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Remote sensing of floodplain geomorphology as a surrogate for biodiversity in a tropical river system (Madre de Dios, Peru)

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Abstract

The complex floodplains of large rivers offer a striking example of how geomorphology, by dictating patterns in the frequency and duration of soil saturation and surface flooding, influences ecosystem structure and function. This study draws on multiple sources of data from remote sensing, together with ground observations and water sampling, to distinguish floodplain ecosystems in the Madre de Dios River, a tributary of the Amazon River in Perú. This remote tropical river meanders across sub-Andean alluvial deposits in a tectonically active region and creates floodplain surfaces of varying ages, including terraces that are above the reach of present-day river floods. Data from Landsat ETM+ (optical multispectral), JERS-1 (L-band radar), and the Shuttle Radar Topography Mission (C-band interferometric Digital Elevation Models) were integrated in an object-oriented image analysis approach to distinguish five classes of floodplain vegetation. Vegetation classes generally correspond with successional age and reflect the activity of the riverine meander belt. Stage data for the river show erratic fluctuations and an annual range exceeding 8 m, but the maximum depth of floodplain inundation varied from >1 m close to the river to approximately 0.1 m on more elevated terraces. The major ion composition of standing waters on the floodplain during the dry season indicated the importance of emergence of local groundwater in maintaining saturated soils, particularly further from the river, where backswamp vegetation is distinct and includes palm swamps. Thus, a hydrological continuum exists from deep but sporadic river inundation near the river to constant soil saturation by groundwater emergence in distal backswamps, reflecting the geomorphological origin and age of the floodplain deposits. This hydrogeomorphic continuum results in fundamental ecological differences. The exceptionally rich biodiversity of the sub-Andean region may be ascribed in part to the enhanced biodiversity associated with fluvial geomorphological features, and, thus, conservation planning must account for the diverse landforms created by fluvial dynamics.

Keywords: Floodplains; Rivers; Remote sensing; Amazon; Biodiversity; Conservation

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1. Introduction

Biodiversity encompasses the species, communities, and ecological processes and interactions within ecosystems (Purvis and Hector, 2000), and is intimately related to physical features of ecosystems including geomorphology and hydrology. The complex floodplains of many large rivers offer a striking example of the influence of geomorphology on hydrology and, consequently, on ecosystem biodiversity. Much of this influence can be attributed to spatially variable patterns in the frequency and duration of soil saturation and surface flooding (Winter, 2001; Hamilton, 2002). This variation is dictated by the elevation and position of fluvial landforms (i.e., fluvial geomorphology) in relation to the local water table and the annual range in river levels (Church, 2002). Thus, geomorphological patterns are fundamentally linked to biodiversity in floodplain environments (Brinson, 1993; Junk, 1997; Lewis et al., 2000; Ward et al., 2002).

Accumulation of water on floodplains can result from riverine overflow or from delayed drainage of local rainfall and runoff, and often these sources of water have distinct chemical and nutrient compositions. Riverine overflow often produces greater sediment and nutrient inputs and consequently higher biological productivity compared to areas flooded with locally derived waters (Klinge et al., 1990; Kalliola et al., 1991a; Mertes, 1997), particularly in lowland rivers fed by mountainous watersheds. Riverine overflow tends to be episodic, albeit lasting for months in the largest rivers (Hamilton et al., 2002), while saturation because of the emergence of local groundwater may be constant and persist through the dry season. Soil saturation and surface flooding determine the species composition and relative abundance of plants and animals as well as the characteristics of soil, sediments, and detrital organic matter derived from the vegetation (i.e., ecological structure). In addition, saturation and flooding control biological productivity and rates of key ecological processes such as decomposition and biogeochemical transformations of elements. Biological activity, in turn, affects floodplain geomorphology and hydrology by influencing sediment accretion, soil development, and the flow paths of surface water and the movement of subsurface water.

The spatial and temporal complexity of floodplain ecosystems renders them important components of regional biodiversity (Puhakka et al., 1992; Lewis et al., 2000). Floodplains, with permanent water bodies or long-lasting inundation, provide critical habitat for aquatic biota and are essential to maintain native riverine fisheries (Junk, 1997). Plants and animals on floodplains exhibit numerous adaptations to cope with and benefit from episodic or seasonal soil saturation or inundation. Even relatively short episodes of saturation or inundation (days to weeks) can profoundly affect the species composition of floodplain vegetation (Losos, 1995) and may be important in the life cycles of many aquatic animals (Junk, 1997). Variation in hydroperiod (the duration and temporal pattern of saturation or inundation), which can result from seemingly minor spatial variation in elevation, position, and soil composition of fluvial landforms, often produces dramatic differences in vegetation across floodplains and thereby contributes to biodiversity across the landscape (Salo et al., 1986; Hupp, 1988; Lamotte, 1990; Kalliola et al., 1991b). Over long time scales, the migration of river channels produces landform gradients of varying age, soil development, and vegetation succession, and thereby enhancing the biodiversity of environments of fluvial origin that are no longer subject to saturation or inundation (Puhakka et al., 1992).

Floodplain ecosystems tend to be strongly impacted by the impoundment of river channels and other modifications that alter and generally reduce the natural hydrological variability of parent rivers. The most extensive and biologically diverse floodplain ecosystems in the world are found along lowland rivers of the humid tropics, including the Amazon, Orinoco, and Paraguay rivers of South America, which largely retain natural flow regimes (Junk, 1997; Hamilton et al., 2002). These floodplains lie along rivers with very low longitudinal slopes. Major river alterations for purposes such as navigation and hydroelectric generation have recently been proposed for each of these river systems, and such projects could affect extensive areas of floodplains through alteration of the natural flood regime (Hamilton, 1999).

The lowland tropical regions of South America include a substantial fraction of the biodiversity in the world, and hence, are a focus of national and international conservation efforts. The vast area of these remote regions and the paucity of scientific information on the biodiversity present challenges for delineating and justifying priority areas for reserves or other protection or management measures. The southwestern portion of the Amazon basin, in particular the "sub-Andean" zone where the Andes mountain range borders the alluvial plains, has been identified as one of the "Global 200" biodiversity hotspots (Macquarrie, 2001; Olson and Dinerstein, 2002). This remote and sparsely inhabited region is a scientific frontier where the ecology has been little explored except in the vicinity of a few field outposts.

The Amazon Conservation Association (ACA) and World Wildlife Fund (WWF) have been engaged in conservation planning in the southwestern Amazon watershed, with initial emphasis on the sub-Andean watershed of the Madre de Díos River in Perú (Barthem et al., 2003). This sparsely inhabited watershed already contains several large protected areas (including the Manu and Bahuaja–Sonene national parks), but the extent to which the biodiversity of regional floodplain environments is represented in these areas has not been evaluated. Floodplains are also of particular interest in this region because they provide sustenance to local inhabitants (Kvist and Nebel, 2001). Disturbance from activities such as timber harvesting and gold mining, however, can negatively impact floodplain environments (Goulding et al., 2003).

Systematic conservation planning is a framework for evaluating conservation priorities and targets across large regions for which biodiversity information, collected on the ground, is spatially uneven or even sporadic in coverage (Margules and Pressey, 2000; Balmford, 2003). Recent advances in remote sensing and spatial data analysis provide an unprecedented opportunity for systematic analysis of large floodplain regions based on ecosystem features observable from space (Mertes, 2002; Alsdorf and Lettenmaier, 2003). While it remains difficult to directly measure biodiversity from space, the fluvial landforms of floodplains are readily observable by remote sensing and provide a surrogate for biodiversity in these environments.

