1 Title:

An Explicit GIS-Based River Basin Framework for Aquatic Ecosystem Conservation in the Amazon

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2 Abstract

Despite large-scale infrastructure development, deforestation, mining and petroleum exploration in the Amazon Basin, relatively little attention has been given to the management scale required for the protection of wetlands, fisheries and other aspects of aquatic ecosystems. This is due, in part, to the enormous size, multinational composition and interconnected nature of the Amazon River system, but also to the absence of an adequate spatial model for integrating data across the entire Amazon Basin. In this data article we present a spatially uniform multi-scale GIS framework that was developed especially for the analysis, management and monitoring of various aspects of aquatic systems in the Amazon Basin. The *Amazon GIS-Based River Basin Framework* is accessible as an ESRI geodatabase at https://knb.ecoinformatics.org/#view/doi:10.5063/F1BG2KX8.

3 Key words: Aquatic ecosystems, Amazon, basins, hydrology, wetlands, monitoring, scale, database

4 Introduction

4.1 Amazon Basin System

The Amazon is the largest river basin in the world. Its strict hydrographical area covers 6.3 million km^2 (Milliman and Farnsworth, 2011), and when the Tocantins Basin and estuarine coastal areas are included to define the Amazon Region, the total area is 7.287 million km^2. The average discharge of the Amazon River at its mouth is approximately 206,000 m^3/sec, contributing approximately 17% of all river water reaching the world's oceans, at least 4 times that of the Congo, the second largest tributary (Richey et al., 1986; Callede et al., 2010; Callede et al., 2004). Two of the Amazon River's tributaries, the Madeira and Negro, are also among the 10 largest rivers in the world as measured by average discharge (Milliman and Farnsworth, 2011). Wetlands occupy 14% of the Amazon Basin (Melack and Hess, 2010) and play an important role in the ecology and biogeochemistry of this immense fluvial ecosystem. These environments include nearly all of the 35 inland or coastal wetland types defined by the Ramsar Convention (Mathews, 2013) but are composed primarily of alluvial floodplain habitats. Tree-dominated wetlands are the dominant habitat types on the floodplains, often covering 75% or more of inundated areas where there has not been deforestation (Melack and Hess, 2010; Junk et al., 2012; Cunha et al., 2015; Melack, 2016). Floodplains are also characterized by lake-like waterbodies where water depth prevents the establishment of forest but where large rooted and floating herbaceous communities develop, especially along whitewater rivers that receive nutrients from the Andes (Junk, 1970; Piedade et al., 2010) and are under the strong influence of seasonal inundation pulses, which are monomodal for most of the lowland region and range from 5-15 m depending on the exact location, but can be bimodal near the equator or with numerous spikes in or near the Andes. Flooding in the easternmost part of the Amazon floodplain is tidally influenced though river discharge prevents an invasion of salt water except during the lowest water period in the Marajó Bay area (Barthem and Schwassmann, 1994). Due to a backwater effect caused by the temporally different contributions of the southern and northern tributaries, the Amazon River and the lower courses of most of its tributaries remain in flood longer than expected from the tributary flood pulses alone (Meade et al., 1991). During the high-water period the lower courses of the tributary basins also become functionally a part of the Amazon main stem and the latter, although not a basin, behaves as an ecologically distinct hydrological unit.

The spatial and temporal variability of the river flood pulse and its influence on inundation patterns in floodplain environments play a fundamental role in sustaining the diversity and productivity of floodplain biota and the lively-hoods of human populations throughout the Amazon. Infrastructural development, including plans to construct new dams, roads, and hydrovias across the basin, together with accelerating land use and climate change, threaten to disrupt this complex hydro-ecological system, with predictable negative consequences for the biota and river dwelling populations that depend on its integrity. The conservation and management of the natural resources and services provided by this ecosystem will require a uniform hydrological framework, covering the entire Amazon region, specifically adapted for this objective.

4.2 Actual spatial framework

River basins are the most natural spatial units of aquatic ecosystems and are also the units generally used by the agencies or authorities (Agência/Autoridad Nacional de Águas/Agua - ANA) charged with managing waters in Amazonian countries. The ANAs have traditionally used a basin coding system based on the work of Otto Pfafstetter, usually called the Pfafstetter Coding System (Pfafstetter, 1989), and the basins delineated in this system are referred to as Pfafstetter Basins (or Otto-Basins, in Brazil). Each delineated basin is assigned an identification number that establishes a hierarchical and sequential arrangement of basins, often with a larger basin divided into at least 9 smaller units (Verdin and Verdin, 1999). The Pfafstetter methodology was applied to the Amazon Basin in the Hydrosheds product (World Wildlife Fund-US) which includes 12 basin levels (Lehner, 2013), and has also been applied to North America river basins (Verdin and Verdin, 1999). Pfafstetter Basin classifications, especially those used by the ANAs, will undoubtedly continue to be the geographical basis for water use management in Amazonian countries, but complementary classifications, adapted for specific local objectives, such as the development of the Strategic Plan of Hydrological Resources of the Right Margin of the Rio Amazonas have also been adopted (Agência-Nacional-de-Águas-(Brasil)-ANA, 2012). The Pfafstetter methodology and most other basin classifications, used to date in the Amazon, have not considered the main stem and its associated floodplains as a hydrological unit. These areas contain the most productive river and wetland habitats and should thus be managed in the same way as large tributary basins. By including the main channel and surrounding floodplains of the Amazon River and it largest tributaries as discrete sub-basins in a regional basin hierarchy we have produced a new spatially explicit integrated river basin framework, specifically adapted for the management and conservation of the Amazon fluvial ecosystem.

