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COVER SHEET

Title: Lakes, paleolakes and reservoirs in the Amazon basin

Name: Edgardo Manuel Latrubesse

Affiliation/Address: Instituto de Geomorfología y Suelos, Universidad Nacional de La Plata-CONICET, Calle 3 N^o 584, La Plata (1900), Argentina

Phone: 0221-4229923

Fax: 0221-4229923

E-mail latrubesse@igs.edu.ar

LAKES, PALEOLAKES AND RESERVOIRS IN THE AMAZON BASIN

1. Introduction

With ~6,200,000 km² of drainage area mainly covered by the Amazon rainforest and discharging near 18% of the total flow of fresh water to the ocean, the Amazon fluvial system continues to intrigue naturalists across the world.

Carrying an average water discharge of more than 200,000 m³s⁻¹ and a sedimentary load of 1.2 billions of tons per year at Obidos, close to the mouth (Meade, 1994), the Amazon river is the largest and most peculiar fluvial system of the world with respect to water discharge. The Amazon rainforest, the largest tropical forest in the world, originally occupied more than 5 million km² spreading mainly over the Amazon fluvial basin. Humid tropical climate prevails and rainfall, averaging 2000 mm/yr increases in the northwestern direction and in some parts of the Sub-Andean zone to more than 5000 mm/yr. Although the rainforest extends into various countries, 70–80% of the total area is located in Brazil (Oldeman 1981). In reality, the Amazon region is a complex mosaic of different vegetation types, including closed rainforest, flooded forests, campina forests, savannas, bamboo forests, mangroves, montane and sub-montane forests, and liana forests (Murcia–Pires 1984; Oldeman 1981; Witmore and Prance 1987).

The Amazon fluvial system is characterized for supporting the most extensive floodplain system of the planet comprising a fascinating mosaic of wetlands and floodplain lakes, which sustain a huge biodiversity and have a main role in the emission of carbon dioxide and methane to the atmosphere. In fact, the Amazon fluvial system functions as a major collector to the water and sediments of a large variety of tributaries. Large tributary systems such as the Madeira, Negro, Japurá, Purus River and others rank between the 20 largest rivers of the planet.

Lakes are a main source of information to understand the quaternary paleogeography and paleoecology of the Amazon as well as key pieces to understand the present day “physiology” of the environmental system. This chapter, focused on the lake record in the basin since the Late Cenozoic, attempts to understand the role lakes play in the basin, the

main mechanisms generating them, their present distribution, as well as the environmental effects of dams and planned dam construction.

2.Lakes in the Amazon: when the jungle feeds amazing theories

As in other parts of the world considered “exotic”, by both the scientific community and the public in general, the Amazon has fed several fantastic theories concerning the interpretation of its Late Cenozoic paleogeography. Since the times of the Spanish and Portuguese Empires, the fantastic Lake Paraima, supposedly located in northern Amazonia, inhabited in the imagination of conquerors dreaming with the “El Dorado”.

The mythological existence of a huge lake in the Amazon basin has persisted up to recent times. The actions of catastrophic floods, as well as the existence of a huge lake and marine ingressions were typical theories that producing immediate response in the media and, curiously, in part of the scientific community devoted to natural sciences.

Examples include the 80's megafloods theory, which postulated that the southwestern Amazonia was erased by megafloods coming from the Andes in response to the fluvial captures of the Late Pleistocene Bolivian Altiplano lakes (which extend in the present time over the Titicaca and Salar de Uyuni) (Campbell and Frailey, 1984, Campbell et al, 1985) and that a huge lake developed in the Amazon during the Late Pleistocene spreading on the lowlands (Frailey et al., 1988). According to this theory, this lake would have occupied an area larger than the Mediterranean Sea during the end of the Pleistocene, where today we have the richest and most extensive tropical rainforest and the main fluvial network of the planet.

More recently, it was postulated the existence of weak marine transgressions reaching the northern Amazonia during the Late Miocene (Horn, 1993). In addition, based on outcrops descriptions of the uppermost levels of the Solimões Formation in Acre territory (southwestern Amazonia), it was proposed that a huge sea way, connecting the Caribbean Sea with the Parana basin all across the South America and crossing the Amazon was installed in the continent during Late Miocene time (Rassanen et al, (1995).

Interestingly, no any researcher has found any unequivocal evidence of marine environments in the sediments of the Solimões Formation, the geological unit which is being thoroughly investigated through outcrops and boreholes by geologists, paleontologists, geo-chemistries and others earth scientists.

While concrete Late Miocene marine environments does not appear in the geological record, some authors have resuscitated and adapted the mega-lake hypothesis in the Amazon, which occurred, instead, during the Middle-Late Miocene. This mega lake, Named Lake Pebas, could occupied nearly all the lowlands of the Amazon basin western of the Purus Arch, i.e. roughly all the lowlands territory located west of Manaus (Wesselingh et al., 2002)

Very likely, the Pebas mega-lake is “more of the same”. An alternative and more realistic scenario for the Late Miocene of the Solimões Formation consists of a paleoenvironmental model formed by a mosaic of wetlands, active and abandoned fluvial belts, lakes, and floodplain areas (some drier, with development of paleosoils); i.e. an area dominated by complex mega-fan hiperavulsive rivers, floodbasins, and other wetlands areas (isolated swamps and lakes of several sizes) in a mosaic of environments as observed nowadays in several wetlands of the world and somewhat analogous to the Chaco and the Pantanal of Mato Grosso-Paraguay axis today (although the Amazon was wetter during the late Miocene than good part of Chaco) (Latrubese et al., 2007).

3. Where are the lakes in the Amazon?

In spite the fact the Amazon is the larges fluvial basin of the world, located mainly in the humid tropics, the significance and extension of lakes is not so much spectacular as one could expect.

There are not huge lakes in the Amazon. Lakes are restricted mainly to particular geomorphic features in uplands and plateaus or developed as a consequence of fluvial processes in floodplain environments. The largest lakes are in reality flooded fluvial valleys.

A tentative classification of the lake system is shown below. It is possible to differentiate four main categories, including some flooded areas that are not “typical lakes”.

- a) Lakes developed on older terrains without direct relation to the fluvial systems
- b) Lakes developed in fluvial valleys and soft Quaternary sediments but not directly related to fluvial landforms
- c) Lakes generated by fluvial processes.
- d) A variety of wetlands (and not really typical) “lakes”

3.1. Lakes developed on older terrains without direct relation to the fluvial systems:

This kind of lake is mainly developed on older Precambrian rocks, affected by intense chemical weathering along the geological time. There is scarce information about the geomorphic processes generating these lakes, usually located on Regional Surfaces of Planation, often topped with thick laterite crusts, currently undergoing dismantling. Of course, whenever limestone is present, carstic processes can generate a mosaic of small lakes. Lakes can also be generated by “pseudo-carstic” processes, related to the dismantling of the laterite crust or to a more impermeable saprolite associated to the existence of conjugated fractures and the action of sub-surficial flow of the water table following the regional slope. Similar processes have been studied in some detail by the author in the Cerrado (savannas) area of Central Brazil and in the Cerrado-Rainforest ecotone.