This study demonstrates a remote sensing framework for mapping floodplain environments in support of systematic conservation planning in the watershed of the Madre de Dios River in Perú. We employed optical (Landsat) and microwave (JERS-1 synthetic aperture radar) remote sensing as well as a digital elevation model derived from the Shuttle Radar Topography Mission (SRTM) to delineate floodplain environments and discern major geomorphological and ecological units within the floodplains. These diverse forms of spatial data were analyzed simultaneously with an object-oriented image analysis approach. The resultant maps were field-checked in a representative area along the Madre de Dios River, and diverse waters on the floodplain were sampled for analysis of major solute composition to indicate water sources (i.e., river vs. local rainfall and runoff) based on concentrations of conservative solutes. This initial examination of floodplains of the Madre de Dios system reveals the geomorphological and hydrological diversity of these environments. Once extended to the overall watershed, this approach would suggest which kinds of floodplain environments may not be well represented in existing protected areas, thereby serving as a guide to direct

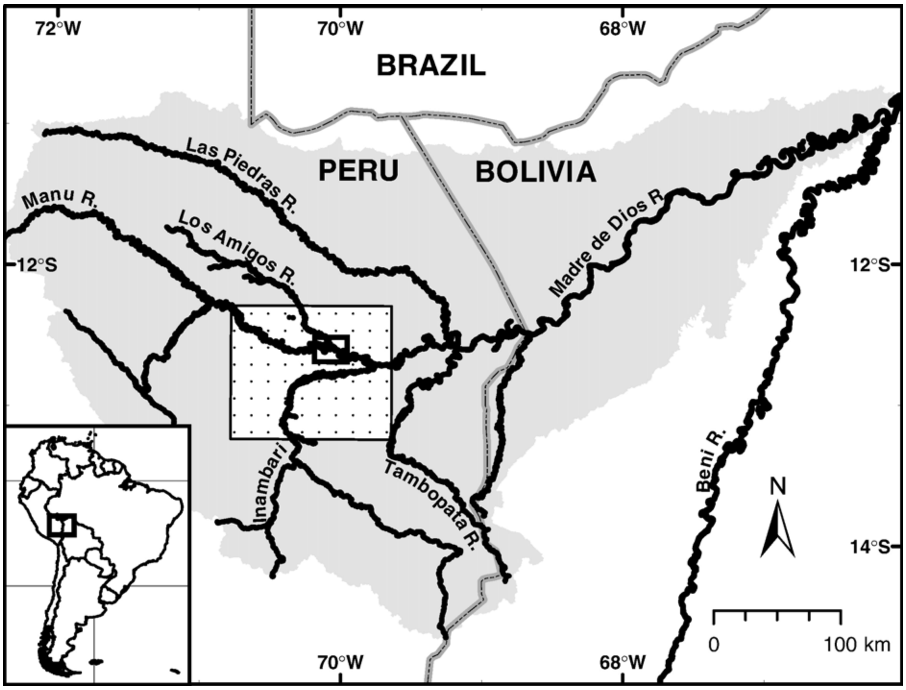

Fig. 1. Location of the study region in Perú. The shaded area depicts the watershed of the Madre de Dios River, the stippled box is the image analysis area in Fig. 2, and the smaller box inside of it is the area enlarged in Fig. 3.

future conservation priorities (see for example Thieme et al. (in press)).

2. Study site

The study site was centered within the Peruvian part of the watershed of the Madre de Dios River (Fig. 1). Image analysis was performed on an area covered by a single Landsat ETM+ scene (Fig. 2) that included the lower reaches of the Inambari, Los Amigos, and Colorado rivers in addition to the Madre de Dios River. Field work was performed primarily in the vicinity of the field station known as the *Centro de Investigación y Capacitación Río de los Amigos* (CICRA), operated by the Amazon Conservation Association as part of the Los Amigos Conservation Concession (http://www.amazonconservation.org/). This station is located on the Madre de Dios River ~6 km upriver of its confluence with the Los Amigos River.

The Madre de Dios River drains a portion of the Sub-Andean Fold and Thrust Belt along the Eastern Cordillera (Dumont et al., 1991). The lowland portion of the Madre de Dios watershed is composed of Andean alluvium that has aggraded because of sub-Andean foreland subsidence throughout the Neogene and Quaternary (Räsänen et al., 1987, 1992). River avulsions have been common and most of the lowland landscape shows remnant fluvial features such as paleochannels and meander scrolls. Stream valleys have dissected the older areas of alluvium, as for example to the north of the mainstem Madre de Dios River. Soils vary in texture from clay to sand and often show abrupt changes associated with remnant fluvial features, with corresponding changes in vegetation (Räsänen et al., 1987; Osher and Buol, 1998). Poorly drained soils occur on the floodplains fringing the rivers and also on local watershed divides of some relatively level parts of the uplands, and possibly in some ancient river courses (Kalliola et al., 1991a; Osher and Buol, 1998).

Floodplains are most extensive below 500 m above sea level. Floodplain depositional sequences, readily visible along river banks, reveal layers created by near-channel deposition of coarse sands overlain by flood basin (backswamp) accumulations of fine-grained material (Räsänen et al., 1992). Asymmetric terraces dating to the Pleistocene (30 to 180 ka: Räsänen et al., 1990) are visible along the north side of the Madre de Dios valley above the Los Amigos River, where the Madre de Dios River evidently has migrated to the southwest (Kalliola et al., 1992). These terraces are above the reach of present-day river flooding but are often quite wet from the accumulation of rainfall and local runoff.

The mainstem Madre de Dios River carries a high load of suspended sediments and displays meander scroll morphology with rapid rates of lateral channel migration (e.g., approximately 5 m/year; Salo and Räsänen, 1989; Puhakka et al., 1992). Tributaries with braided channels (Alto Madre de Dios, Colorado, and Inambari rivers) bring the highest sediment loads from the Andes and result in rapid aggradation on the plains. Much of the riverine suspended loads originate below 500 m elevation and may be derived by downcutting into previously deposited alluvium (Puhakka et al., 1992; Goulding et al., 2003). Poorly dissected aggradational features in the vicinity of these tributaries include alluvial fans and extensive areas of sheetflood deposition (Räsänen et al., 1992).

Broad-scale geomorphological features are visible on the Landsat image in Fig. 2. With this combination of bands (R/G/B color set to bands 5/4/3), darker blue indicates water or relatively wet land, green indicates vegetation, and herbaceous vegetation and early successional forests appear brighter green than mature forests. Exposed soil appears pink. River channels vary from the strongly meandering form of the mainstem Madre de Dios River to the braided Inambari River. Almost all of the non-river open waters are oxbow (cutoff) lakes associated with the meandering channels. Backswamps on fluvial terraces flanking the fringing floodplain are particularly visible along the left bank of the Madre de Dios River.

Two major areas of land use conversion are also apparent on the Landsat image (Fig. 2). One is the deforestation along the road from Puerto Maldonado to the Inambari River, which is visible to the south of the Inambari River. Bare land created by placer mining of gold deposits is particularly visible at the foot of the Andes mountains, west of the Inambari River (Goulding et al., 2003).