The digital river networks currently available for the Amazon region also lack some aspects essential for the management of aquatic ecosystems. The Hydrosheds product (http://hydrosheds.cr.usgs.gov/index.php), the most accurate and regionally uniform river network that was available previous to the present work, lacks lower order streams which are important habitats for many aquatic organisms; an equally uniform but higher resolution vector product was thus needed to include these habitats. Ecologically and geographically important attributes such as stream order, river name, river length and water type are also needed for a spatially robust conservation and management framework.

Accelerating land use, infrastructure development and resource exploitation present a growing threat to the integrity of Amazon river ecosystem (Castello and Macedo, 2016). The *Amazon GIS-Based River Basin Framework* presented here, including an ecologically consistent basin hierarchy and a spatially uniform, high resolution, classified river drainage network, should help by providing a spatial basis to increase the scope of management and conservation efforts to meet the challenges of large-scale impacts.

4.3 Data

Two types of hydrological data are inucluded in this spatial framework for the Amazon Basin.

1. *Polygon*: a hierarchical river basin classification and delineation of main stem floodplains. Main stems are considered the large downstream segments of the Amazon River and its major tributaries. Although not basins, per se, these main stem sub-basins contain large areas of wetlands and are important for fisheries production and aquatic biodiversity in the Amazon Basin. The basin classification contains seven basin levels of decreasing area, including main stem floodplain sub-basins, thus allowing data analyses at variable scales.

2. *Line*: a new high density drainage network containing important geographical attributes, including stream order (1 – 11th order), tributary name (6 – 11th order), river type (6 – 11th order) and distance above the Amazon River mouth (4 – 11th order).

5 Materials and Methods

5.1 Acquisition and correction of DEM (Digital Elevation Model)

To obtain a spatially uniform and high-resolution stream network and drainage basin hierarchy for the Amazon Basin, flow direction and flow accumulation patterns were derived from the 90 m resolution SRTM-DEM, which was the most accurate DEM available for the South American continent. The near-global Shuttle Radar Topography Mission (SRTM) digital elevation data set (Farr et al., 2007) was developed by NASA and the U.S. National Geospatial-Intelligence Agency for the entire Earth using stereo C-band imagery acquired by the Space Shuttle Endeavour in February of 2000, which corresponds to the early rising water period in the Central Amazon Region, when the Amazon mainstem begins its 10-12 meter annual flood cycle. The data product has a spatial resolution of 3 arc seconds, approximately 90 m in the Amazon region, and a vertical accuracy of 1 m locally and 4 m globally. Like most DEMs derived from synthetic aperture radar, the SRTM-DEM contains regions where useable data were not obtained (voids) and also regions where spatial variation in elevations are close to the vertical accuracy of the product, and consequently poorly represented. These latter areas include large lakes, river channels and wetlands. Furthermore, the SRTM DEM is not a "bare earth" DEM, but represents the elevation of a scattering centroid that varies as a function of vegetation height and density (Carabajal and Harding, 2005). For our analysis, we used the version 4.1 DEM available through CGIAR-CSI (Lehner et al., 2006). This “void-filled” DEM was provided in 6,000 X 6,000 pixel panels which we mosaicked using the “mosaic tool” available in the Spatial Analyst Extension of ArcGis 10.1 (ESRI, Inc.) to produce a uniform DEM covering all of South America above 22° south latitude.

Three additional modifications of the SRTM-DEM mosaic were performed before flow direction patterns were analyzed to improve the quality of the final drainage network. First, we manually modified the DEM at one location in the headwaters of the Caquetá River in Colombia where the river passed through a channel in a large rock formation that was so narrow that it was not represented in the DEM. To ensure that water "flowed" through this point in the final stream network, it was necessary to "excavate" the channel digitally so that it was wider than the 90 m resolution of the DEM image. To ensure that the main river channels followed the correct path as they crossed the extensive floodplains in the central Amazon lowlands, we also "burned" all channels above 7th order into the DEM, using the trajectories of these rivers derived from the lower resolution Hydrosheds product (Lehner et al., 2008). The "DEM Reconditioning" tool in the Hydro Tools extension of ArcGIS 10.1 was used to accomplish this. Finally, the "Fill Sinks" tool in the Hydro Tools extension of ArcGIS was used to fill any remaining depressions in the reconditioned DEM which might impede water flow.

5.2 Area of basins and length of river calculations

For all calculations of area of the basins, length of rivers and distance to the mouth we used the Albers projection with the following parameter configuration (Table 1).