A particular case regards the Carbonatic intrusive rocks which remain as isolated hills above the predominant lowered substrate of the Regional Surfaces of Planations. A good example is the Six Lakes hills in the northern Amazonia (Amazon State), where the Carbonatic rocks were deeply altered by more than 180meters of tropical weathering processes and body lakes were generated by dissolution processes.

3.1.2. The Quaternary record

The main record of Quaternary palinology of the Amazon basin includes a marine core of the Amazon cone and five points from the following lakes: Carajás (6°S, 50°W), Hill of Six Lakes (0°16'N, 66°4'W), Maicurú (0°30'S, 54°14'W), Laguna Bella Vista (13°37'S, 61°33'W), Laguna Chaplin (14°28'S, 61°04'W).

In the state of Para, in a little lake on the Carajás Plateau, dry periods were recorded with replacement of rainforest by savanna at 60 ky, 40 ky and 23–11 ky BP (Absy et al. 1991). All the records show a hiatus in sedimentation between ~23,000 and 13,000 14Cyr BP (Carajás), 30,000 and 16,000 14C yr BP or between 25,690 and 17,410 14C yr BP (Maicurú), and 38,600 and 11,030 14C yr BP (Laguna Bella Vista). These hiatus are associated with a lack of deposition of organic material during thousands of years (Ledru et al., 1998) and / or strong erosive conditions. Presence of tropical semideciduous dry forest at the Cerrado-rainforest boundary in northeastern Bolivia (Bella Vista: Mayle et al., 2000)

was documented at ca. 30,000 yr BP after which a hiatus was recorded lasting until the beginning of the Holocene.

This small palinological record together with another locality in alluvial sediments in Rondonia (Catira Site) were enough to keep a strong discussion on the Last Glacial Maximum Amazon paleoecology and paleogeography of the basin during at least two decades, between palinologists of different groups. However, because the hiatus existing in the lakes record no pollen was recorded during good part of this period. All these studies used similar approaches, consisting of drilling lakes without record and mapping of Quaternary landforms and deposit, i.e. without additional observations or correlations with the sedimentary and geomorphologic units for each region.

With exception of Hooghiemstra and Van der Hammen (1998), the majority of the palinologists either ignored or misinterpreted the abundant geomorphologic, sedimentologic and paleo-vertebrates information obtained in the basin during the last two decades, relying only on the palinological record (see Colinvaux et al.,2000, Bush, et al., 2004, Anhuf et al., 2006, among others). Interpretations taking into account just a local record and one “proxy” indicator (pollen) have produced a significant drawback in the understanding of the Quaternary climatic changes of the South American tropics, in special in the Amazon basin.

3.2. Lakes developed in fluvial valleys and soft Quaternary sediments but not directly related to fluvial landforms:

Rounded small lakes, permanent and mainly seasonal, are recorded in Roraima plain, northern Amazonia (Latrubesse and Nelson 2001). The flat area cribbed by a large number of shallow depressions was affected by aeolian activity during the Late Pleistocene and Holocene. Very dissipated dune fields are recorded in this flat area forming the uppermost units of the Boa Vista Formation,

The lakes are circular, pear-shaped or otherwise rounded in form and small in size — tens to hundreds of meters in diameter. The temporary lakes are affected by frequent grass fires in the dry season. They are consequently bare of woody vegetation, developing only a thin seasonal herbaceous cover. Some of the permanent lakes, however, contain dense communities of rooted shrubs. Depressions with open water or bare damp soil are also distinguishable from the surrounding non-flooded grasslands.

In the Cauame' dune field, the damp depressions are largely elongate and parallel to the prevailing NE-SW wind direction which generated dunes. Closed contours are taken to be the result of deflation behind apices of parabolic dunes followed by incomplete erosional fill-in or a remnant damming effect where younger slip faces once advanced up the deflation corridor of older dunes. In other parts of the sandy and silty realms of the Boa Vista Formation, the depressions are connected by a reticulate system of channels, or are chained like a string of pearls along a single valley. These landforms may be circular blow hollows or pans produced by ascendant helicoid winds active in a drier climate, during the hours of greatest solar heating. Circular blow hollows small rounded pans are active where the water table is low; the soil has a low water retention capacity and sediment is unconsolidated. Circular blow hollows may also have reworked the elongate depressions of the Cauame' parabolic dune field, making them more circular or creating strings of broadened circular depressions along an elongate valley originally entrained by the deflation troughs of a stabilized parabolic dune. Such circular expansions and the development of an interconnected drainage field can explain why the elongate dune axes are difficult to detect in remote sensing products. The blow hollows now occupied by temporary or permanent lakes are inferred to have formed during a Holocene relatively dry phase (middle to lower Holocene) evolving from a mixture of hydro-eolian conditions.

3.3. Lakes generated by fluvial processes.

The Amazon Rivers can be classified roughly into two main groups due to the sedimentary load they carry and in several sub-groups, according to their geological setting and the geomorphology of the channels and floodplains.

Regarding the geologic-geomorphologic context, tropical rivers flowing along fluvial linear belts can be grouped in: orogenic mountains belts, Paleozoic and Mesozoic sedimentary and basaltic plateaus/platforms, Pre-Cambrian cratons, Lowland plains in sedimentary Cenozoic basins and Mixed Terrains (Table1) (Latrubesse et al, 2005).

Regardless the geology and relief they drain, rivers carrying abundant sediments are

rich in dissolved nutrients, while rivers carrying low quantities of sediments have high dissolved organic carbon and low levels of nutrients and other solutes (e.g. Negro River) or intermediate in solute contents (e.g. Tapajós River).

Floodplain lakes are generated by fluvial processes and are a component of the floodplain morphologies. In the case of the Amazon basin, the huge variety of channel patterns and the existence of complex (in time and space) floodplains induce a mosaic of lakes with large diversity in origin, shape and functioning.

The floodplain along the Amazon main stem in Brazil (~2800 km length) occupies approximately 92400km², of which 11% was estimated to be covered by 6510 lakes. However, only 10% of the floodplain lakes are larger than 2km² (Sippel et al, 1992), with small lakes predominating over these landscapes.

Additionally, Sippel et al (1992) estimated that the lower 400 km of the major tributaries occupy 62033 km² and that the lake abundance and area of the four main tributaries

(Negro, Purus, Japurá, Madeira) spreading in relation to floodplain range from 5 to 12 %.

For the same area of the Amazon system the mean flooded area between 1903 and 1996 was estimated in 46,800km², of which river channels water and floodplain lakes comprised approximately 20,700km² (Sippel et al, 1998).

Hydrologic modeling of the Amazon flooding wave along the main channel suggests that up to 30% of the main stem flow exchange water with the floodplain (Richey et al, 1989). The annual sediment exchange between the main channel and the flood plain on the basis of transport models should be more than twice the flux through the river gauge located at Obidos, in the lower Amazon (Dunne et al, 1998).