The lowland Madre de Dios watershed has a humid tropical climate (Osher and Buol, 1998) with rainfall varying from approximately 1200 to 3300 mm, generally increasing from east to west. Rainfall is seasonal and lowest from Jun–Sep at Puerto Maldonado, where the Tambopata and Madre de Dios rivers meet. Vegetation is predominantly evergreen or semi-evergreen forest (Osher and Buol, 1998), and bamboo thickets are common on poorly drained parts of upland alluvium. The general characteristics and classification of floodplain vegetation were reviewed by Kalliola et al. (1991a) and Kvist and Nebel (2001), although they emphasize the more extensive floodplains of the Marañon and Ucayali rivers in northern Perú. Floating and emergent, non-woody vascular plants (aquatic

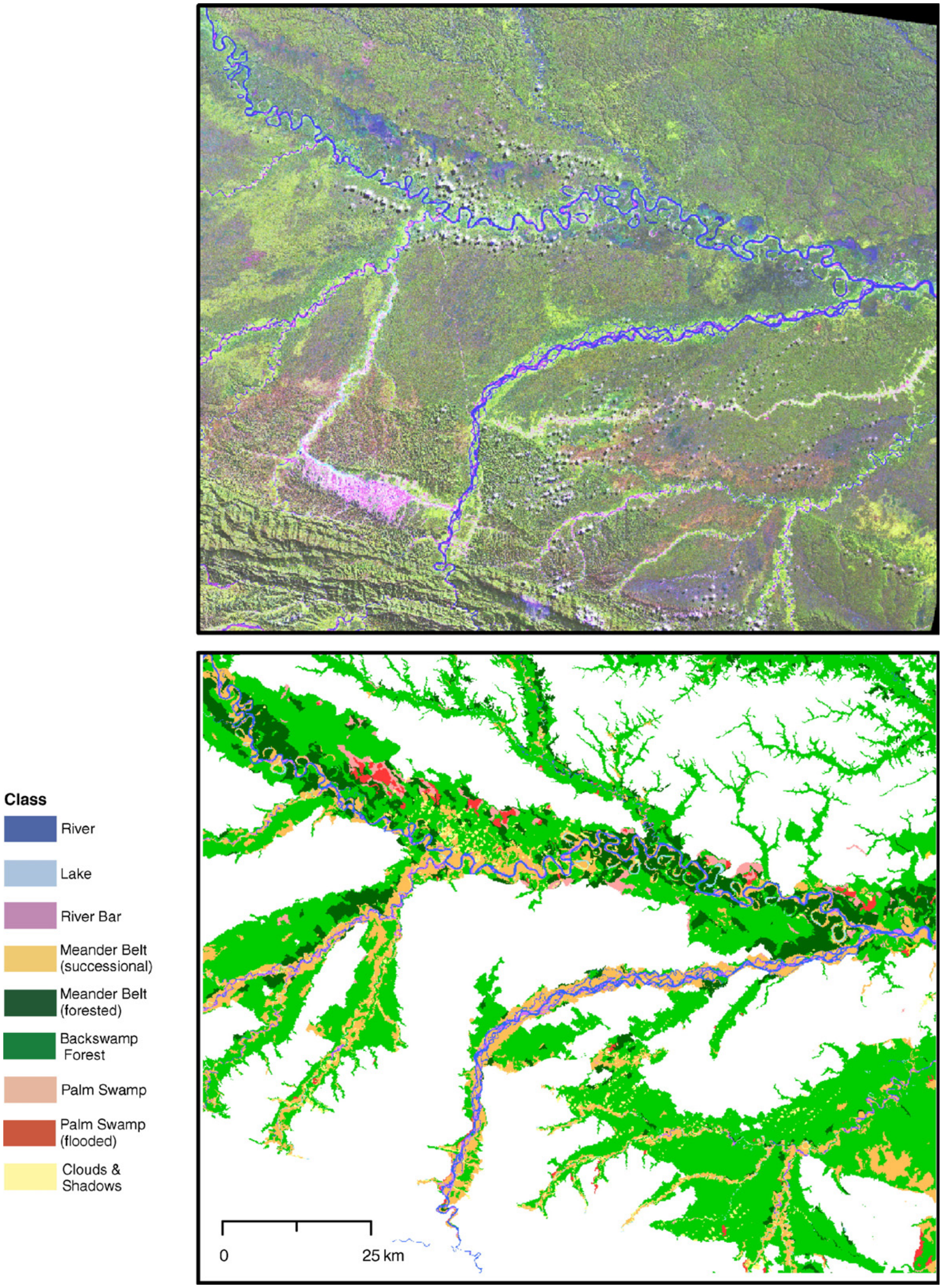

Fig. 2. Image analysis study area, showing the Landsat ETM+ satellite image of the study region (top), acquired on 23 May 2000 and here depicted as bands 5/4/3 (red/green/blue), and the floodplain classification based on SRTM, Landsat ETM+, and JERS-1 data (bottom).

macrophytes) are much less abundant on the Madre de Dios floodplain compared with floodplains that have long-lasting inundation, such as the central Amazon (Junk, 1997; Goulding et al., 2003).

The rich biodiversity of this relatively undisturbed region provides the motivation for present conservation initiatives (Terborgh, 1983; Gentry and Terborgh, 1990; Patterson et al., 1998; Tuomisto, 1998; Macquarrie, 2001; Goulding et al., 2003). Much of the field ecology research has been carried out at the Cocha Cashu research station on the Manu River, upriver of the present study area (Terborgh, 1990; Pitman et al., 1999), with more recent work at a station on the Tambopata River (Macquarrie, 2001) and at the CICRA station (Barthem et al., 2003). Primates, birds, butterflies, and higher plants appear to be particularly diverse. The high diversity of forest species at Cocha Cashu and elsewhere has been ascribed to patchiness in soil texture, moisture, and nutrient content, and to variable ages of vegetation succession, all of which may be influenced by past and present fluvial deposition and disturbance (Salo et al., 1986; Foster, 1990; Gentry and Terborgh, 1990). Nevertheless, floodplain swamp forests with permanent soil saturation tend to be less diverse, presumably because conditions are harsh for plant growth (Kalliola et al., 1991a), although they support some specialist species and are utilized by wide-ranging animals.

3. Methods

3.1. River stage data

The only known record of river levels (stage) for the Madre de Dios River has been collected at the CICRA field station. Several cross-referenced gauges were installed along the sloping river bank. An arbitrary zero datum was established; the absolute elevation of the gauge has not been surveyed. Manual readings of the gauges were recorded twice daily. Some periods have missing data because of problems with destruction of the gauges by floods.

3.2. Elevation data

We employed a digital elevation model based on data from the NASA Shuttle Radar Topography Mission (SRTM), which was flown onboard the Space Shuttle Endeavor during mission STS-99, in orbit from 11–22 Feb 2000 (USGS, 2003). This is a near-global dataset derived from interferometric processing of single-pass data collected by a C-band (5.6 cm) synthetic aperture radar (SAR). A raster digital elevation model dataset is available at a spacing of 3″ (~90 m) for South America. Performance evaluations show an absolute vertical error of ±5–6 m, and relative errors are estimated to be smaller (Curkendall et al., 2003; Smith and Sandwell, 2003). In forested landscapes, however, the elevation estimates are affected by scattering from woody biomass, and, thus, elevations lie somewhere between the height of the ground surface and the height of the forest canopy (Kellndorfer et al., 2004), which often reaches 20–30 m in the study area. Deforested patches within such tall forest can thus appear as depressions.