5.3 Drainage network development

Once the DEM was corrected, the "Flow Direction" tool in the Spatial Analyst Extension of ArcGIS was used to map the directional pattern of flow through the entire DEM mosaic. The resulting flow direction grid image was then used together with the Spatial Analyst "Flow Accumulation" tool to map the spatial patterns of accumulated flow, based on accumulated upstream drainage area, and to generate a flow accumulation grid image. The flow accumulation grid was then used to generate a stream grid in raster format with the Hydro Tools "Stream Definition" tool. The "stream threshold" value, specified with the stream definition tool, determines the size of the upstream drainage area at which the stream grid begins to be delineated, and consequently the final resolution of the drainage network. This threshold is specified in upstream pixels, which in the SRTM-DEM represent approximately 0.81 hectare.

A stream grid with an upstream stream threshold of 100 pixels (approximately 81 ha) was used together with the flow direction grid and the Spatial Analyst "Stream Order" tool to create an ordered (Strahler, 1957) high resolution stream grid. This ordered stream grid was then vectorized with the Spatial Analyst "Stream to Feature" tool to produce a single high resolution stream network shape file for the entire

Amazon Basin containing a stream order attribute. The calculated stream order varied from 1 to 11 in this product which is probably underestimated by 1 order, since the drainage areas of first order streams, defined according to Strahler (Strahler, 1957) as permanent streams with no permanent upstream tributaries, tend to vary from 10-50 ha in the central Amazon Basin. Assuming that this is correct, the smallest streams in the stream network developed here would be approximately 2nd order and the Amazon River main channel near its mouth would be 12th order. The order included in the attribute table of the final shapefile was the value generated originally by the stream order tool. Three different stream network shapefiles were created from this high resolution product, containing streams from 1-11th order, 6 – 11th order and 7 – 11th order, respectively. Tributary names, derived from existing data bases, were added to the 6 – 11th order river network.

The shapefile containing 1-11th order streams was filtered to remove anomalous 1st to 3nd order streams which were generated on open water surfaces and wetlands due to the inaccuracy of the DEM and the flow direction grid that was generated from it. These anomalies consisted of spurious low order stream segments, generated predominantly in low relief wetland environments where variation in elevation was either extremely low (open water environments) or due primarily to variations in vegetation height. The filter eliminated 1-3 order streams present in the wetland mask and stream segments adjacent to and intersecting the mask that were delimited by BL7 basins. While most of the anomalous segments were removed by the filter, some are still apparent at higher resolutions.
The length (km) of each segment in the full resolution network was also determined with ArcGis 10.1 in South America Albers Equal Area Conic projection.

5.4 Development of basin hierarchy

Seven different scales or hierarchical levels were delineated in our basin hierarchy, denominated Basin Level 1- Basin Level 7 (BL1-BL7) (Fig. 1 and Fig. 2).

Basin code generation, Basin codes for BL1 and BL4 basins were derived from the names of the principal rivers in each polygon. Codes for BL5 – BL7 basins were created combining the associated BL2 basin name with the ID numbers generated automatically when each basin was delimited.

Basin Level 1 (BL1), *Regional basins* - divides the working area into 3 drainage polygons: one large polygon containing the Amazon and Tocantins river basins; and two smaller ones containing the northern and southern coastal basins draining directly into the Atlantic.

Basin Level 2 (BL2), *Major Amazon Tributary basins* - delimits all tributary basins larger than 100,000 km^2 (main basins) whose main stems flow into the Amazon River main channel, as well as an Amazon River Main Stem polygon that consists of the open waters of the Amazon River, its floodplain and adjacent small tributary basins (Fig. 3).

Basin Level 3 (BL3), *Major Tributary Basins* - delimits all basins larger than 100,000 km^2, including those that do not flow directly into the Amazon River main channel; all tributary basins larger than 10,000 km^2 and less than 100,000 km^2 that flow into the Amazon River Main Stem; and a single central floodplain drainage polygon.

Basin Level 4 (BL4), *Minor Tributary Basins* - delimits all tributary basins greater than 10,000 km^2 and less than 100,000 km^2. Floodplain drainages include all tributaries with basins less than 10,000 km^2 flowing toward the floodplain at high water.

Basin Levels 5-7, *Minor sub-basins* - The remaining three basin levels, BL5, BL6 and BL7, were created by subdividing BL4 basins into drainage subunits with threshold sizes of 5,000, 1,000 and 300 km^2, respectively.

Basin grids for major Amazon tributaries (BL2), major tributaries (BL3) and minor tributaries (BL4) were created from the flow direction grid and a point shapefile for basin outlets using the watershed delineation tool of ArcHydro 2.0 for ArcGis. Basin outlets were created with the point generation feature of this tool. Basin grids were converted to polygon shapefiles using the Hydro Tools “polygon processing” tool. All major and minor tributary basins were attributed areas and the name of the principal tributaries in each polygon. Sub-basin grids with thresholds of 5,000 (BL5), 1,000 (BL6) and 300 km^2 (BL7) were created for the entire Amazon Basin using the flow direction grid, segmented stream grids developed at these scales and the Hydro Tools “catchment grid delineation” tool. These sub-basin grids were then transformed into separate polygon shapefiles using the Hydro Tools “catchment polygon processing” tool. General characteristics and statistics for each basin level are summarized in Table 2.

