodplain near the confluence of the Purus and Solimões rivers. The model matched well with inundation extent estimated from SAR data at high water levels but over-predicted inundation at low water because small drainage channels were below the spatial resolution of the topographic data used. Rudorff, Melack, and Bates (2014a, 2014b) applied the LISFLOOD-FP model, together with a local hydrological model, to the Curuaí floodplain over 15 years. They combined digital topography derived from the Shuttle Radar Topography Mission with extensive echo-sounding data to generate a digital elevation model that included narrow channels. The model simulated changes in water elevation, flooding extent, and river–floodplain flows. Dominant sources of inflow varied seasonally, and average annual inflow from the Amazon River represented 82% of inputs from all sources.

Several models of river discharge and associated inundation have been applied at the basin scale (Beighley et al., 2009; Coe, Costa, & Howard, 2007; Getirana et al., 2012; Miguez-Macho & Fan, 2012; Paiva et al., 2013; Yamazaki, Kanae, Kim, & Oki, 2011). When forced with climate data, these models can provide estimates of inundated area and water depth for relatively long time periods (> 50 years) and of interannual and spatial variations in floodplain inundation associated with variations in precipitation. Although these models calculate river discharges reasonably well, their ability to represent inundation of floodplains and wetlands varies. The lack of sufficiently accurate and detailed digital elevation models is one major issue arising from the complex and subtle topography of floodplains. For example, Coe et al. (2007) and Paiva et al. (2013) had good matches between modelled area flooded and remotely sensed inundation in the central basin but underestimated flooded area in the Bolivian Amazon and lower mainstem in comparison with remotely sensed inundation.

Basin-scale models, because of simplifications or the coarse spatial resolution required to simulate large areas, cannot simulate small but important spatial differences in water height across the floodplain. Interferometric processing of SAR data indicates that considerable spatial and temporal variations in elevations of water surfaces occur across Amazon floodplains (Alsdorf et al., 2000; Alsdorf, Bates, Melack, Wilson, & Dunne, 2007). These gradients, although typically only a few centimetres per kilometre, can determine the direction of flow across the floodplains.

Another issue is that most models assume that flooding of the floodplains occurs only when river stage surpasses bankfull, when in fact it occurs via channels, which allow water to enter before levees are overtopped, and these channels and the levee heights are often not represented by the topographic data (Figure 6). Hence, the timing of inundation is not correct. Conversely, at low water, the channels can result in lower water levels on the floodplains than indicated by the levees.

Other important aspects of floodplain hydrology are the proportion of water flowing in the rivers that exchanges with the floodplains and the length of time the water remains in the river channels and on the floodplains. Sorribas (2016) modelled both aspects by combining a new water-parcel tracking module with the basin-scale hydrological model used by Paiva et al. (2013). He found that simulated travel time of water in the main channels is generally less than 70 days and that total travel time on floodplains exceeds 120 days. Although, on average, ~20% of the total flux of water in the basin is exchanged with the floodplains, the ratio between river–floodplain discharge and basin discharge ranged between 5 and 40%, which is comparable with the range estimated from observations by Richey, Mertes et al. (1989) and Alsdorf, Han, Bates, and Melack (2010).

2.2.3 | Remote sensing of floodplains

Areal extent, water level, and temporal changes of inundation on local, regional, and basin-wide scales can be determined with remote sensing, including passive and active microwave, laser, visible and near-infrared, and gravity anomaly detection systems (Melack, 2004, 2016). Several products derived from remote sensing are of particular relevance to hydrological aspects of aquatic conservation. Hess et al. (2015) used SAR data to determine (at low and high water levels and at spatial resolution of about 100 m) floodable area, inundated area, and areal extent of major habitats in the whole lowland Amazon basin. The high-resolution videography used to validate this SAR



FIGURE 6 Channel connecting the Amazon and Tapajós rivers in the eastern Amazon basin with typical river boat

product provides detailed habitat information (Hess et al., 2002). Time-series of optical and SAR data have been analysed for specific locations and can complement ecological studies (Arnesen et al., 2013; Canisius, Brisco, Murnaghan, Van Der Kooij, & Keizer, 2019; Ferreira-Ferreira et al., 2015; Renó, Novo, Suemitsu, Renno, & Silva, 2011). Besides providing valuable scientific information, these remote-sensing products can be used to identify priority areas for protection and conservation, and to aid in proper management of these areas.