However the Amazon alluvial plain is stated to be not totally inundated during the typical flood season (Tricart, 1977; Iriondo, 1982). Mertes et al. (1996), using Iriondo's interpretation of landforms, estimated that, 40,000 km² of flood plain and 4000 km² of islands are inundated by direct flooding of the Amazon, between Vargem Grande and Obidos. Some 20,000 km² of deposits of the alluvial belt remain dry or are flooded not by the Amazon but by small tributaries, groundwater seepage or rainfall (Mertes, 1997).

More recently Hess et al (2003), using JERS imagery, estimated that seventeen percent of a 1.77 million km² study quadrat in Central Amazonia, which includes the main stem of the Amazon River from slightly downstream of the Napo River confluence to slightly downstream of the Tapajós River, the Negro River south of the Uaupe's River confluence,

and the lower reaches of the Tapajós, Trombetas, Madeira, Purus, Japurá, Juruá, and Içá rivers, are occupied by wetlands, which were 96% and 26% inundated at high and low waters, respectively. In relation to these figures, about half of the wetland area was occupied by floodplains and channels of the Amazon main stem and major tributaries. Hess et al (2003) remarked that 70% of the wetland areas are constituted by flooded forest. However, the mapped classes of vegetation physiognomy and flooding status show large variations because floodplain geomorphology and with respect to white and black water environments.

Although these results are very valuable, the lack of a detailed geomorphologic mapping and the establishment of clearer relations between hydro-geomorphologic and vegetation units, as well as the use of hydrology without considerations about the dynamic and nature of the physic environment, does not allow a better understanding of the hydro-geomorphologic and ecologic behavior of the floodplain and other flooded areas, including lakes systems. A multidisciplinary approach strongly based on fluvial geomorphology and detailed hydro-geomorphologic mapping become necessary. Lake morphology and behavior are related to the fluvial regime and to the geomorphologic style of the rivers, as well as to the paleohydrologic landform heritages recorded in the floodplain and lower terraces, which are also related to the floodplain sedimentary architecture.

The Amazon floodplain lakes can be classified as a function of the genetically related fluvial processes, with the following main types:

- A) Lakes related to lateral channel shifting: Lakes in abandoned channels tracts, oxbows (lakes or swamps depending the degree of siltation), composite chained oxbows, scroll bars lakes, composite scroll bars lakes, lakes in lateral accretion processes attaching islands to the floodplain.
- B) Lakes generated by landforms built by vertical accretion processes in the main channel and by floods on the floodplain, affecting the floodplain and tributaries rivers: round floodplain lakes, lakes generated by floodplain deltas, levee lakes, island levee lakes, blocked valley (Ria Lakes).

3.3.1. Lakes related to lateral channel shifting:

Oxbows (lakes or swamps as related to the degree of siltation): Ox bows lakes are typical elements of meandering floodplains. In the Amazon basin, there is a considerable number of tributaries which show meandering patterns, and, in all of them, oxbows lakes are the dominant lacustrine landforms.

Rivers with abundant sedimentary load draining the lowlands (Jurua, Purus, Javari), as well as mixing terrains (orogenic areas and lowlands), such as Mamore, Madre de Dios, Beni, Ucayali, Iça, among others, show a variety of meandering patterns. In these rivers, it is possible to identify several generations of abandoned meanders in several stages of siltation in the floodplains and swampy areas, occupying old meanders in the lower Holocene-Late Pleistocene terrace (Figures 1 and 2A). Vegetation is a main indicator to determine the level of evolution/siltation of these lakes.

The typical channel pattern of lowland tropical rivers, such as Jurua and Purus, is that of single sinuous channel with medium to high sinuosity occurring in between shorter straight reaches. The meanders are compounded and asymmetric, and several reaches exhibit irregular and tortuous pattern. Sinuosity in the meandering reaches varies, with values as high as 2.7 and width-depth channel ratio values mostly between 17 and 27. Because of the irregular and tortuous channel pattern, meander geometry shows a wide range of values. Suspended load is dominant, reaching 98% of the total sediment load (Gibbs, 1967, Mertes, 1985). Meanders are abandoned mainly by neck cutoffs and lateral rates of channel migration are low. Radiocarbon dating in fluvial deposits indicate that during part of the Late Pleistocene (Middle Pleniglacial to early upper Pleniglacial) and Holocene, the lowland rivers suffered important paleohydrological changes, although meandering patterns were always dominant and oxbow lakes a characteristic of these kind of rivers (Latrubesse and Kalicki, 2002, Latrubesse and Rancy, 1998, 2000)

Oxbow lakes are very rare in the Solimões-Amazon main stem and in the Madeira River because the tendency of the channel to generate an anabranching low sinuosity pattern. However, it is possible to identify a big ox bow lake north of Xibeco which is located on an avulsed fluvial belt of the Solimões main stem (Mertes et al, 1996).

Scroll bar lakes (simple and compounded)

These kinds of lakes are generated in between scroll bars, in a meandering scrolled floodplain. The lakes are elongated, usually intermittent and dependent on the floods

dynamic. Scroll bars lakes are mainly found in meandering tributaries draining mixed terrains such as the Mamore, Beni, Madre de Dios, Ucayali and Iça rivers, for example. Compared to the lowland tributaries (Purus, Jurua, Javari), these rivers have more harmonic meanders, show more lateral activity and scrolled floodplains, and transport relatively more bed sandy load. However, scroll bars lakes can also be found in large and complex rivers with tendency to anabranching, such as the Solimões-Amazon. The Upper Solimões have a tendency to anabranching and to generate complex multi-channels tracts like the meanders from Iquitos to Tefe (along a reach ~1100km in length). The channel-dominated floodplain is a complex mosaic of fluvial forms, including younger channels, active sandbars, islands, levees, scroll dominated plains, and abandoned belts. The curvature of the scroll morphology suggests that generation by secondary channels or parana's are the main factors in the genesis of these deposits and morphologies (Mertes et al., 1996, Latrubesse and Franzinelli, 2002). Specifically, scrolls are mainly generated by lateral activity of the parana's (Figures 1 and 3B). Elongated, narrow and arched lakes occur in the swales. In some places, these lakes may have a finger like shape, as a result of the ridge and swale topography and the different angles of intersection between the scrolls. With respect to the scrolls, these relate to an upper point bar, and are typically composed of fine sediments.

Lakes in abandoned channels tracts: Abandoned channel tracts are associated to avulsion processes, which are particularly related to sunken tectonic blocks or other areas of tectonic instability, as well as to channel instability in flooded basins where rivers shows a tendency to generate vertical accretion floodplains. In the Amazon, these lakes are mainly associated to sunken prismatic tectonic blocks. These “lakes” are in reality a complex relation of pounded areas occupying abandoned channels and floodplain channels connections and, depending on the flood stage, many of them can behave as lakes or have a fluvial tendency to interconnecting and draining away the floodplain. Due to their channel morphology and well developed banks, these lakes are rather stable in area.