5.5 Definition of floodplain drainage polygons

Large river floodplains play an important role in the Amazon, sustaining aquatic primary production and fish yields in the region. At high water, when the inundated area of floodplains is greatest, many small tributaries are completely flooded altering regional drainage patterns. Many of these tributaries which are independent of the main channel at low water are “captured” by flooding and incorporated in the mainstem drainage at high water. Due to their ecological importance, we prioritized these high water drainage patterns in the delineation of floodplain drainage polygons. The drainage areas of major tributary floodplains were delineated initially at the BL4 level with the drainage network derived from the DEM and then adjusted manually with a wetland mask to better represent high water drainage patterns. The wetland mask used to identify floodplain environments was generated by (Hess et al., 2003) from the analysis of JERS-1 L band radar imagery covering most of the lowland Amazon Basin acquired during both low and high water periods. Detailed methods are provided in the original reference. Wetlands were defined as areas that were inundated during either of both periods together with areas adjacent to flooded areas which displayed landforms consistent with floodplain geomorphology. Tidal wetlands in the lower Amazon and Tocantins rivers that were missing from this product were delineated here using a similar methodology and then annexed to the larger Amazon Basin mask. The final wetland mask, together with the BL5 and BL7 sub-basin shape files, was used to identify and delimit the floodplain drainages of major tributaries. Floodplain drainages were defined to include all main stem floodplain wetlands identified with the mask plus all upland sub-basins less than 10,000 km^2 that flowed directly into them. All tributary wetland drainage polygons were attributed with the name of the associated major tributary. The floodplain drainage associated with the Amazon River Main Stem was further divided into four areas based on geomorphology (Dunne et al., 1998), habitat distribution (Hess et al., 2015) and fisheries.

Once all major floodplain drainages were delineated, vectored data and metadata were added and they were aggregated as polygons to the BL4 shape file and as attributes to the BL5, BL6 and BL7 shape files.

5.6 Classification of river type

Water quality or type varies considerably in the Amazon River system and has been shown to have a major influence on biogeochemical processes and on the distribution and dynamics of aquatic habitats and biota. There are three main types of rivers in the Amazon Basin based on natural differences in water color and quality (Sioli, 1968): 1) *whitewater rivers*, with neutral pH, rich in suspended sediments and nutrients, 2) *blackwater rivers,* low in pH, nutrients and suspended sediments, high in dissolved organic carbon and 3) *clearwater rivers*, low to neutral pH, low in nutrients, suspended sediments and dissolved organic carbon. We defined water type (white, black or clear) in 6^{th} – 11^{th} order rivers based on regional knowledge and visual analysis of optical imagery of various resolutions available through

Google Earth (Google Inc). The resulting assignment of river types based on water color is shown in Figure 4; it represents a first approximation based on current knowledge.

5.7 Definition and mapping of fish spawning nodes

Many migratory characiform fish species spawn at the confluences of whitewater and blackwater or clearwater rivers. These fish spawning nodes were identified and incorporated in a shapefile for 6^{th} – 11^{th} order rivers. The "feature vertices to points" tool in ArcGis 10.1 was used to convert the last downstream drainage line before each confluence in the 6^{th} – 11^{th} order river network into a point. Next a buffer of 1,000 meters around each point was generated in order to define the confluence areas where spawning takes place. For each buffer area a spatial join was applied for the following information: order and type of tributary and order and type of river into which tributary flows. Important confluence areas for spawning were then derived from the intersection of spawning nodes and sub-basins or main stem drainages important for commercial fishing. The resulting distribution of fish spawning zones is indicated in Figure 5.

5.8 River distances

Distances along the river network from the mouth of the Amazon River to specific points in the river system can be important for characterizing spawning routes and calculating the resident time and velocities of fish larvae/juvenile during downstream migrations and other materials in the system. Distances from the Amazon's mouth to all stream segments between 4^{th} – 11^{th} order were calculated using the Barrier Analysis Tool (BAT) extension for ArcMap 10.1 developed for The Nature Conservancy (Software Developer: Duncan Hornby of the University of Southampton's GeoData Institute). The tool uses point data to divide a routed river network (polylines with from-node and to-node coding) into connected networks from which a direct path distance calculation can then be made. The data provide not only distances to specific points from the Amazon River mouth but also to distant regions (Fig. 6). Distance values and stream order were included as segment attributes in the final river network shapefile.

6 Data availability

Interested researchers can access the data and metadata at https://knb.ecoinformatics.org/#view/doi:10.5063/F1BG2KX8 (Eduardo Venticinque, Bruce Forsberg, Ronaldo B. Barthem, Paulo Petry, Laura Hess, Armando Mercado, Carlos Canas, Mariana Montoya, Carlos Durigan, and Michael Goulding. 2016. SNAPP Western Amazon Group - Amazon Aquatic Ecosystem Spatial Framework. KNB Data Repository).