Multiyear seasonal variations in inundation are available at a 25 km scale (Hamilton, Sippel, & Melack, 2002, 2004; Papa, Prigent, Jimenez, Aires, & Rossow, 2010; Prigent, Papa, Aires, Rossow, & Matthews, 2007). Aires, Papa, and Prigent (2013) suggested an approach to downscale these spatially coarse products. Comparison of these products with SAR-based estimates of inundation areas indicates generally good agreement for moderate to large inundated units. Seasonal variations in the water stored on Amazon floodplains at ~100,000 km² resolution can be detected from anomalies in the Earth's gravity field (Chen, Wilson, & Tapley, 2010; Xavier et al., 2010). These products are especially useful in the detection of large-scale changes in hydrological and ecological conditions associated with climate anomalies and in the validation of regional models of inundation.

Although recent remote-sensing and modelling results are valuable and promising, limitations of the available measurements continue to hinder estimation of inundation dynamics. Gauges of river stage are widely spaced, floodplains remain ungauged except during field studies at a few locations, and satellite-borne altimeters, both radar and laser based, have wide spacing between tracks. Passive microwave and gravity anomaly sensors have coarse spatial resolution, and SAR systems have had limited temporal or spatial coverage, although new SAR sensors offer repeated regional coverage at high resolution. Topographic data require considerable work to remove vegetation, and bathymetric data are available for few floodplains. A promising approach derived from a time series of Landsat imagery and water levels developed by Fassoni-Andrade (2020) provides improved regional floodplain bathymetry. There is a critical need to collect additional hydrological and floodplain habitat data in order to produce more accurate and comprehensive data sets that could be used to inform ecological studies on Amazon floodplains.

3 | IMPLICATIONS FOR AQUATIC CONSERVATION OF HYDROLOGICAL CONDITIONS AND CHANGES

Floodplain ecology is governed by the seasonal water balance, including the amounts and sources of inputs and outputs, and their natural variations and modifications by human activity. Although this hydrological information is lacking for most sites, regional models and remote-sensing products can be incorporated into aquatic conservation studies and efforts. Metrics that characterize hydrological variability and connectivity, and their modification by dams, land cover

and land use change, and prolonged droughts or exceptional floods, have direct application to the ecological status of aquatic ecosystems. These types of information are available and have the potential to improve understanding of the underlying processes leading to observed patterns of and changes to hydrology and floodplain characteristics. To illustrate their application, examples are provided of how hydrological information and analyses of current and likely future hydrological changes can be applied to aquatic conservation in the Amazon basin.

3.1 | Legal protection

Effective legislation to protect floodplains and other wetlands depends on operational definitions that require application of hydrological data. In Brazil, although the benefits of floodplains to local populations and the value of biodiversity in wetlands are well known, no national policy regulating wetland protection or management exists. Although not specifically designed to protect wetlands, the Brazilian Forest Code directs that riparian forests must remain intact on all private and public lands. The definition of how much forest adjacent to streams and water bodies must remain intact (from 30 to 500 m from the stream, depending on stream width) is not necessarily science based, and restoration requirements of illegally deforested riparian zones have been weakened in recent years. However, the overall intent and outcome of the law is to protect aquatic conditions and resources (Soares-Filho et al., 2014).