The SRTM elevation data served to delineate present or past floodplains, which have relatively level terrain compared to the more dissected ancient alluvium of adjacent uplands. The raw elevation data, which were obtained from the public ftp site of the US Geological Survey (ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/) on November 2003, show some data gaps within the study area, particularly for large open water surfaces such as wide river channels. These data gaps were filled prior to applying the SRTM data using a custom interpolation algorithm that effectively inserts relatively flat and low surfaces.

3.3. Landsat imagery

Landsat ETM+ satellite imagery was obtained from the archives of the Tropical Rain Forest Information Center (TRFIC) (http://www.bsrsi.msu.edu/trfic/home.html). For the image analysis we selected the most cloud-free image available from approximately the same period as the SRTM data collection, and also visually examined similar images from other dates to reveal seasonal and interannual variability. Concurrence in timing of the remote sensing information was desirable because of the high rates of changes in the river channels in this region. The image we selected was for Path 03, Row 069, dated 23 May 2000 (normally on the falling limb of the river hydrograph), and was orthorectified and projected to UTM Zone 19 S. All bands except the thermal one were included in the image analysis. The coverage of this image defined the area of study. Elevations above 400 m above sea level were excluded because they contain little floodplain and present complications for image analysis because of topographic variation, steep slopes, and exposed soil and rock.

3.4. Radar imagery

We used the radar imagery from the Japanese Earth Resources Satellite-1 (JERS-1) 1996 mosaic of the Amazon basin, which is based on an L-band (~23 cm), horizontally transmitted and received SAR (Chapman et al., 2002). After extracting the data for the study area, the imagery was registered to an orthorectified Landsat–Thematic Mapper image from the year 2000. The spatial resolution of the reprojected imagery was 100 m.

The principal utility of the radar imagery was to identify flooded forests because these are clearly revealed as areas of exceptionally high backscatter compared to adjacent, non-flooded vegetation, or to open waters which exhibit low backscatter because of specular reflection. Mosaics were available for two dates (late 1995 and mid-1996) but showed little difference in the study area. We were able to visit four distinct areas of high backscatter along the left bank of the Madre de Dios River, where standing water occurred in swamps dominated by the *aguaje* palm (*Mauritia flexuosa*). JERS-1 data alone have been used to delineate Amazon floodplains, comparing the two mosaics for evidence of seasonal inundation (Hess et al., 2003). In this case the combination of SRTM data and Landsat ETM+ imagery proved more useful because most of the floodplains evidently were not inundated on the dates when remote sensing data were acquired, including the two JERS-1 mosaics. Data for river stages are not available for that period.

3.5. Image analysis

Image analysis was performed using the eCognition® Professional Version 4 software (Definiens Imaging, Munich). The object-oriented basis of this image analysis software differs fundamentally from traditional pixel-based image analysis for feature extraction and classification. Spatial data of varying spatial and spectral resolution and bit depths can be integrated and analyzed simultaneously in an image segmentation procedure that defines homogeneous image objects. These objects can be combined in a hierarchical fashion to achieve a desired level of resolution in the classification. Knowledge-based classification can be based on sample objects, can employ fuzzy logic, and can account for spectral information, as in traditional image classification, and also shape, texture, area, context, and information from other hierarchical object layers.

A multi-scale hierarchical classification scheme was designed using eCognition software. Initial image segmentation was based on joint inputs of high-resolution Landsat panchromatic data (15 m resolution), JERS-1 data (100 m), SRTM elevation data (90 m), and a Landsat band 3/5 ratio-based water layer (30 m). Geolocation compared well between the Landsat, JERS, and SRTM data, as indicated by isolated oxbow (cutoff) lakes, which are relatively static features (Räsänen et al., 1991) distributed along the Madre de Dios River. Image objects were generated by segmentation that accounted for the 6 Landsat ETM+ bands and the SRTM elevation data, with the latter weighted by 1/2 because of its greater variance. JERS data were not used during the segmentation step but included in a subsequent image classification step. Two segmentation levels were produced, one at a finer scale preserving small scale features like oxbow lakes and smaller vegetation units, and another at a coarser scale separating macro-scale floodplain features from upland. At the coarser scale the separation of floodplains from uplands was mostly driven by the geomorphological characteristics derived from the SRTM data, while at the finer scale the classification of environments within the floodplain was driven by Landsat bands and JERS-1 data.

Open waters of rivers and lakes were clearly visible on Landsat images and were also apparent on JERS images unless they were too small to resolve. We observed good correspondence between the open water boundaries ascertained in this way and those depicted on a digital hydrography data layer in Digital Perú Version 1.0, derived from topographic maps made by the U.S. Defense Mapping Agency and the *Instituto Panamericano de Geografía e Historia*, except where channel meandering had recently taken place. River channels were distinguished from lakes based on the degree of skeleton branching and length:width ratios. The river channels were interrupted in some places, perhaps because they were too narrow or partially filled with woody debris; river-channel objects were manually linked as needed.

The SRTM elevation data served to delineate the floodplains, defined for our purposes as land adjacent to the rivers that is relatively level, in contrast to the older alluvium of the uplands that has subsequently become dissected by stream courses. A useful feature to identify the floodplain was found to be a ratio index computed as the mean height of a specific image object divided by the mean height of all objects surrounding it at a distance of 500 pixels, i.e., 15 km (=30 m × 500). Using a threshold of 0.98, this index excluded areas of obviously dissected alluvium and included all areas that we knew to be floodplain.

Classes of floodplain environments, in addition to open waters of rivers and lakes, were selected to represent the broad ecosystem diversity of the floodplain (Table 1), based on our field experience as well as published descriptions of the geomorphology and vegetation of floodplains of the Peruvian Amazon (Gentry and Terborgh, 1990; Lamotte, 1990; Kalliola et al., 1991a,b; Salo et al., 1986; Puhakka et al., 1992; Räsänen et al., 1992; Pitman et al., 1999; Kvist and

Table 1
Floodplain environments distinguished within the floodplain river systems of the Madre de Dios watershed

Class	Description
Rivers	Open waters of river channels
Lakes	Open waters; mostly oxbow lakes in the study area
River bars	Adjacent to rivers; seasonally exposed gravel, sand, or mud
Meander belt forest — early successional	Herbaceous vegetation or, most often, either stands of *Tessaria* or *Cecropia* with *Gynerium* understory
Meander belt forest	Diverse, late successional broadleaf forest; largely closed canopy
Palm swamps	Often dominated by the palm *Mauritia flexuosa* and figs; not flooded in the dry season
Palm swamps — flooded in dry season	Similar vegetation but with standing water as indicated by radar
Floodplain (unclassified)	All other floodplain; likely composed of diverse broadleaf forest

All other land was classified as “Uplands”.