7 Conclusions

The multi-level basin hierarchy and classified river network presented here provides a new spatial framework for analyzing aquatic and terrestrial data at a variety of sub-basin levels, including the Amazon Basin and Amazon Region as a whole. Its architecture is appropriate for use in the monitoring and management of aquatic ecosystems, especially within an integrated river basin management framework at distinct spatial scales. The principal data products provided in the GIS include:

1. A multi-level basin hierarchy specifically designed for the conservation and management of river basins and floodplain environments at a variety of basin and sub-basin scales.
2. A high resolution, spatially uniform, ordered drainage network for the Amazon Basin and its adjacent coastal basins (Coastal North, Coastal South and Tocantins).
3. A first approximation of river types based on water color as a proxy for distinct chemical characteristics, included as an attribute for 6-11th order tributaries.
4. Estimates of the distance of individual stream segments from the mouth of the Amazon River, included as an attribute for 4-11th order streams in the Amazon basin.
5. A point shape file indicating confluences (nodes) of different river types that are critical spawning zones for migrating fish species.

This regional hydrological database provides a coherent framework for the integration and analysis a wide array of spatial data, critical for management and conservation of this valuable fluvial ecosystem.

8 Team List (Author contributions)

MG coordinated the general development of this GIS framework, EV and BF processed the data to generate the hydrography and basins; EV, BF, RB, MG, and PP prepared the manuscript with contributions from AM, CC, MM and CD. LH prepared the wetland mask for the Tocantins Basin and the estuary to complete the wetland mask for most of the Amazon Basin.

9 **Copyright statement**

NA

10 Appendices

NA

11 Supplement Link

NA

12 Team List

NA

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14 Disclaimer

NA

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Table 1 - Parameters configuration of projection used for all calculations of area and length in this database.

Parameter	Value
Projection	South America Albers Equal Area Conic
False_Easting	0.00000000
False_Northing	0.00000000
Central_Meridian	-60.00000000
Standard_Parallel_1	-5.00000000
Standard_Parallel_2	-42.00000000
Latitude_Of_Origin	-32.00000000
Linear Unit	Meter

Table 2 - General description of catchments system for Amazon Region.

General description	Level	N catchments	Average area (km^2)	Main Stem
Amazon and coastal basins	BL1	3		No
Major Amazon tributary basins > 100,000 km^2	BL2	21	385,386	Yes
Major tributary basins > 100,000 km^2	BL3	38	170,277	Yes
Minor tributary basins < 100,000 km^2 & >10,000 km^2	BL4	199	36,625	Yes
10,000 km^2 < Sub-basins> 5000 km^2	BL5	1075	6,811	No
5000 km^2 < Sub-basins > 1000 km^2	BL6	4606	1,589	No
1000 km^2 < Sub-basins > 300 km^2	BL7	15269	479	No

Figures and Captions

Fig. 1. Cartographic representation of first four levels of Amazon Basin classification: BL1, BL2, BL3 and BL4. BL = Basin Level