In Brazil, we identified three main areas with this kind of lakes. The first one is located in the lower reaches of the Moa River, a tributary of the Jurua River in the Brazilian southwestern Amazonia (Figures 1 and 2B).

The second one (and a good example of a lake developed in abandoned channel) is the area of confluence between the Japurá and Solimões rivers, where is the Reserve of Sustainable Development of Mamirauá.

The third one is associated to a sequence of neotectonic blocks affecting the Solimões from Xibeco to the Purus River confluence (Figures 1 and 3B). Avulsion on the Solimões River, north of Xibeco, has been described by Mertes et al. (1996), while Latrubese and Franzinelli (2002) found a large abandoned belt of the Solimões River upstream of the confluence with the Purus. At present, the Solimões River flows through the north of this area, close to the northern border of the V shaped block and near the contact with the upper tertiary Solimões Formation. The abandoned belt cuts the previously deposited sediments of the impeded floodplain that currently includes a large number of lakes. It is evident that the Solimões River avulsion caused abandonment of approximately 160 km of the river reach. Radiocarbon dating of the sediments of the Solimões alluvial plain, close to the mouth of the Purus, yielded an age of 1000 years BP.

In Amazon lowland rivers such as Purus River, older meandering belts abandoned by avulsion were recorded during the early-middle Holocene (Latrubesse and Kalicki, 2002) which indicate that during this aggradation phase, oxbows, as well as lakes in abandoned meandering channel tracks were the main elements of the floodplain. In fact, many of these areas are now occupied by swampy environments.

The Ucamara depression in the Peruvian Amazonia can also be used as a good example of lake generation in abandoned channel belts because in this area abandoned meander belts of the Marañón and Ucayali Rivers have been described (Dumont and García, 1991).

3.3.2. Lakes generated by landforms built by vertical accretion processes in the main channel and by floods on the floodplain, affecting the floodplain and tributaries rivers:

These kinds of lakes are generated by flood dynamic mainly in anabranching low sinuosity rivers such as the Solimões-Amazon, the Madeira, and the Japurá. The floodplain of these rivers presents an impeded floodplain alternating with a channel dominated floodplain as described by Latrubesse and Franzinelli (2002) in the Solimões-Amazon

main stem. The impeded floodplain has a complex origin. Its sediments originated in several Holocene temporal stages, but overall, there is a tendency for vertical accretion in this geomorphic unit. Round floodplain lakes, levee lakes, island levee lakes, lakes generated by floodplain deltas are typical features of this geomorphic unit.

Levee lakes:

Large levee complexes lay on the sides of the channels and their development depend on the hydraulic geometry of the channel section and channel stability. Low anabranching rivers transporting abundant sedimentary load generate important levee complexes. In the Solimões-Amazon, these complexes increase in importance downstream Manacapuru (Figures 1 and 3A). The height of the levee complex typically varies between 1 and 10 m above the low water level of the river. The sediments characteristically are composed by the intercalation of sandy and fine deposits. Nevertheless, the existence of a sandy platform at the base of the levee is common. The amount of fine sediment and the intercalation of fine and sandy deposits increase upward and highly bioturbated muddy sediments occur at the upper levels as a consequence of the vegetation colonization of the levee. For example, in the Solimões River at Iranduba, upstream of Manaus, the levee complex is approximately 22 km in length and up to 4 km in width, and the contact between the fluvial sediments and the banks of the Cretaceous sedimentary rocks of the Alter do Chão Formation are visible.

Likewise, levee lakes are also very important features in rivers carrying today a small amount of sedimentary load. As described in the Negro River by Latrubesse and Franzineli (2005), important paleohydrological changes happened in the Amazon basin during the Late Holocene. Many rivers draining cratonic areas, such as the Negro, the Tapajós, the Xingú, the Trombetas and the Aripuaná, exhausted their yield of fine sediments, aborting the development of floodplains in recent times. These rivers carry today an insignificant quantity of suspended load and behave as blocked valleys having almost a lacustrine dynamic in their lower reaches. Huge and spectacular levees can be observed inside huge flooded valleys, covered by Igapó forest (Figure 4). In between these levee complexes, lakes, interconnected with the other elements of the floodplain during floods, are present.

Round floodplain lakes and lakes generated by floodplain deltas: Both kinds of lakes are characteristics of the impeded floodplain. As mentioned before, the impeded floodplain is a widespread unit characterized by a number of round or irregularly shaped lakes on a very flat surface, dominated by low sinuosity anabranching rivers such as Solimões-Amazon, Madeira and Japurá (Figures 3A and 3B). Some of these lakes are connected to the main system by small channels. Others, however, are isolated from the main channel. At times, this unit is inundated by annual floods, although it is not totally flooded every year. This unit resembles local flood-basins formed by grey to grey-green muddy sediments. Orange or yellow bioturbated mottled sediments are also frequently found, as opposed to primary sedimentary structures. In several places, it is possible to find remnants of tree trunks, some of them in “life” position. In certain circumstances, trunks were associated with strata primarily composed of leaves and stems. Radiocarbon dating of trunks from the basal beds of the Careiro Island, in the Solimões-Amazon River, indicated ages ranging between 300 and 2500 years (Latrubesse and Franzinelli, 2002; Absy, 1979; Sternberg, 1960).

A conspicuous quantity of round lakes are recorded in the sunken tectonic block of the Solimões River upstream the Purus-Solimões confluence as described before (Figure 3B). The increment in the numbers of lakes was also noticed by Sippel et al, (2002), who, however, did not identify the cause of this increment which is as a consequence of avulsion activity and channel abandonment of the Solimões River in this area (Figure 3A).

Although the sediments of the impeded floodplain originated in several temporal stages, there is a tendency for vertical accretion in this geomorphic unit. Levees played an important role in alluvial sedimentation. As normally happens, the distal levee areas consists of more depressed areas that, in some cases, are covered by tropical alluvial plain vegetation. When levees are broken during floods, the distal levee areas become swampy or flooded. Splay-like systems or minor channels develop, connecting the main system with the back-flooded areas. As the splay deltas coalesce with other levees, these depressed areas are constrained and limited, generating lakes.

As expected, these lakes are shallow and their depths correspond to the maximum heights of levees and thickness of the splay deltas. The vegetation (including arboreal physiognomies) frequently covering a flooded area has resulted in several profiles containing large quantities of organic strata at the base of the sedimentary column. Organic

strata are formed by detritus such as stems and leaves marking the original soil/substrate of the newly generated lake or flooded area. While low energy sedimentation is in process, the dead flooded trees are buried in a vertical position.

Additionally, recent sediment of the present day channel occurs locally on the impeded floodplain, indicating that the modern alluvial system is actively blanketing and reworking the impeded floodplain deposits.