Nebel, 2001). The meander belts of the larger rivers were delineated based on Landsat ETM+ spectral characteristics, which also allowed further subdivision of the meander belts into early successional vegetation and late successional forest. Backswamp forest, defined as forest on low-lying areas outside of the meander belt, are often dominated by *aguaje* palms (forming palm swamp forests known as *aguajales*), although other tree species and especially figs (*Ficus* spp.) can be abundant as well. Backswamp forests tend to contain saturated soils during the dry season (which is when the Landsat image was obtained), and these areas were delineated based on bands 4 and 5 of the Landsat image. Palm swamps have a distinct optical signature, and were classified based either on Landsat or JERS to include non-flooded or flooded subclasses. Floodplain areas with high backscatter on JERS imagery were assumed to be palms with standing water among the trunks (flooded palm swamps) based on field verification (described later). Unvegetated bars (“river bars”) along the rivers can be composed of gravel, sand, or fine sediments, and all three types were included in the image analysis after verifying examples in the field. Such banks are typically exposed only during low river levels. Along the Madre de Dios River, we observed that at low water many of these had recently been disturbed by placer mining for gold.

Clouds and their shadows were present over some of the floodplain, although in this particular Landsat image cloud coverage was minor. We devised methods to identify and classify cloud shadows, and we subsequently identified the corresponding clouds based on the optical features and proximity to the shadows. A few obvious cloud shadows that happened to be contiguous with open water bodies were misclassified as open water and required manual reclassification in eCognition.

3.6. Field verification

The accuracy of the initial classification was assessed by consultation with scientists who have worked in the region, and was further field-checked along the Madre de Dios River, particularly in the area around the confluence of the Madre de Dios and Los Amigos rivers (Fig. 3). Field work was conducted during the dry season (mainly on July 2004), several months since any significant overbank flooding by the river. We accessed floodplain areas further from the rivers on foot, including the vicinity of the CICRA field station as well as a transect across the floodplain to the south of the Madre de Dios River near the confluence with the Los Amigos River. In addition, over 100 km of the mainstem river was traveled by boat between the port town of Laberinto (below the Inambari River) up to several km upriver of the field station, as was the lower 10 km of the Los Amigos River. Palm swamps on terraces along the left bank of the Madre de Dios River above and below the Los Amigos River were visited in July and October 2004.

While traveling on foot or by boat, the preliminary classified images were examined and over 100 observations of geomorphology and vegetation were made. Observations included dominant trees (if a particular species clearly dominated), GPS coordinates, presence of standing water or saturated soils, and, if apparent, high-water marks on trees indicating the maximum level of prior inundation. Water was collected from the major rivers, upland streams entering the floodplain, seeps and springs along the escarpment, flowing waters on the floodplain, oxbow lakes, palm swamps, and shallow pools on the floodplain. None of these sources of water was deep enough to show persistent thermal stratification so all samples were collected near the surface. The water samples were filtered upon collection (Millipore HA membrane, pore size 0.45 μm) and stored in polyethylene bottles until analysis. Analyses included specific conductance and concentrations of major anions and cations using membrane-suppressor ion chromatography and flame atomic absorption, respectively.

3.7. Refining the image analysis based on field observations

The field observations were used to refine the image analysis. Much better accuracy was attained in most

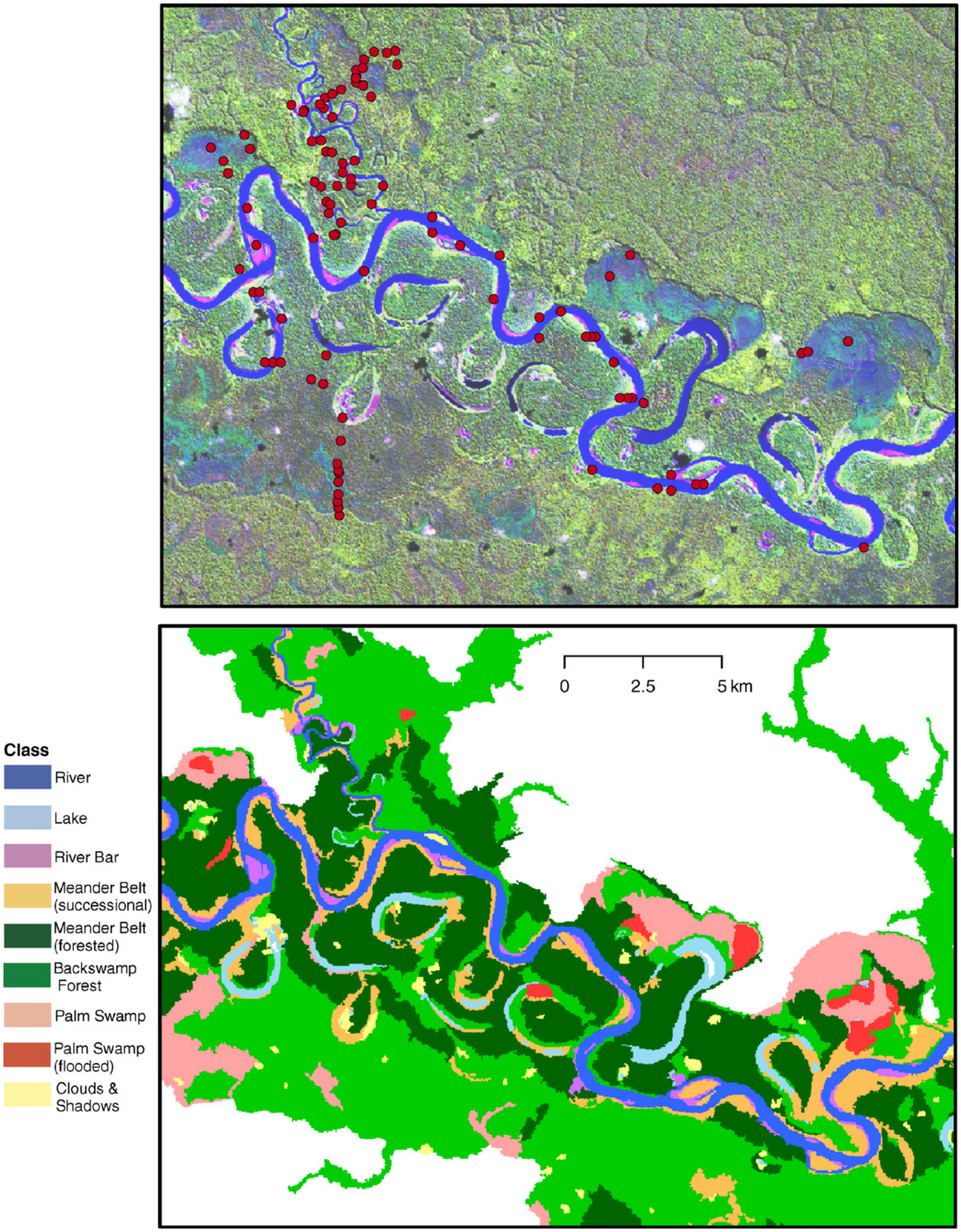

Fig. 3. Closeup from Fig. 2 of the confluence of the Madre de Dios and Los Amigos rivers, showing the Landsat ETM+ satellite image with GPS locations of ground observations (top); and the floodplain classification (bottom).

cases of disagreement simply by including a wider variety of sample areas for image classification. For example, the initial attempt at image analysis in eCognition misclassified some oxbow lakes as vegetated areas; field visits to these lakes revealed open waters high in inorganic turbidity with light surface scums of microscopic algae, while several properly classified lakes we visited were much less turbid. Inclusion of these turbid lakes as field-verified lake sample areas in addition to the original sample areas correctly classified all known open waters. The same was true for river bars; we found that sample areas had to span the range of sediment types from mud to coarse gravel and cobble.