To guide implementation of needed floodplain-specific policy, Junk et al. (2014) suggested criteria that consider hydrological and biological conditions to define, classify, and delineate wetlands. Although the predictability of the flood pulse is one key criterion, few wetlands have the required hydrological data. A combination of remotely sensed information, distributed sensors, and modelling offers an approach to delineate wetlands and implement legislation for their protection. As is clear from the integrated nature of hydrological systems, the conservation of aquatic habitats requires approaches that encompass whole catchments. In the Amazon, the Jaú National Park is the only example that protects almost all the catchment of a large river (www.icmbio.gov.br). A good example of an application of inundation mapping to aquatic conservation is provided by Ferreira-Ferreira et al. (2015), where the use of SAR was linked to vegetation for the Mamirauá Sustainable Development Reserve, the largest Brazilian protected area dedicated to wetland conservation.

3.2 | Hydrological characteristics linked to aquatic ecology, ecosystem integrity, and biodiversity

Several studies have integrated combinations of recently available satellite remote-sensing products, hydrological model output, and locally derived field data to gain novel insights into the relationships between inundation variations and fish and forest ecology. These studies demonstrate that seasonal means, natural variations, and anthropogenic

changes to flooded area and hydrological connectivity are all relevant to understanding the ecology of fish and forests. In turn, the integrated understanding of hydrology and ecology can guide management of fisheries and land use development on floodplains.

Lobón-Cervia, Hess, Melack, and Araujo-Lima (2015) combined flooded forest areas derived from SAR analyses with sampling of fish in 35 Amazon floodplain lakes over a 1,300 km reach in the central basin. They demonstrated that fish richness and abundance were directly related to flooded forests and inversely related to distance from the river. In another application of remote sensing data, Arantes et al. (2017) used both Landsat and SAR data to characterize aquatic habitats and found that spatial patterns of fish biodiversity on Amazon floodplains were associated with forest cover and landscape gradients.

Understanding hydrological influences on fish abundance and movements can improve assessments of fishery yields, as is evident by the dependence of fish catches on natural hydrological cycles along the lower Amazon River found by Isaac, Castello, Santos, and Ruffino (2016). An application of a multivariate time-series technique to investigate intra-annual and interannual dynamics and long-term trends in fish catch for the 10 most abundant fish species in the Madeira River by Lima, Kaplan, and Rodrigues da Costa Doria (2017) showed that the best explanatory variables were maximum water level, flooding duration, previous year's flow, and rate of change in flow with species-specific responses to these hydrological variables. More specifically, Castello, Bayley, Fabré, and Batista (2019) examined the abundance and catch of *Colossoma macropomum*, a long-lived fish, and found that inundation positively and non-linearly affected abundance of the age-1 cohort, but not of older age classes, and did not find flooding effects on total catch. Of particular importance was the expansion and contraction of the ATTZ, because it provides habitat and rich food sources. Hence, an evaluation of the effects of floodplain deforestation on fishery yields along the lower Amazon that found forest cover was positively related to multispecies fish capture per unit effort indicates the interplay of hydrology, land use, and fisheries (Castello et al., 2017).

Using data on fish yields aggregated for all the states in the Brazilian Amazon during the period of 1980 to 1998, Melack, Novo, Forsberg, Piedade, and Maurice (2009) found no significant relationship between maximum total flooded area and total annual fish yield, independent of the lag time used between variables. However, when yields for adult fish of different sizes and trophic levels were analysed separately, using longer lag times for larger species and species from higher trophic levels, several significant relationships were found between fish yield and flooding: small species at lower trophic levels generally had short lag times (0–1 year), whereas those for large species at higher trophic levels had longer lag times (3–5 years).

Understanding how climate changes affect Andean river hydrology is key to understanding responses of pimelodid catfishes, a diverse and economically important group, to environmental changes (Barthem & Goulding, 1997; Barthem et al., 2017). For example, Feng et al. (in press) used a hydrological model forced with historical and projected climate data to characterize changes in river flows on the eastern

Andean slopes that provide access for pimelodid catfish to spawning grounds. Their results imply that the hydrological conditions may be favourable for catfish movement in the north west but disadvantageous in other regions as the climate changes. Uncertainties in channel morphology are the major source of error in the hydrological model.