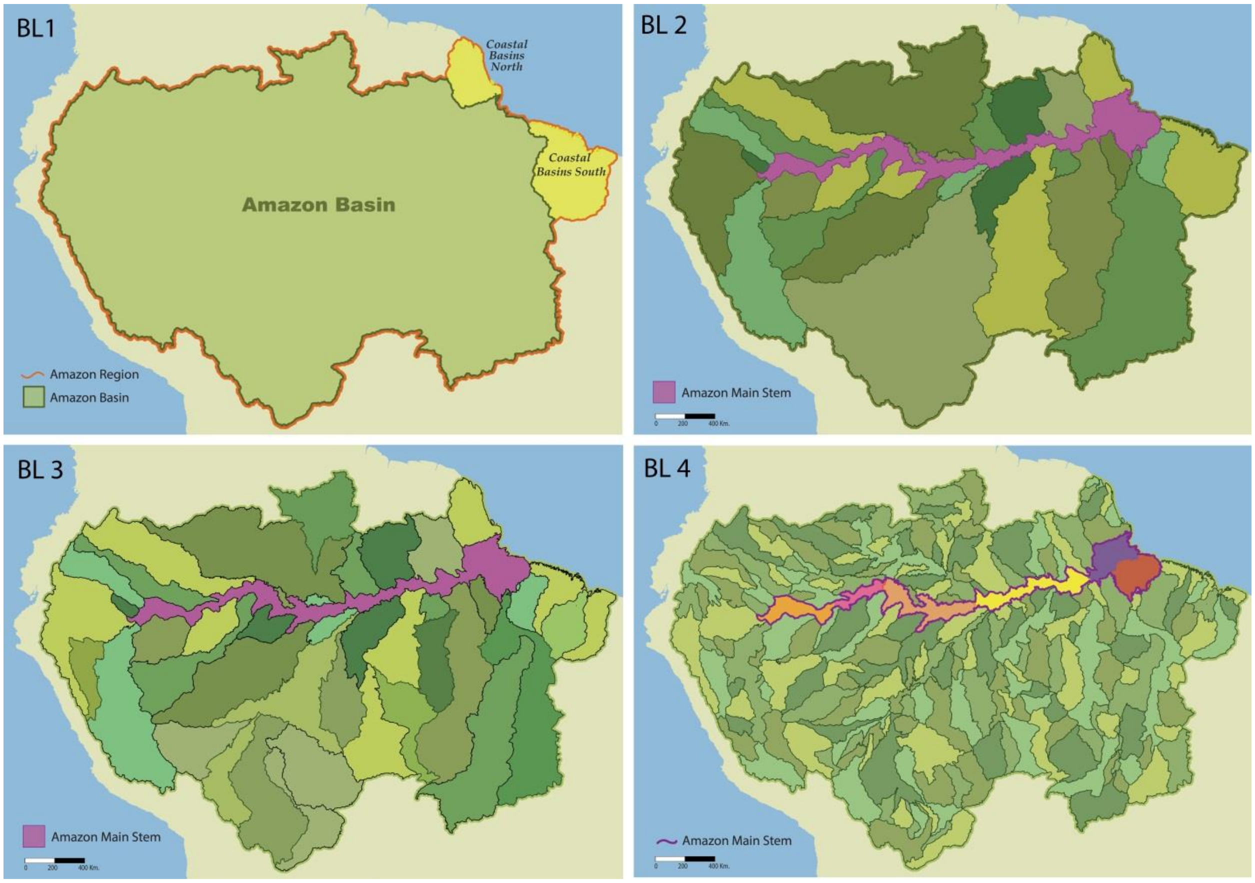

Fig. 2. Cartographic representation of Amazon Basin classification levels 4, 5, 6 and 7.

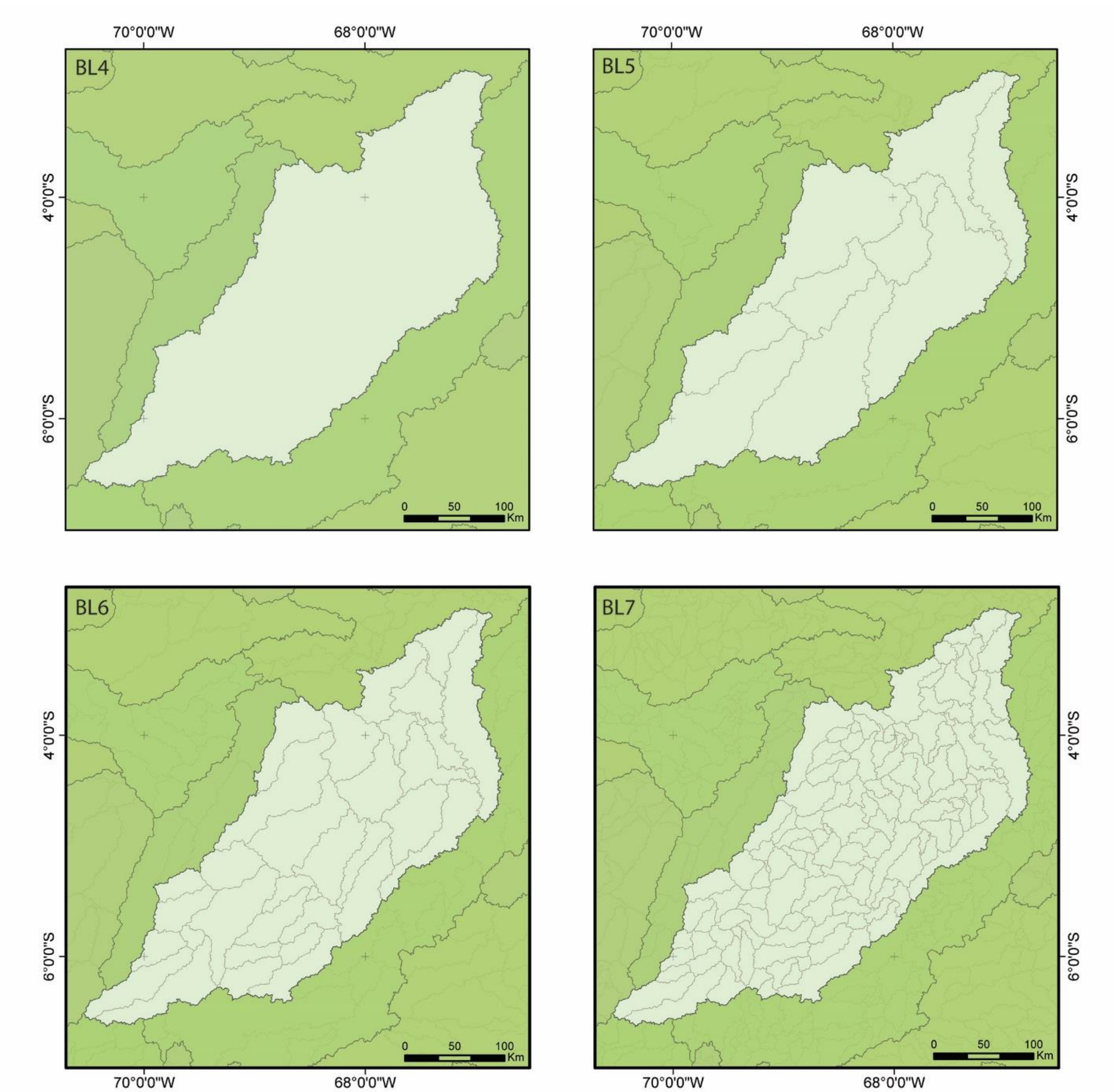

Fig. 3. Schematic definition of main stem sub-basins.