4. Results and analyses

4.1. River stage

The river stage record shows a distinct seasonal pattern of flow. Superimposed on that pattern are remarkably rapid short-term fluctuations of up to 2–3 m/day, which can occur at any time of year (Fig. 4). The annual range in river level exceeded 8 m in the first 2 years of record but the flood peaks were lower in the flood season preceding our field work (this was verified by local residents; 2004 data are incomplete). Barthem et al. (2003), who presented these data through early 2003, noted that the high gradient of the river system within the Andes combined with high rates of rainfall in some parts of the Andean watershed likely explained the rapid response of the river to individual storms.

Bankfull stage in this reach is not known, but judging from levee heights (5–6 m) and maximum high-water marks (1–2 m) on the floodplains during our July 2004 visit, it is likely to be around 4 m. The 3-year record in Fig. 4 only includes four episodes of stage >4 m, two lasting 6 days, one lasting 4 days, and one incompletely documented. The short duration of flooding episodes in this river system also was noted in studies done upriver at Cocha Cashu (e.g., Losos, 1995). The lack of visible attenuation of the flow peaks above 4 m suggests that the fringing floodplains of the Madre de Dios River have little influence on flood flows; stage in many Amazonian rivers shows a distinct floodplain effect in which the increase slows or even stops as the river water spreads onto the floodplain (Sippel et al., 1998).

4.2. Image analysis and floodplain classification

The Landsat image and corresponding floodplain classification are presented for the entire study area (Fig. 2) and for the area around the field station where ground observations were concentrated (Fig. 3). Beyond the areas visited, the classification of land as floodplain, which is based on the relative lack of topographical variation derived from SRTM elevation data (see Methods), must be considered tentative until field verification can be performed. The uniform elevation and lack of dissected stream valleys in the areas classified as floodplain, in combination with the high rate and seasonal nature of rainfall in this region, suggests that floodplains may be poorly drained during the wet season, even in the absence of river flooding.

Manual corrections in the classified image were needed in a few cases. An extensive interfluvial area between the Madre de Dios and Inambari rivers appeared to be floodplain but some features (objects) well within this area were evidently misclassified as upland, probably because they were slightly higher or lower than neighboring floodplain areas; these were manually changed to floodplain (unclassified). In addition, the deforested corridor of land along the only lowland road in the image, which runs east–west between Puerto Maldonado and the Inambari River,

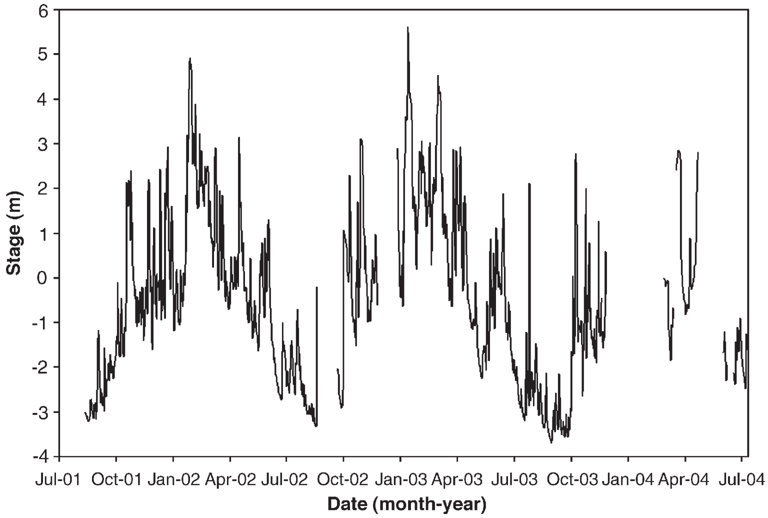

Fig. 4. Stage record for the Madre de Dios River above the confluence with the Los Amigos River (courtesy of CICRA).

was misclassified as floodplain and had to be reclassified manually as upland. Also, as noted above, a few cloud shadows were misclassified as water.

Extensive areas of floodplain remained unclassified, including remote, broad plains along the sub-Andean foreland that are not associated with the large rivers. The published information we had available as well as our field verification described below pertain only to the floodplains along the large rivers. The unclassified floodplain areas may be more heterogeneous than our classification suggests, but further subclassification was impossible without information from the ground.

4.3. Field verification

Most of the field observations were made in the vicinity of the confluence of the Madre de Dios and Los Amigos rivers (Fig. 3). The image classification agreed well with nearly all of the field observations and indicated that the various environments distinguished within the floodplains were identified correctly, at least for the areas we visited. Reconnaissance by foot in the vicinity of the confluence of the Los Amigos and Madre de Dios rivers (occasional GPS points marked in Fig. 3) revealed the upland/floodplain boundaries to be in good agreement with the classified image, except for an area of floodplain terrace to the northwest of the mouth of the Los Amigos River. The four most northeastern points in Fig. 3 lie on an area classified as floodplain based on its elevation, but these points showed no field evidence of recent soil saturation or inundation. This particular terrace was fairly level but had some dissection by stream courses, and was sufficiently elevated in relation to the adjacent floodplain to be out of reach of river flooding. Some parts were impenetrable because of bamboo thickets. Soils were sandy, and thus in spite of the level terrain, it appeared unlikely that extensive pools of locally derived water would accumulate at that part on the terrace. It is possible that other relatively elevated and level but well-drained terraces occur that were similarly misclassified as floodplain in the image analysis.

Floodplain soils were generally unsaturated close to the rivers but overlain by shallow (<10 cm deep) pooled water further from the river, especially close to the upland escarpments. Evidence of prior flooding included high-water marks on tree trunks (created by deposition of inorganic matter or the lack of lichens and mosses below the water mark) and, in some lower areas, adventitious roots on shrubs and lianas that grow during inundation. High-water marks were often 1–2 m above ground close to the rivers and only ~10 cm above ground in the backswamp forests far from the rivers. An inverse relation occurred between soil saturation and maximum inundation: floodplain close to the rivers evidently is deeply inundated for short episodes but readily drains to the river and hence the soils are unsaturated for much of the year, while distal, poorly drained backswamps have constant soil saturation with relatively little seasonal change in the depth of flooding.

The major solute composition of waters on the floodplain showed that most surface water was ionically dilute compared to the parent river (Table 2). Two of the most conservative major solutes in waters of this ionic strength are Na^+ and Mg^{2+}, which are not subject to mineral precipitation and are little affected by biological uptake and release (Hamilton et al., 1997). The concentrations and ratios of these ions serve to distinguish water sources in this area (Fig. 5). Potential water sources besides the river include groundwater springs and streams emanating from the adjacent uplands, as well as direct rainfall on the floodplain. Floodplain waters of the Madre de Dios River spanned a wide range of Na^+ and Mg^{2+} concentrations but showed markedly different ratios of Na^+:Mg^{2+} compared to those found in the river during the dry season (Fig. 5), with the exception of one floodplain channel that apparently received river water. Locally derived water, as represented by springs and upland streams, is a more plausible source of water on the Madre de Dios floodplain in the dry season; floodplain waters with higher concentrations of these ions could reflect evaporative concentration.