When comparing hydrological and ecological impacts of the 1997 and 2005 droughts, Tomasella et al. (2013) found that rainfall was lower, evaporation was higher, and, as a result, lake levels were lower during the dry season of 2005 compared with 1997. These results demonstrate the importance of conditions in local catchments, as well as mainstem rivers, as indicated by the water balance studies at Calado, Curuai, and Janauacá. The low-water conditions during these droughts were associated with higher fish mortality and increased growth rates of floodplain trees. Floodplain forests are adapted to seasonal changes in inundation, and their growth, as indicated by annual ring widths, is often greater during non-flooded periods and increases with longer non-flooded periods (Schöngart et al., 2004; Schöngart, Piedade, Wittmann, Junk, & Worbes, 2005). However, drought and prolonged low water can cause higher seedling mortality and reduced seedling growth and photosynthetic activity (Parolin, Lucas, Piedade, & Wittmann, 2010). Herbaceous, aquatic macrophytes are another important type of vegetation on Amazon floodplains. These plants have notably high net primary productivity, and regression models developed by Silva, Melack, and Novo (2013) indicated that years with especially high water result in the especially high net primary productivity. Clearly, woody and herbaceous plants on Amazon floodplains are responsive to hydrological variability.

3.3 | Dams

Large hydroelectric reservoirs have been built, are under construction, or are planned throughout the Amazon basin (Almeida et al., 2019). As discussed in Forsberg et al. (2017), Latrubesse et al. (2017), Anderson et al. (2018), Finer and Jenkins (2012), and Melack, Amaral, Kasper, Barbosa, and Forsberg (2021), dam construction reduces river system connectivity and has major implications for floodplain ecosystems adapted to and dependent on a natural flood regime. One of the most significant impacts of dams is alternations of river flows and variations in stage. For example, reductions in peak flows and increased base flows can keep riparian forests flooded and result in their deterioration and mortality (Assahira et al., 2017; Resende et al., 2019). Furthermore, climate changes may modify the performance of hydroelectric dams as precipitation and runoff rise or fall, perhaps causing significant changes to reservoir management, with unknown ecological impacts. Studies of projected hydrological changes in the Tapajós (Arias et al., 2020) and Xingu (Stickler et al., 2013) rivers, as a result of climate change and deforestation, found increased inter-annual variability and an overall decrease in annual hydropower production potential (as much as 75%). In turn, the considerable outgassing of greenhouse gases from hydroelectric reservoirs may exacerbate climate warming (Kemenes, Forsberg, & Melack, 2007, 2011).

How changes associated with hydroelectric dams affect floodplain ecology is a complex function of reservoir management, climate changes, and ecosystem vulnerability and is challenging to quantify with available data. Tempe and Kaplan (2017) developed indices of hydrological alternation by dams and applied them to dams across the Brazilian Amazon. Relative differences between pre- and post-dam hydrological regimes were determined and related to ecological parameters. The indices characterized extremes, such as the magnitude and duration of high or low flows, timing of annual maxima or minima, and the rate of change of water levels. They evaluated the length of record required for robust conclusions and found, in general, that large lowland rivers needed shorter records than smaller highland rivers. Although all dams altered the hydrological regimes, and large hydroelectric dams often had the largest impact, some smaller dams had similar or even greater impacts. Even road crossings that block streams alter instream habitats (Macedo et al., 2013). The greatest impacts were associated with modifications of the flood pulse, a key aspect of floodplain ecological functioning. Observations, hydrological models, and satellite products have improved understanding of the vulnerability of infrastructure and the potential to magnify climate disturbances on discharge and the flood pulse, but more explicit links to ecological processes on the floodplain need to be made.