Island levee lakes:

The islands in large anabranching low sinuosity rivers such as the Solimões-Amazon and the Madeira usually have a “sandy core” formed by sandy bar deposits (Figures 3A and 3B). The creation of an island includes two distinct processes: (1) the generation of a sandy bar or sandy core of the island (on - or without - a “skeletal base” of impeded floodplain deposits), and (2) a mix of vertical and lateral accretion processes associated with main channel dynamics. However, in some cases, the base of the impeded flood plain is not found, resulting in a base composed of channel sandy bar. The typical evolution of an island begins with the development of large channel bars mentioned above. These sandy units are then stabilized by pioneer vegetation. The original bar takes a hexagonal shape. At a later stage, levees begin to develop and to characterize the mix of vertical and lateral accretion stage of the island. The vertical accretion processes build an emerging area frequently flooded during the annual floods. The island surface presents a ridge and swale topography similar to that of the scroll-dominated flood plain, but with straighter scroll morphologies. The upstream ends of the islands have abrupt erosive banks up to several meters high during lower water level. On the other hand, the low sinuosity of the main channel favors the development of low sinuosity scroll/levee morphologies. Thus, an undulated landscape with a straight ridge-and-swale topography develops on the island surface. A few small elongated lakes persist in the swales in which fine sediments are deposited until the lakes become filled. Because the smoothing of the older core ridges in the island, a large “inland” rounded to digitate lake can appear in the core of the islands.

Blocked valley (Ria Lakes):

Blocked valleys are characteristic of the Amazon basin and probably in no other fluvial basin of the world this kind of geomorphic features are more spectacular than here (Figures 3A and 3B).

Blocked valleys or “ria lakes” were interpreted to be formed when valleys scoured during periods of lowered sea levels of the Late Pleistocene related to a sea level ~100 lower than today which were subsequently flooded during the Holocene (Sioli 1957, Irion, 1984) or related to tectonic effect in prismatic sunken blocks (Dumont, 1993, Iriondo, 1982) but in concrete they are related to the difference in sediment transport and energy between a main system carrying abundant sedimentary load developing a significant floodplain blocking the mouth of a tributary which have lower energy and lower sediment discharge than the collector system. The eustatic effect is not necessary to develop this kind of lakes. Adjustments in longitudinal profiles as response to eustatic changes can be produced in some hundred kilometers from the mouth position because the low slopes large rivers had. In the Amazon River water slope is extremely low, oscillating from ~6 to 3 cm/km and blocked valleys are recorded in regions that were without direct effect of sea level changes. Blocked valleys are founded very far from the ocean, in areas which were not affected by sea level changes such as the Ucamara depression in Perú, the upper floodplain of the Araguaia River (tributary of the Tocantins) and others.

Additionally we need to take account that the sea level was changing along the glacial cycle and not permanently located to 100m below present sea level. In this case the adjustments along the longitudinal profile were dynamics and would not be only related to the lowermost level reached by the marine regression as claimed by Sioli and others when comparing the ~100m depth channels of the Amazon or the ~80m of the Negro river near Manaus.

Lakes in blocked valleys have “clear” and “black” waters because the production of sediments of the blocked tributaries basins is very low.

Other big rivers were almost blocked by the Solimoes-Amazon as well. For example the lower Negro was partially blocked by the Xiborema levee complex but the huge discharge of the Negro which is constrained by geologic effect in the lower reach permit that the river reaches the Solimões. The Tapajos River, which have less discharge than the Negro, suffered strongly the blocking effect because the development of a very stable levee complex on the right side of the Amazonas River. The huge Tapajos valley is flooded and

the river connects to the Amazon by a small and narrow mouth. Sediments of the Amazon transfer behind the levee, as described for delta lakes entering the water saturated floodplain, with the only difference that here they enter in a huge blocked fluvial system, the Tapajós, forming a delta system as earlier described by Sioli, (1957).

4. Reservoirs in the Amazon basin

Near 93% of the electric power of Brazil is generated by over 400 large and medium-size power-dams. In the Amazon basin, dams are concentrated in the Brazilian territory (table 2), with two large reservoirs located in the Amazon fluvial basin: Balbina, built on the Uatuma River in 1987 to supply power to Manaus, and Samuel, also built on a relatively small size river, the Jamarí, a tributary of the Madeira River. Balbina has flooded 2400 km² of rainforest to produce 250 megawatts, enough for only half of the city's present needs Balbina is a good example of an engineering and environmental disaster because the large impacts and the small hydropower production.

Other dams built in the Amazon rainforest during the last decades are in the Tocantins River basin. This basin has experienced a huge human pressure during the last decades since the construction of Tucuruí dam and the expansion of the agricultural and cattle ranch frontier along the savannas (Cerrado) of Central Brazil and the development of the Tocantins State. The Tucuruí Hydro-Power Complex, completed in 1984 in the lower Tocantins River, was the first large dam built in the Amazon rainforest for hydropower generation but today six large dams exist on the Tocantins River.

The role of large dams in the generation of green house gasses (carbon dioxide and methane) is remarkable. Estimates of emissions during the first decade after reservoir filling for the year 1990 (i.e., the baseline year for national greenhouse gas inventories under the climate convention) totaled 10 million tons of carbon for the existing dams in Brazilian Amazonia: 2.55 at Tucuruí 6.43 at Balbina, 1.13 at Samuel and 0.01 at Curuá-Una while methane emissions should be 90,000 tons and 140,000 tons in Tucuruí and Balbina respectively (Fearnside, 1995).

Feasibility studies are currently being carried out on the Xingu, Madeira, Tapajós, Teles Pires, Trombetas and Araguaia rivers in the rainforest environment and the rainforest-

cerrado ecotones. Without exception, all the related projects are marked by severe social, economical, and environmental controversies.

Particularly controversial are the planned dams in the Madeira and Xingú rivers.

Two hydroelectric dams being considered are Jirau and Santo Antonio, on an uneven stretch of the Madeira River, in the western Brazilian State of Rondonia. These complexes, part of a larger four-dam cascade to generate electricity and permit navigation along the Peruvian and Bolivian tributaries, could have a potential energy production of 3,300 and 3,150 megawatts, respectively, and a cost of \$9 billions.

From a hydro-geomorphologic point of view, the Madeira River offers a tremendous challenge for river management and dam building because the inexistence of gorges or abrupt relief. The river valley cuts a low landscape and a lower terrace and at this reach the mean annual discharge is more than 22,000 m³/s with peaks that reach more than 80,000m³/s and ~400 Mt of transported fine sediments (i.e. more sediments and water than Three Gorges in Yangtze River). Because the insignificant relief, mistakes in the project can produce huge environmental impacts due to the permanent flooding of the lower terrace, generating swamps in both sides of the river (in Bolivian and Brazilian territory), as well as affecting the longitudinal profile of the tributaries, what would transmit environmental impacts to their floodplains.

