Freshwater conservation planning in data-poor areas: An example from a remote Amazonian basin (Madre de Dios River, Peru and Bolivia)

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ABSTRACT

Using the 160,000-km² drainage basin of the Madre de Dios and Orthon rivers in the southwest Amazon as a test case, we piloted an approach for large-scale conservation planning for freshwater systems characterized by a near-complete lack of biological and physical data. We used newly available spatial and remote sensing datasets, including spaceborne optical and radar observations, and new techniques of spatial data analysis to generate subbasin (>100 km²), stream, and floodplain and wetland habitat classifications. We then generated a preliminary plan for a network of conservation areas to protect the most intact examples of representative habitat types while maximizing longitudinal and lateral connectivity. Proposed additions for freshwater conservation complement existing reserves and build on earlier conservation planning efforts for terrestrial ecosystems. In the resulting integrated plan, at least 20% of the area of each major freshwater habitat type is represented and two continuous corridors exist from the mouth of the Madre de Dios to its headwaters in the Andes. In total, we highlighted 84 currently unprotected subbasins to fulfill our representation and connectivity goals. About two-thirds of these subbasins were considered relatively undisturbed and are identified as Level I (critical management zones) or Level II (indigenous territories), whereas one-third are potentially degraded and thus were designated as Level III (threat mitigation zones). This exercise provides an example of how newly available remote-sensing datasets and analytical tools may be used to advance freshwater conservation planning, particularly in data-poor regions.

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1. Introduction

The Amazon River system presents both substantial opportunities and daunting challenges for conserving a globally outstanding share of the world’s freshwater biodiversity. The Amazon hosts the greatest richness of freshwater fish species of any basin in the world, though precise numbers may be many decades off (Revenga et al., 1998; Goulding, personal communication). Even less information is available for most other groups of aquatic taxa, but the sheer amount and great diversity of aquatic habitat suggest that other biotic groups may be represented by high numbers as well. Among the Amazon’s most noteworthy but vulnerable taxa are its long-distance migratory fishes; some species of large catfish may travel from the Amazon’s mouth to its headwaters over the course of their lifetimes (Goulding et al., 1996).

Many opportunities for protecting freshwater species and their habitats exist, particularly in the western portion of the basin, where entire river systems are still relatively intact and where there are few large dams and other major structural changes to river channels (Nilsson et al., 2005). However, development in the form of dams, commercial navigation waterways, oil and gas exploration, and roads is on the horizon, and mining and logging concessions already cover large areas (Laurance et al., 2001; Maki et al., 2001; Fearnside, 2002; Steininger et al., 2002). Oil and gas exploration is active throughout the Peruvian Amazon and extraction is expected to increase markedly over the next decade. Development plans and concessions, while on the one hand ominous from a biodiversity conservation perspective, also present an opportunity to infuse decisions proactively with sound environmental recommendations.

There is growing evidence that the loss of functioning freshwater systems can have long-term ecological and economic repercussions over large geographic areas (Holmlund and Hammer, 1999; Gram et al., 2001). Costly fisheries declines following the construction of large dams around the world, such as the Tucurui Dam on Brazil’s Tocantins River, provide just one example (La Rovere and Mendes, 2000; World Commission on Dams, 2000; Fearnside, 2001). South America’s freshwaters are imperiled by a range of threats, of which dams are only the most obvious (Allan and Flecker, 1993; Pringle et al., 2000). In Amazonian headwater systems, threats may actually derive as much or more from upland and riparian land uses as from water engineering projects (Neill et al., 2001; Bernardes et al., 2004).

The science to guide decision makers on how to protect Amazonian freshwater systems, either explicitly or within larger terrestrial initiatives, is inadequate. Some of the key scientific gaps are generic to freshwater systems around the world, whereas others are specific to the Amazon and other data-poor regions. Information gaps hindering nearly all freshwater conservation efforts include a poor understanding of species dispersal processes, metapopulation structures, and population viability; of species adaptations to and reliance on natural regimes of flow and flooding; and how populations, communities, and ecosystems are affected by interacting anthropogenic disturbances, including those originating on the terrestrial landscape (Abell, 2002).

By nature of its vast size and remoteness, the Amazon Basin suffers from additional information gaps. There are insufficient hydrologic data to characterize the flow regime for large portions of the basin, and biological data describing species distributions are lacking over much of the region. Even ‘focal species’ like migratory catfish are so poorly known that designing a conservation plan around their specific minimum habitat requirements would be virtually impossible at this time, though within a decade that information might be within reach through new genetic analyses (Harvey and Carolsfeld, 2004).