3.4 | Deforestation

An understanding of how deforestation alters the Amazon's hydrological cycle has been possible in recent years through the application of numerical models and satellite observations in combination with local observations (Coe, Costa, & Soares-Filho, 2009; D'Almeida et al., 2007; Levy, Lopes, Cohn, Larsen, & Thompson, 2018; Panday, Coe, Macedo, Silvério, & Brando, 2015; Silvério et al., 2015). Local observations alone are not sufficient to clarify this complex issue. Deforestation can decrease evapotranspiration and increase discharge and flooded area (Coe, Latrubesse, Ferreira, & Amsler, 2011; D'Almeida et al., 2006). However, reduced evapotranspiration and energy balance changes caused by deforestation can also lead to increased dry-season length (Costa & Pires, 2009; Wright et al., 2017), decreased rainfall (Butt, Oliveira, & Costa, 2011; Knox, Bisht, Wang, & Bras, 2011; Stickler et al., 2013), and decreased discharge and flooded area (Coe et al., 2009). Levy et al. (2018) estimated that stream discharge during the dry season increased between 4 and 10% (relative to the forested condition) in the 'arc of deforestation' along the southern border of the Amazon basin, as deforestation and agricultural development occurred from 1950 to 2013. Furthermore, they found that concurrent changes in temperature and rainfall reduced the regional increase in discharge expected from deforestation. Thus, the net effect of deforestation on the discharge and flooded area is a complex combination of local and regional effects. Discharge and flooded area can either increase or decrease depending on whether the decrease in evapotranspiration (increased flood) or the decrease in rainfall (decreased flood) dominates (Coe et al., 2009; Panday et al., 2015; Stickler et al., 2013).

3.5 | Climate variability and change

Trends and variability in climate are influencing the hydrology of the Amazon basin. An analysis of the output of 35 climate models, as part of the Coupled Model Intercomparison Project as summarized in the Intergovernmental Panel on Climate Change Fifth Assessment Report, indicates that increasing greenhouse gases are likely to result in increased rainfall in the western Amazon basin and decreased rainfall and more frequent drought in the southern and eastern basin this century (Duffy, Brando, Asner, & Field, 2015). Analysis of satellite and ground-based data suggests that this change is well under way. Observations and model outputs confirm a climatically driven decrease in rainfall and soil moisture and increase in evapotranspiration in the Xingu River basin, which has resulted in a decrease in discharge since the 1970s (Panday et al., 2015). Recent years have had an increase in extreme events. Exceptionally high river levels occurred in 2009 (Chen et al., 2010), and severe droughts resulted in record-breaking low water levels in 2005 and 2010 (Marengo et al., 2008; Marengo, Tomasella, Alves, Soares, & Rodriguez, 2011; Zeng et al., 2008). These extreme events are consistent with increased variability in climatic conditions projected by global models (Gloor et al., 2013; Lau, Wu, & Kim, 2013; Liu, Wang, Cane, Yim, & Lee, 2013; Marengo & Espinoza, 2016).

These hydrological conditions appear to influence Amazon fish and indicate the importance of incorporating climatic and hydrological forecasts into evaluations of fish communities. Specifically, Freitas, Siqueira-Souza, Humston, and Hurd (2013) sampled fish in six lakes along a 400 km reach of the Solimões River over 4 years (2004–2007) before, during, and after the severe 2005 drought that resulted in especially low water levels and isolated the lakes from the river. They found varied responses among trophic levels or migratory behaviour: after this drought, planktivores, herbivores and detritivores increased, carnivores and omnivores decreased, and migratory species increased disproportionately compared with non-migratory species.

Based on modelled and remotely sensed seasonal and interannual variations in inundation extent as a function of climatic conditions, Costa, Coe, and Guyot (2009) concluded that, although ENSO strongly influences variability in discharge, a 28-year mode in precipitation variability explains most of the interannual differences in extent of inundation. Rainfall anomalies are known to be associated with El Niño conditions and sea surface temperatures in the equatorial Pacific and tropical Atlantic oceans (Ronchail et al., 2002).