Table 2
Summary of major solute measurements in potential source water, floodplain pools, and palm swamps of the Madre de Dios floodplain

	Madre de Dios River	Upland streams and springs	Madre de Dios floodplain pools	*Aguajales* (palm swamps)
No. samples	2	11	9	14
Conductance (μS/cm; 25 °C)	123 (122–124)	15 (7–34)	34 (15–69)	24 (11–42)
Ca^{2+} (mg/L)	18.1 (17.7–18.4)	1.4 (0.3–5.6)	2.1 (0.8–5.6)	1.39 (0.28–3.19)
Mg^{2+} (mg/L)	2.6 (2.5–2.7)	0.33 (0.19–0.78)	0.92 (0.36–1.69)	0.59 (0.34–1.00)
Na^+ (mg/L)	3.3 (3.3–3.3)	0.42 (0.17–1.12)	3.6 (1.8–6.1)	1.54 (0.12–3.55)
K^+ (mg/L)	1.0 (1.0–1.0)	1.4 (0.3–1.9)	0.63 (0.16–1.30)	1.18 (0.09–4.26)
Cl^- (mg/L)	0.20 (0.20–0.21)	0.15 (0.08–0.37)	0.12 (0.07–0.25)	0.46 (0.06–1.60)
SO_4^{2-} (mg/L)	7.0 (6.8–7.3)	0.25 (0.10–0.47)	0.30 (0.02–1.24)	0.09 (0.02–0.63)

Waters in the *aguajales* (palm swamps) were generally more dilute than other floodplain waters, with some lying closer to the concentrations found in springs. The chemistry of rainfall has not been monitored here but based on studies elsewhere in the central Amazon region (Lesack and Melack, 1991), rain is expected to be at least as dilute in ionic concentrations as the springs and streams that we sampled.

The waters of the floodplain of the Los Amigos River showed less clear separation using Na^+ and Mg^{2+} (Fig. 6). Upland streams and springs are the same data as in Fig. 5, but we also sampled three streams that flow into the floodplain on the west side of the river, in the vicinity of several *colpas* (clay licks) that attract wildlife. Two of these streams carried water richer in ions compared with streams to the east of the Los Amigos River. The two oxbow lakes with relatively high ion concentrations were east of the river. Surface water in a small *aguajal* located on the floodplain between the Los Amigos and Madre de Dios rivers had low ion concentrations, and field observations showed local groundwater emerging from the adjacent upland and flowing through the swamp before draining to an outflow stream.

Most pooled waters in the backswamp forests, including two areas dominated by *Mauritia* palms, were observed to be slowly flowing. Many pools and

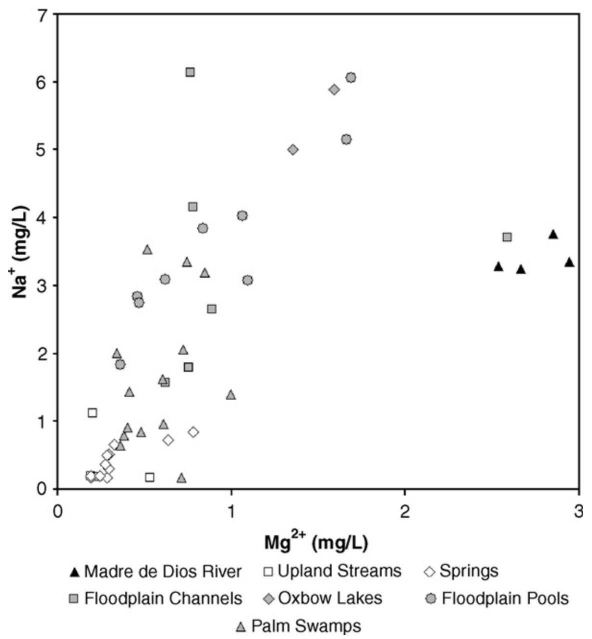

Fig. 5. Concentrations of the conservative ion tracers sodium (Na^+) and magnesium (Mg^{2+}) in floodplain waters and in potential sources of those waters (parent river, upland streams, ground water springs) for the Madre de Dios floodplain (area shown in Fig. 3).

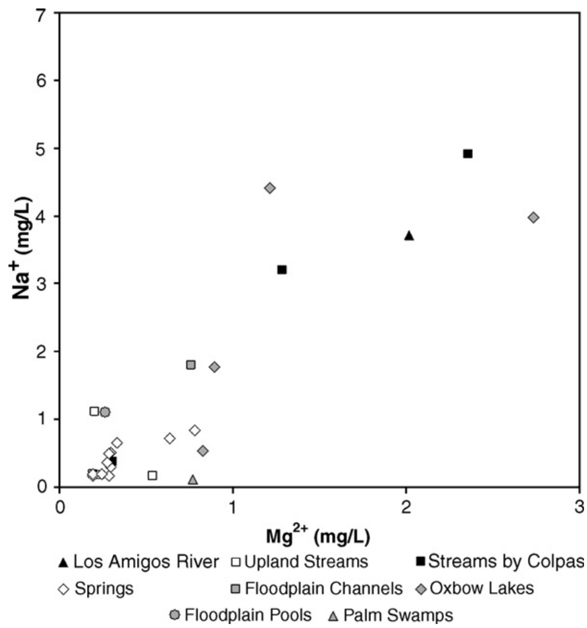

Fig. 6. Concentrations of the conservative ion tracers sodium (Na^+) and magnesium (Mg^{2+}) in floodplain waters and in potential sources of those waters (parent river, upland streams, ground water springs) for the Los Amigos floodplain (area shown in Fig. 3).

channels contained copious precipitation of oxidized iron, especially closer to escarpments where springs were found. Some areas of pooled water had little vegetation even though they were well illuminated. Trees growing in these wet areas tended to have roots with thick aerenchyma (gas-filled) tissue or, in the case of *Mauritia*, numerous emergent pneumatophores; both are structural adaptations to obtain oxygen from the overlying air for root respiration. Soils were often light-colored clays. Considering these observations, the dilute chemical composition of the waters, and that the field station had recorded <200 mm of rainfall in each of the 3 months prior to our visit, groundwater emergence is likely to be the water source for these swamps. This explains why the soils remain saturated throughout the year.

5. Discussion and conclusions

5.1. Floodplain boundaries and classification

The remote sensing and image analysis revealed the existence of extensive and complex floodplains fringing the main rivers as well as on depositional plains bordering the Andes. The extent to which floodplain landforms, many of which are relics of past fluvial deposition, are presently subject to seasonal or permanent inundation is unknown over most of the study region. Remote sensing information available so far does not provide the temporal resolution to capture the episodic flooding by the river, and dense forest canopies obscure the presence of water. We were only able to visit the floodplains in a minority of the study region, and only during the dry season when the floodplain was accessible on foot. Our observations of prior inundation depths and of standing water of local origin at distance from the rivers are consistent with published descriptions of this and other sub-Andean river floodplains (Puhakka et al., 1992; Losos, 1995; Terborgh et al., 1996), although those studies did not employ water sampling to confirm field observations. The existence of areas with seasonal soil saturation that are not contiguous with presently active river floodplains has been reported by Osher and Buol (1998) and Kalliola et al. (1991a) near Puerto Maldonado, to the east of our image analysis area. Thus, much of the floodplain mapping in Fig. 2 reflects areas hypothesized to be wetland ecosystems based on the limited available evidence. The water sources, however, are not necessarily the parent rivers.