These data gaps present serious obstacles to answering the standard conservation planning questions, such as how much area to protect, in what configuration, with what level of habitat replication, and with what protection strategies. This study builds on a growing body of work on freshwater conservation planning (Roux et al., 2002; Smith et al., 2002; Stein et al., 2002; Weitzell et al., 2003; Chadderton et al., 2004; Sowa et al., 2004) that provides guidance on these critical questions, although all of these analyses are from regions with significantly greater data availability than the Amazon. Addressing these questions within the Amazon will require long-term scientific investigations, but the combination of existing opportunities and impending threats necessitates that the scientific community develop provisional hypotheses in the near-term that can be tested in the field over time. Within this context, we propose an approach for developing large-scale conservation plans for freshwater systems that are characterized by a near-complete lack of biological and physical data. We use the Madre de Dios Basin in the southwest Amazon as a test case. This approach is exciting because it uses new datasets and analytical tools that we anticipate will have broad applicability and utility for freshwater conservation in other data-poor regions around the world. Following principles of conservation biology and freshwater ecology (Margules and Pressey, 2000; Higgins, 2003), the approach focuses on protecting the most intact examples of representative habitat types and maximizing longitudinal and lateral connectivity through a network of conservation areas that complement existing reserves as well as terrestrial conservation plans.

2. Methods

2.1. Region of analysis

The region of analysis is defined by the drainage basins of the Madre de Dios and Orthon rivers of Peru and Bolivia (hereafter referred to as the “Madre de Dios Basin”; approximately 160,000 km²; Fig. 1). This region is part of the Southwestern Amazonian Moist Forests Global 200 ecoregion, which has been identified as outstanding for both terrestrial and freshwater biodiversity (Olson and Dinerstein, 1998).

Much of the runoff in the Madre de Dios system has its origin in the Andes. In particular, the Manu, Alto Madre de Dios, Blanco, Azul, Colorado, Inambari, and Tambopata rivers drain from the Cordillera Oriental of the Andes (elevation approx. 800–6300 m), which extends in a band covering the most southwestern edge of the region. Only the Orthon and Las Pídras rivers lack drainage from the Andes. The rivers and streams flowing through the Andes tend to be relatively clear...
and highly responsive to rainfall. During the rainy season between October and April, they may rise and fall quickly and carry higher sediment loads than at other times. Andean tropical montane forests (also called yungas), which include cloud forests, occur in a band from about 1000 to 3000 m. Above this elevation, sub-alpine forests grade into tropical alpine communities (puna). Some streams running through cloud forest tend to be more acidic (pH 4.2–5.2) than those running through other forest types (pH 6–7) (Goulding et al., 2003).

After descending from the Andes, the rivers start meandering at about 350 m elevation. Extensive floodplains with oxbow lakes (cochas) occur along the courses of these lower elevation rivers. The rivers remain turbid throughout the year, but carry their highest sediment loads during the rainy season. Floodplain forests occur alongside the rivers; portions of these forests are typically inundated several times between December and April for brief periods (often <1–2 weeks). Large areas of slightly more elevated floodplain also border the rivers. These areas are seasonally flooded largely due to local precipitation and poor drainage; they may infrequently or never receive floodwaters from the river. Along certain reaches of the Madre de Dios and Tahuamanu rivers, palm swamps or aguajales (dominated by Mauritia flexuosa L.) occur in depressions on fluvial terraces and appear to receive little or no water from the mainstem river. The waters of those palm swamps tend to be clear and acidic, in contrast to the higher turbidity and circumneutral pH of lowland rivers of the basin (Goulding et al., 2003).

The lowland Madre de Dios basin has a humid tropical climate (Osher and Buol, 1998) with rainfall varying from about 1200 to 3300 mm, generally increasing from east to west. Rainfall is seasonal and lowest from June to September. Lowland vegetation is predominantly evergreen or semi-evergreen forest (Osher and Buol, 1998), and bamboo thickets are common on poorly drained parts of upland alluvium (Griscom and Ashton, 2003; Hamilton et al., in press).

2.2. **Delineation of stream networks and subbasins**

There is widespread agreement that drainage basins or watersheds are logical conservation planning and management units for freshwater biodiversity and water resource conservation, although some species will require larger spatial scales than others and may use habitats within multiple basins (Wishart and Davies, 2003). Basins are nested hierarchical units, and a larger basin can be subdivided into smaller basins that may serve as more tractable planning or management units. These units need to be coarse enough in scale to be useful for planning efforts across a large area, yet detailed enough to make meaningful distinctions among freshwater habitat types (FitzHugh, 2005; Higgins et al., 2005). We used subbasins, named such to distinguish them from the larger Madre de Dios Basin, as our main unit of analysis, and our recommended areas for conservation intervention are built from these subbasins.

Subbasins are particularly appropriate units of analysis in headwater regions, where a subbasin’s physical landscape characteristics largely determine the characteristics of the streams draining it. On their passage downstream, however, small streams grow to larger rivers, which are increasingly influenced by upstream as well as local conditions. With increasing distance from their source, the hydrologic characteristics and ecological functionality of larger streams and rivers may therefore deviate more and more from the local conditions of a given subbasin through which they are passing. To account for this distinction, we introduced a second scheme of analysis units and explicitly distinguished polygonal subbasins from linear streams. Furthermore, floodplains

Fig. 1 – Major rivers within the drainage basin (gray) of the Madre de Dios and Orthon rivers.
associated with larger lowland rivers comprise a distinct landscape unit that was considered separately. Thus our conservation planning approach integrates features of the upland drainage basins, the stream and river channels, and associated floodplains where they are large enough to warrant separate treatment.