Sorribas et al. (2016) used a regional hydrological model with a river hydraulic and floodplain water storage simulation and output from five global climate models to create future climate projections for the period from 2070 to 2099. Analyses such as these should be used with caution, given the considerable uncertainty inherent with climate projections. Their results indicate that increased river discharge for large rivers draining the Andes in the north west will contribute to increased discharge and inundation extent over Peruvian floodplains and the Solimões River in the western Amazon basin. Decreased river discharges were projected for the eastern basin and decreased inundation extent at low water in the central and lower Amazon basin.

3.6 | Dams, land cover, and climate changes

The combination of infrastructure development, such as dams, changing land cover – which effects both water yield and climate – and a changing climate caused by increasing greenhouse gases makes predicting and preparing for the future difficult. As illustrated in the previous sections, each of these factors alone can significantly affect discharge and floodplain inundation; together in varying combinations they will create many different responses throughout the Amazon basin. In one large-scale example, Melack and Coe (2013) simulated inundation of the mainstem of the Amazon under altered climate and land uses using a hydrological model forced with climate data from 1950 to 2000. Simulations with 10% and 25% decreases in rainfall resulted in reductions in inundation similar to reductions in rainfall. Based on 35% deforestation coupled to a global climate model, rainfall decreased and evapotranspiration decreased more; hence, average maximum flooded area increased slightly.

The Xingu River, in the south-eastern Amazon, provides an example of the complexities involved. The observed discharge has decreased modestly since the 1970s, suggesting a stable environment, and the Belo Monte dam was built on that assumption. Closer inspection using discharge data, models, and satellite products (Panday et al., 2015) shows that rainfall and evapotranspiration have significantly decreased, which by themselves would result in a nearly 15% decrease in discharge, but it was offset by a 6% increase in discharge from a deforestation-driven evapotranspiration decrease. A numerical-model-based analysis of the potential future of the Xingu River (Stickler et al., 2013) suggested that simulated deforestation of 20% and 40% within the Xingu River basin increased discharge by 4–8% and 10–12% respectively. When climate was allowed to respond to the deforestation, rainfall decreased within the Xingu Basin, counterbalancing the decrease in evapotranspiration and resulting in a decrease in net discharge of between 6 and 36%.

4 | CONCLUSIONS

Climate and land use continue to change in the Amazon basin, causing significant changes to long-term mean and the variability of discharge and floodplain inundation. Aquatic environments in streams and floodplains are shaped by a complex combination of local and non-local effects, such as local topography, forest cover, land use, local runoff, and upstream water input, which are a function of physical characteristics and human actions throughout the larger catchment. Thus, determining the impacts of change on and the resilience of aquatic environments is challenging.

Satellite products and numerical models are already providing considerable data and understanding of the hydrology of the Amazon floodplain system. The last few years has brought a clearer understanding of the sensitivity of this system to human activities and a changing climate. However, the links from hydrological to ecological understanding have been slow to form. As Ramirez-Reyes et al. (2019) pointed out, large-scale incorporation of satellite and model products into

ecosystem assessments is not likely to happen until a series of technical and conceptual challenges are addressed. On the technical side, challenges include issues of data awareness, processing, and access, which stem from the fact that the data were rarely created with aquatic ecosystems in mind. As a result, aquatic ecologists may be unaware of relevant data, the data format can be unfamiliar to them, and access can be difficult. On the conceptual side, there is a mismatch between the spatial and temporal scales being investigated, such as hourly observations versus monthly simulations, or ecosystem properties and parameters, which may be neglected at the large scale but important at the small scale. These challenges can be overcome, however, through systematic investment and interdisciplinary training, collaboration, and creative thinking. Given the long-term nature of solving the technical challenges and creating systematic investments, the scientific community needs to create opportunities for collaboration and creativity on pressing aquatic environmental issues. Working together, those who know the satellite and model products, those who study the hydrology of tropical river-floodplain systems, and those who know the ecology of these system can craft innovative solutions.

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CONFLICT OF INTEREST

The authors do not have conflicts of interest with regard to the material presented.

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