In the Xingu River, Belo Monte dam, first proposed in 1975 by Eletronorte (a state-owned utility company) and originally consisting of two dams (Babaquara and Kararaô), is one of the recurrent projects proposed for hydropower generation since the seventies.

The whole complex would have five generating plants along the Xingu River with the capacity to generate 14,700 MW (Fearnside, 1995). In fact, Electronorte suggested to build up to four additional dams (Altamira, Ipixuna, Krokaimoro, and Jarina), flooding a total area of 22,000 km² (Fearnside, 1995, 2005).

Recently, the project was reevaluated and redesigned for a reservoir area of 440km² and an installed capacity of 11,181 MW. The estimative cost of the reservoir should reach \$3.7 billion (Carvalho, 2006). However, the Altamira/Babaquara Dam which should be located upstream to increase the power generation at Belo Monte would flood an area of 6140 km² (Fearnside, 2006)

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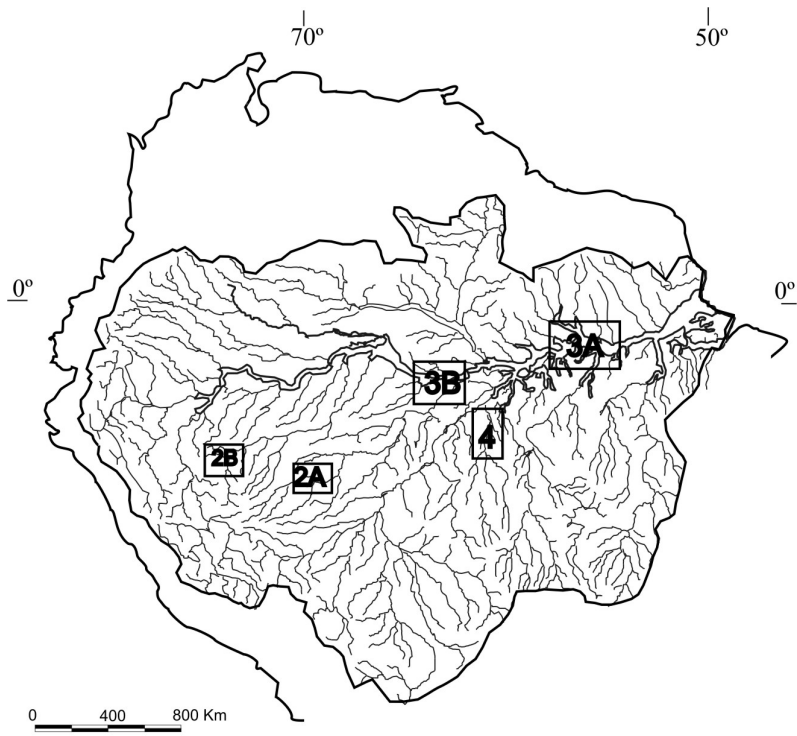
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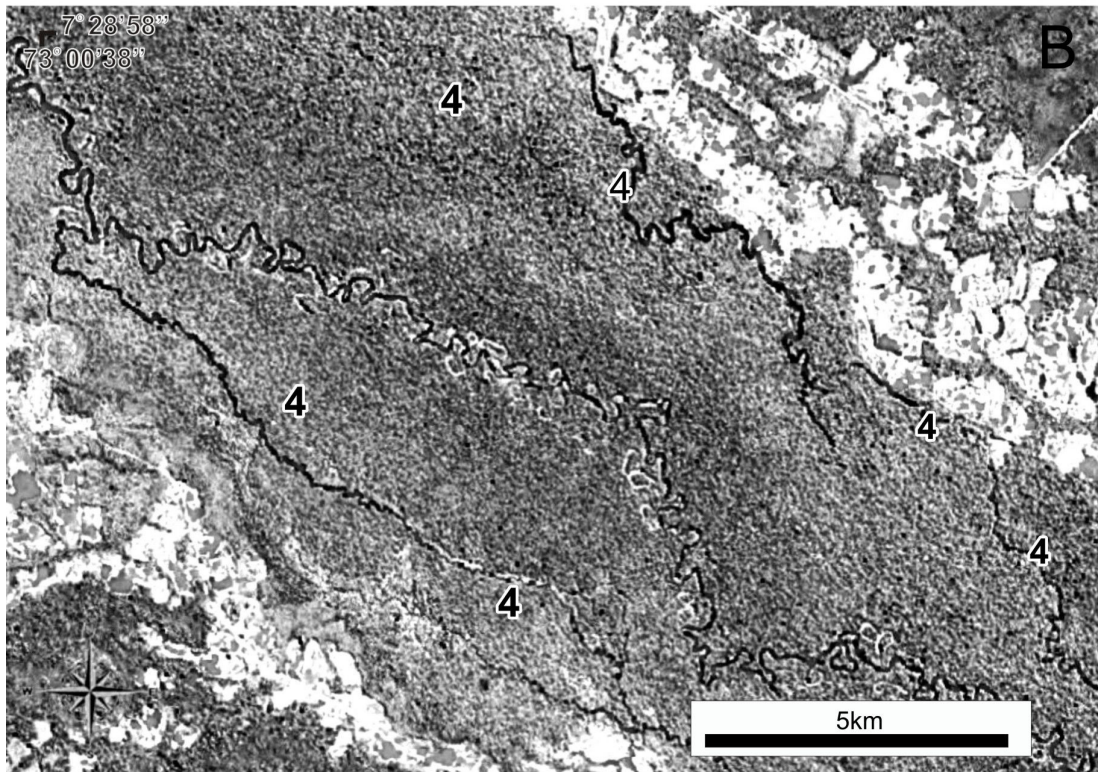
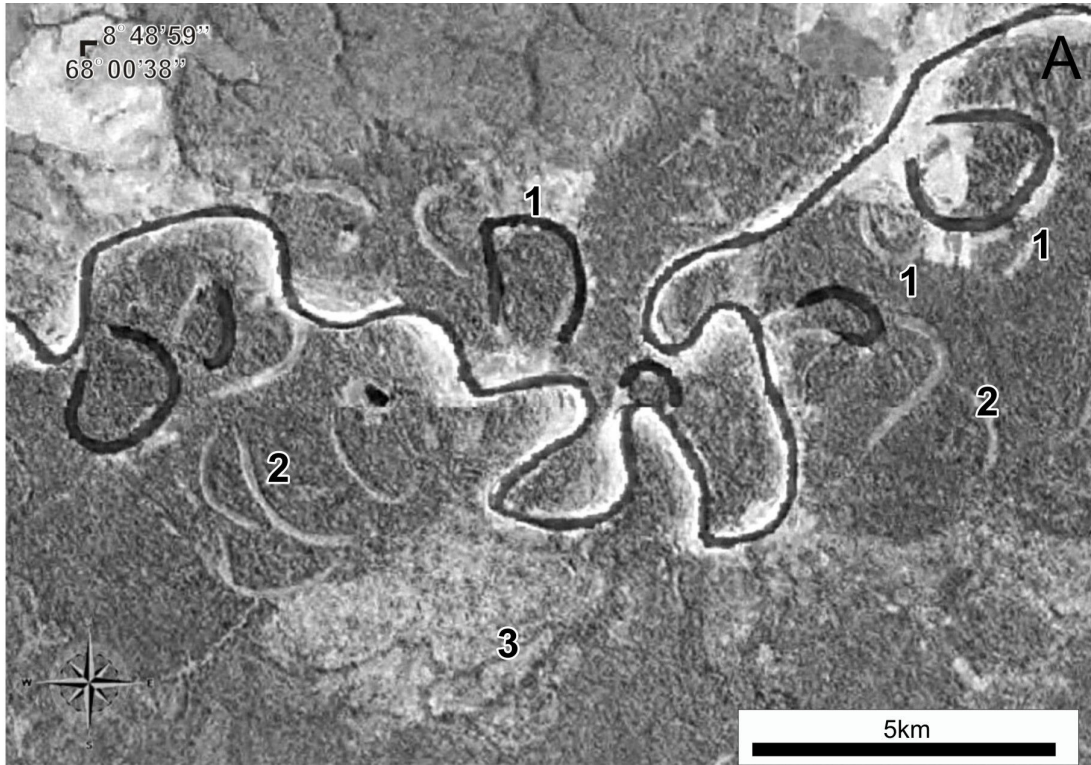
Figure 1. Location map. Numbers indicate the location of the chapter's figures.