Confidence in the floodplain mapping is greater where we were able to examine environments on the ground and confer with other scientists with pertinent field experience. Field observations supported the accuracy of the classification along the banks of the Madre de Dios River and within the floodplains near the Los Amigos confluence (Fig. 3). The correspondence between present-day wetlands and the boundaries, indicated by the floodplain mapping, appeared reasonably good in that area, although one terrace area classified as floodplain did not appear to be subject to seasonal flooding. Classification of environments within the floodplains revealed spatial variation associated with the meander belt, where the river channel has recently migrated, leaving behind ridges and swales that are rapidly colonized by forest. Early successional forest, composed most commonly of mixed stands of *Cecropia membranacea* + *Gynerium sagittatum* or monospecific stands of *Tessaria integrifolia*, occupies the most recently created point bars and ridges close to the river and oxbow lakes, while a diverse broadleaf forest develops in older parts of the meander belt, consistent with published descriptions of vegetation succession (Salo et al., 1986; Lamotte, 1990; Kalliola et al., 1991b; Terborgh et al., 1996). Swales and infilled oxbow lakes fill in first with herbaceous vegetation and take longer for shrubs and then trees to appear (Lamotte, 1990). In floodplain areas that are more distant from the river, the meander belt topography and its associated forest patterns become less perceptible by remote sensing and even harder to observe on the ground. Backswamp forests with saturated soils during the dry season are found closer to the escarpments, sometimes on noticeably elevated terraces.

5.2. Linkages among geomorphology, hydrology, and ecology

Field observations as well as water analyses indicated that much of the distal floodplain area is probably not subject to overbank flow from the rivers during flood pulses. These floodplain areas are maintained as wetlands through the dry season by groundwater emergence, which provides a more continuous source of water originating from local rainfall on adjacent uplands and on the floodplain itself. High rates of groundwater emergence on the floodplain close to the uplands are expected because of hydraulic gradients driven by infiltration of rainfall in the adjacent, more elevated uplands. Goulding et al. (2003) reached similar conclusions regarding the hydrology of *aguajales*. These floodplains, thus, present a hydrological gradient between the river and the uplands in which ecosystems on the youngest floodplain formations experience deep but episodic inundation and the older, more distal floodplain formations have constant soil saturation by locally derived waters, with little fluctuation in water levels.

The water sampling was conducted during low flow, but the rivers are likely to become more dilute in major solute concentrations during flow peaks. Synoptic surveys of rivers in this area at high and low water, reported in Barthem et al. (2003), showed that low-water conductance was higher (Table 3). The combination of these measurements and ours for the Madre de Dios River shows an inverse relation between conductance and river stage, with the peak flood flow falling to 57 μS/cm (Table 3). Thus, flood waters from earlier flow

Table 3
Seasonal variation in specific conductance of the Madre de Dios River above the Los Amigos River

Date	Stage at CICRA	Conductance	Reference
17 Feb 2002	2.80 m	96	a
18 Feb 2002	3.83	57	a
6 Aug 2002	−2.53	143	a
17 Jul 2004	−1.25	124	b
21 Jul 2004	−1.25	122	b

References:
a. Forsberg, B.R. and M. Goulding, pers. comm.
b. This study.
Stage in July 2004 is an approximate estimate because the gauge had been damaged.

peaks were likely lower in Na^+ and Mg^{2+} concentrations, although the ratios of these ions are less likely to have changed greatly. Subsequent evaporative concentration during residence of flood waters on the floodplain would have increased conservative solute concentrations.

The erratic flow regime of the Madre de Dios River might seem to have little influence on floodplain ecosystems fringing the river because the river exceeds bankflow stage only for brief periods. Ecological studies have pointed out, however, the importance of even brief inundation as a structuring force that determines the composition of the vegetation, acting as a disturbance that selectively eliminates some plant species, including trees at the seedling stage (Losos, 1995). This disturbance may result from the action of flowing water, or indirectly from the soil saturation and attendant oxygen depletion that accompanies and follows inundation. In some poorly drained, lower-lying areas, river water persists for longer, favoring the development of more flood-tolerant vegetation such as floating grasses and *Heliconia* (Kalliola et al., 1991a), although in our study area such environments are not extensive. Seed dispersal by even brief episodes of flooding is also likely to be important.

Given the short duration of riverine inundation over most of the floodplain, the extent to which the aquatic biota may be able to adapt to and benefit from the inundation (e.g., fish feeding and reproductive cycles) might be lesser here compared to floodplains with more predictable and prolonged seasonal inundation. As a result, the floodplains of the Madre de Dios River may not support such high production of aquatic animals compared to floodplains with long-lasting flood pulses, such as those of the central Amazon or Orinoco rivers. Even the permanent lakes may show less production if they are subject to erratic flushing by river water, which also likely inhibits the development of the floating mats of herbaceous vegetation that are considered important in other tropical floodplains (Junk, 1997; Goulding et al., 2003).

The constant soil saturation in the groundwater-fed backswamp forests, farther from the rivers, must be a critical limiting factor for the biota. These forests are less diverse; trees must be able to grow in saturated soils that are anoxic all year. The iron precipitation in surface pools indicates that underlying soils are likely to be high in dissolved Fe^{2+}, a toxic substance for plant growth in wetlands (Ernst, 1990). High dissolved Fe^{2+} is expected in anoxic groundwaters because soils in this region show redoximorphic features indicative of Fe leaching under seasonal rainfall regimes (Osher and Buol, 1998). Relatively monospecific stands of the *Mauritia* palm are low in tree species diversity, but can support unique epiphytic plants, and many kinds of animals feed on the abundant fruits of the palms. Therefore, these ecosystems may be disproportionately important relative to the area. The dependence on locally derived groundwater flow and impeded drainage of this water to the river has implications for conservation.

River inundation may not directly affect the distal floodplain areas, but the river stage may be important as the ultimate base level that controls floodplain drainage. Much of the floodplain drainage to the rivers occurs via small channels that connect backswamp basins to the river, and these channels tend to be incised to elevations several meters below the levees. We sampled several of these floodplain channels (Fig. 5), which still supported flow towards the river during our visit during the dry season. An increase in the average river levels, which could be caused by impoundment of the river channel, might produce impacts from backflooding that propagate far beyond the area subject to riverine overflow. Such changes in backflooding could produce large-scale changes in vegetation, as has been observed in northern Perú due to natural geomorphological dynamics (Kalliola et al., 1991a). Conversely, activities, such as gold mining that entail excavation of floodplain alluvial deposits, could enhance the drainage of backswamp areas by removing impediments to drainage at critical points.

5.3. Applications to systematic conservation planning

The mapping of floodplains and classification of environments within the floodplains provides a first indication of the distribution of floodplain ecosystems in this remote region. Extension of this approach to the overall Madre de Dios watershed, and to other watersheds of the southwestern Amazon region, is feasible (Thieme et al., in press). Further field verification is needed to determine the accuracy of the floodplain boundaries. With the maps presented here, field work could be designed to determine the extent to which the floodplain landforms correspond with present wetland environments. Even if some of these floodplains prove not to be wetlands at present, the spatial patterns documented here likely correspond with ecological variability and thus with biodiversity because the floodplain landforms retain a legacy of spatial variability in soil properties long after flooding ceases (Salo et al., 1986; Osher and Buol, 1998; Kalliola et al., 1991b).

Advantages of the remote sensing and image analysis approach outlined here include the use of spaceborne remote sensing data with global coverage, the ability to integrate additional sources of spatial information, and the unbiased image-oriented classification procedure. Disadvantages include the reliance on Landsat optical imagery, which is impeded by cloud cover, and that the classification rules need to be tailored to the particular geomorphological and ecological setting.

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