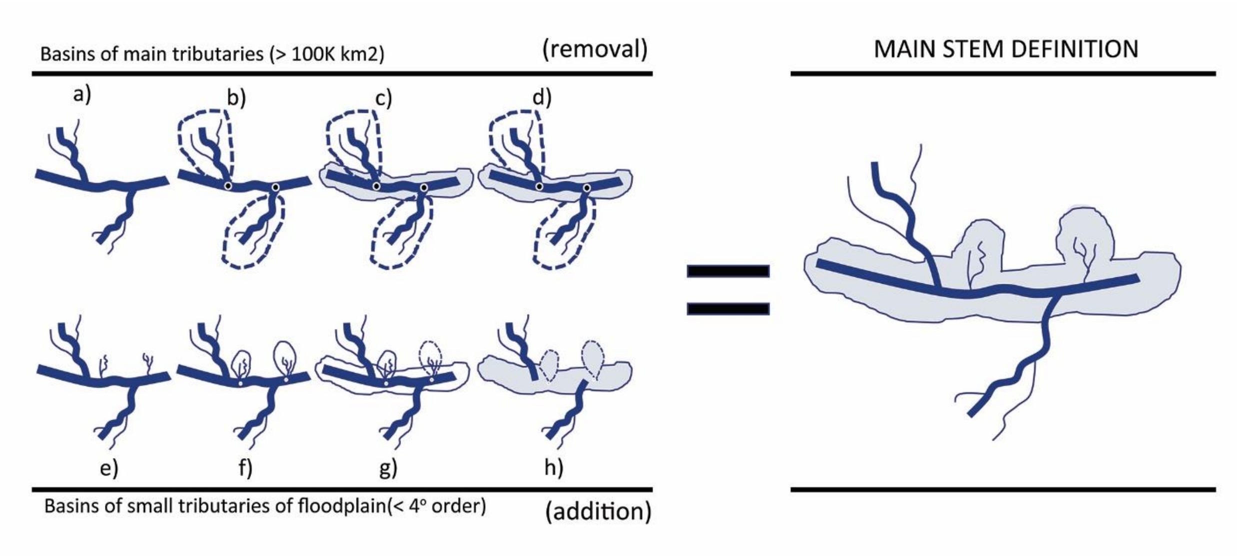

Fig. 4. Cartographic representation of Amazon River type classification .