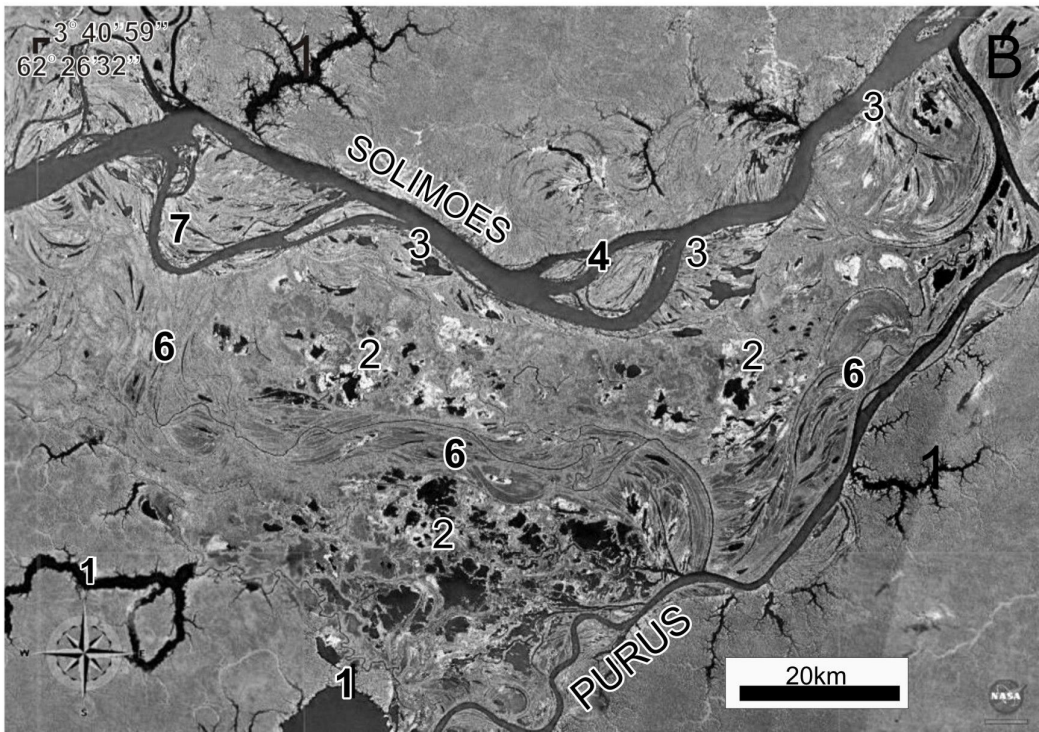
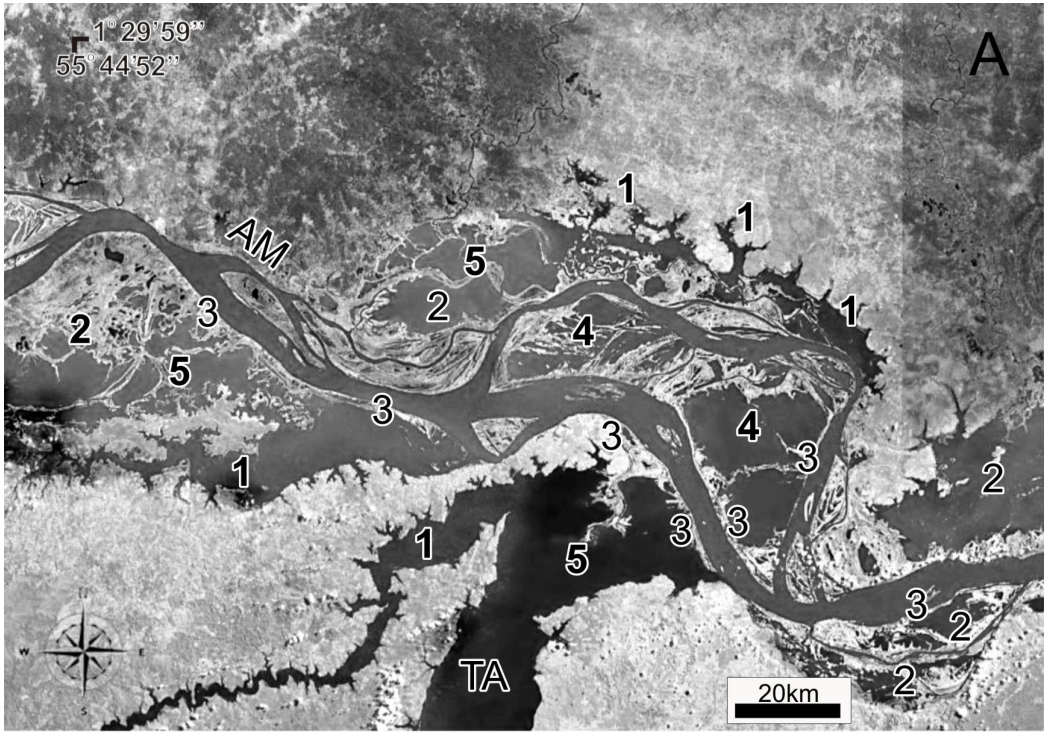
Figure 2. A) Purus River upstream Boca do Acre city. The tortuous meandering pattern generates oxbow lakes (1). Older swampy areas occupy paleomeanders (2) up to ~7kyBP while less spread and shallow swampy areas in old meander scars (3) can be also founded on the Late Pleistocene terrace (~60-20ky BP).
B) Lakes occupying abandoned channels by avulsion in the Moa River floodplain (4). Some of the abandoned channels can be partially and episodically reactivated and feed by floods