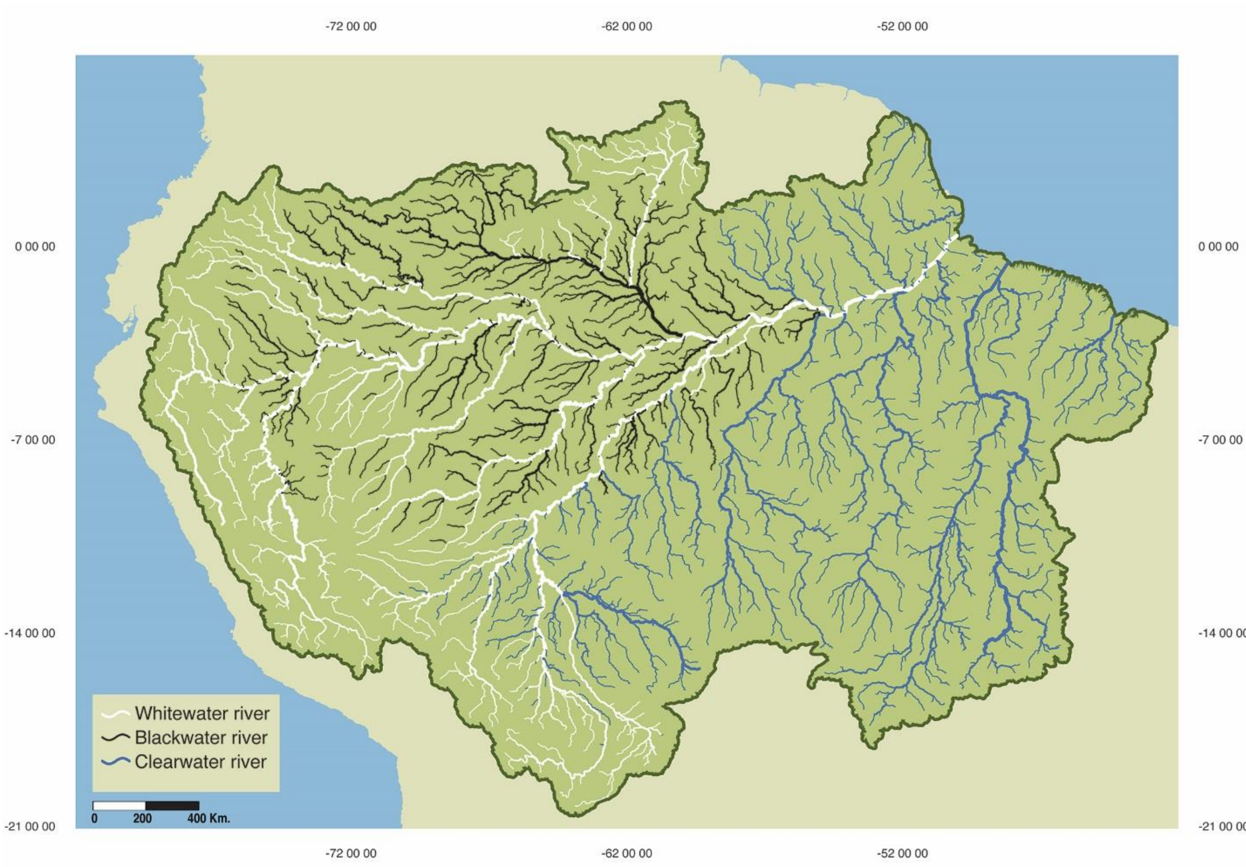

Fig. 5. Cartographic representation of important confluence areas for spawning, derived from the intersection of spawning nodes and sub-basins or main stem drainages important for commercial fishing.

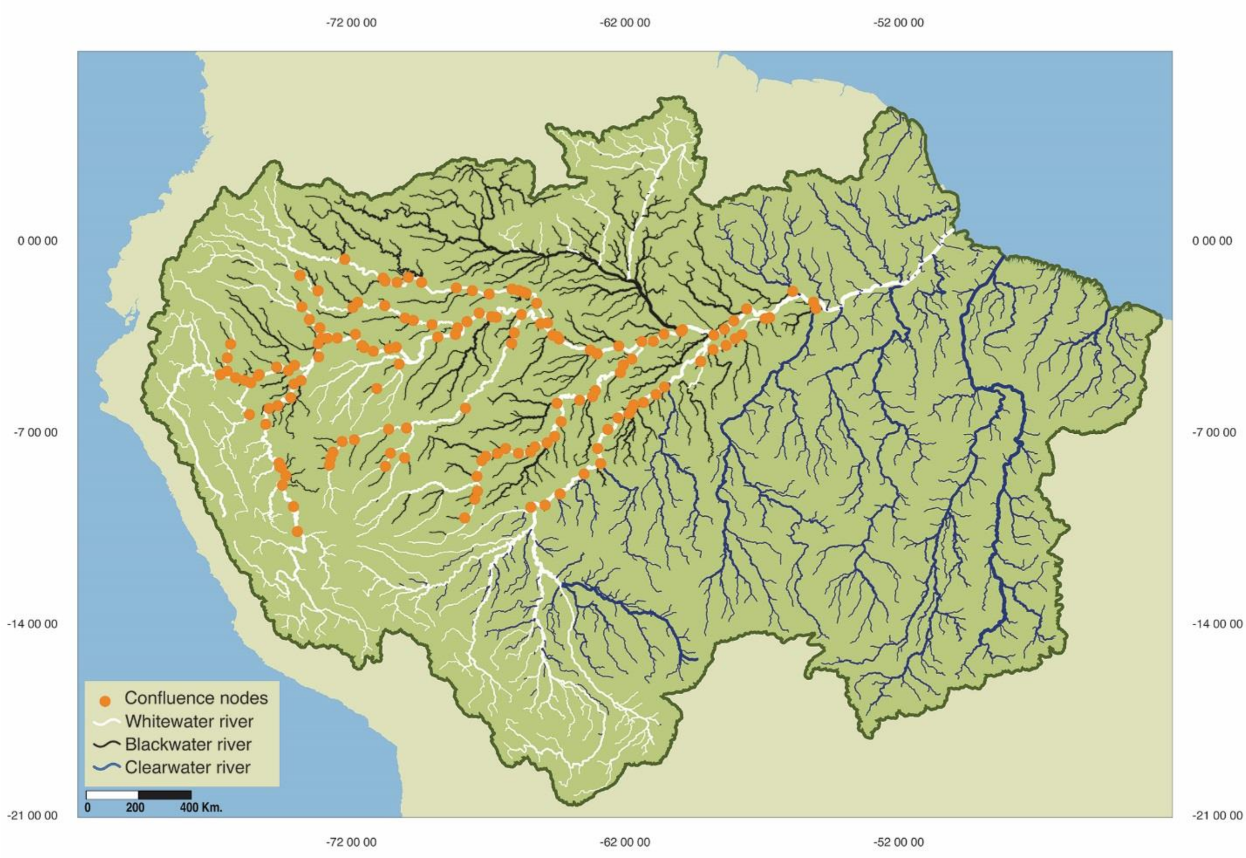

Fig. 6. Cartographic representation of river distances from Amazon River mouth.