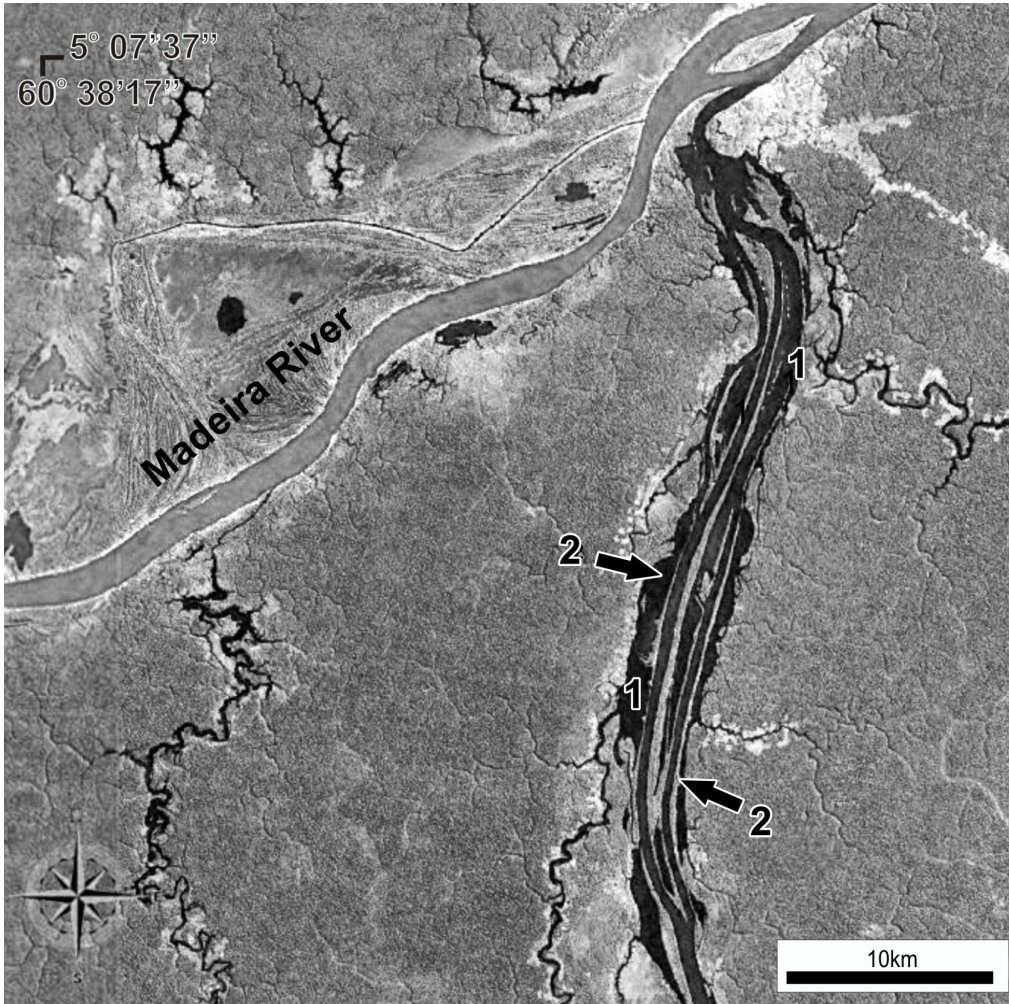
Figure 3: A) Amazon river at the confluence with Tapajos River, Note the abundance of blocked valleys (1), rounded lakes in an impeded drainage floodplain (2), the spectacular levees confining the river flow along a narrow corridor inside a water saturated floodplain (3) , the large islands and island lakes (4), and delta systems entering in the floodplain lakes (5)
B) Solimões River at the confluence with Purus River. Note the large alluvial belt of the Solimões river abandoned by avulsion (6). The area is located in a neotectonic prismatic block. A large quantity of small rounded lakes form the impeded floodplain unit while secondary more sinuous channels generate small lakes in a scrolled topography (7) and small lakes, mainly temporary, can be founded in side the islands (4). Levees are presents (3) and sedimentation of the floodplain blocked several tributaries generating blocked valley lakes (1).

Figure 4. Spectacular levee development in the Aripuana River, a main Brazilian tributary of Madeira River. The river carries today a very low amount of suspended load and function as a blocked valley systems with a lake dynamic (1) behind the levees (2) which confined the channel.









Sub-Category/Description	Examples	Characteristic kinds of Lakes
A. RIVERS GENERATING LINEAR FLUVIAL BELTS		
A1: Transporting low amounts of sedimentary load		
A.1.1 Pre-Cambrian cratonic areas: headwaters in areas of stable		
Pre-Cambrian crystalline basement, low relief		
a) Blocked valley, flooded valleys, very low suspended load	Tapajos, Xingu, Tefê, Coarí	- Blocked valleys lakes
b) Wide valleys with islands alternating with narrow reaches with rapids or nodal points, very low suspended load	Negro, Trombetas, Aripuanã	-Levee lakes and Igapó forests
A2 Transporting abundant sedimentary load		
A.2.1. Lowland plains in sedimentary Cenozoic basins		
single channel, non-harmonic meanders, muddy banks, high suspended load	Purus, Jurua	-Ox bows dominants
A.2.2. Mixed: Rivers draining mixed terrain		
a) Platforms+cratons: mainly braided alternating with incised valleys, bed load dominant	Branco	
b) Orogenic + platforms+cratons (+Lowlands): complex systems, mainly braided tendency, low anabranching, some rivers exhibit rapids alternating with wide alluvial reaches, high sediment load (suspended load dominant)	Madeira, Solimões Amazon	-Levee lakes, round floodplain lakes, island levee lakes, lakes generated by floodplain deltas, scroll lakes, abandoned channel lakes, scarce oxbows.
c) Orogenic+Lowlands: well-defined headwater areas in orogenic belts and narrow alluvial plains, mixed morphologies (braided/meandering) along lowlands.	Japura, Ica, Mamore.	-Ox bows, scroll lakes,(Mamoré, Madre de Dios, Beni, Iça, Ucayali). Island levee, rounded floodplain lakes (Japurá,)

Dam	Latitude	River	Year of Construction	Biome	Power (MW)	Reservoir Area (Km ²)	Estimated Cost
Tucuruí	03° 45' S; 49° 40' W	Tocantins	1984	Rain Forest	4,240	2,430	US\$5.5 Billion
Samuel	08° 45' S; 63° 28' W	Jamari	1988	Rain Forest	217	645	US\$ 836 millions
Balbina	2° 26' 24" S ; 58° 15' 0" W	Uatumá	1987	Rain Forest	218 planned but 112,2 produced	2360	US\$ 1000 millions (estimated)
Curuá Una	2° 50' S; 54° 18' W	Curuá Una	1977	Rainforest	40	72	-----

Table 2: General data of the main dams of the Brazilian Amazon basin