In principle, basin boundaries and stream lines can be imported into a Geographic Information System (GIS) from existing maps. This method, however, produces results that vary according to the scale and quality of the maps, and the product is static. For the Amazon basin, the new digital elevation data of the Shuttle Radar Topography Mission (SRTM; United States Geological Survey, 2003) offers, for the first time, sufficient resolution (approx. 90 m horizontal, 1 m vertical) and accuracy to derive reliable stream and basin delineations. We obtained seamless SRTM data for the entire study area (downloaded from ftp://edcgs9.cr.usgs.gov/pub/data/srtm/) and applied a series of “hydrologic enforcement” algorithms that conditioned the elevation data to enable improved calculations of flow directions and river topology. For these processes we designed and programmed new, customized GIS tools, including algorithms for void filling, hydrologic filtering, stream burning, stream carving, and scaling (Lehner et al., 2006). We further developed tools and approaches that allow for an automated delineation of nested basins and stream networks from the conditioned SRTM data. These tools also support the attribution of the resultant units with physical characteristics based on auxiliary data (e.g. slope, geology, and vegetation). Additionally, network topology was introduced through a stream-order and coding system that permits analyses of up- or down-stream connectivity, distances, or relationships between any units within the study area. Visual comparisons of our results with existing detailed river maps of Peru (scale 1:100,000; Instituto Geográfico Nacional, 1985–1989) and remote sensing imagery for selected areas in Brazil (Side-Looking Airborne Radar; scale 1:1,000,000; Ministério das Minas e Energia, 1982) showed good overall agreement. We used a minimum size threshold of 100 km² for our subbasin delineation in order to obtain a manageable number of units for planning at this scale. Due to the configuration of the river network, the average subbasin size within the study area was 250 km², with the largest subbasin being 1350 km². Streams were traced starting at all outlets of headwater subbasins and were subdivided into individual reaches between all river confluences. In total we distinguished 618 subbasins and 265 stream reaches.

2.3 Classification of stream reaches, subbasins, and floodplains

There is general agreement within the conservation community that protecting representative ecosystem types, or ‘coarse-filter’ targets, should conserve common species and communities, the ecological processes that support them, and the environments in which they have evolved (Hunter, 1991; Higgins et al., 2005). Distributional data for ‘fine-filter’ targets – typically rare, endemic, or endangered species – should ideally be used to complement coarse-filter information, but in regions like the Amazon existing species data are often insufficient. Coarse-filter targets are derived through a process of habitat classification that typically combines automated and manual processes.

Numerous systems of aquatic classification have been developed around the world (Boon et al., 1998; Higgins et al., 2005). Most systems are hierarchical and fall into two categories: divisive or ‘top-down’ approaches or agglomerative or ‘bottom-up’ approaches (Kingsford et al., 2005). ‘Top-down’ approaches start from large, ecologically heterogeneous areas, dividing these into lower more homogeneous levels. ‘Bottom-up’ approaches begin with the lowest levels of the hierarchy and agglomerate them according to shared characteristics (Kingsford et al., 2005). Whereas it is generally agreed that understanding processes and patterns of freshwater systems at multiple scales is critical for conserving freshwater biodiversity, there is still debate over which approach is best to classify these processes and patterns (Frisell et al., 1986; Naiman et al., 1992; Fausch et al., 2002). For the data-poor southwest Amazon the only option was a top-down approach, which we modeled on that developed by The Nature Conservancy (Higgins et al., 2005).

2.3.1 Subbasin and stream classification

We developed the aquatic habitat classification scheme for the Madre de Dios Basin through an iterative process. First, we designed an initial classification framework by including all characteristics and combinations thereof that we considered relevant to distinguish different habitat types, and for which we had geospatial data. This initial scheme led to a large number (several hundred) of possible classes and subclasses, rendering it unmanageable for any practical application. To reduce the complexity of the classification scheme, we analyzed inter-correlations of the various parameters, identified the key variables, removed or grouped dependent layers, and finally consolidated the initial framework into a feasible set of main classes. These steps and decisions were carried out manually and informed by consultation with scientists familiar with the region. The specific classes and thresholds were then reviewed at an expert workshop in Lima, Peru in July 2004 and were further refined through follow-up consultations. We refrained from applying a multivariate statistical analysis because we believe that a fully automated process – despite its objectivity – could neglect important influences like limited data quality or known outliers and thus lead to less desirable results than a user-supervised classification.

The classification framework for subbasins and streams focused on ecological functionality, which in turn is based on hydrogeomorphic characteristics. The classification input categories were:

- System type (e.g., headwater vs. pass-through basin, small vs. large streams, floodplain type).
- Elevation (and derivatives, e.g., slope).
- Geology.
- Vegetation.
- Hydrology (e.g., surface runoff, river discharge).

Based on these categories we developed the initial hierarchical classification scheme: each type class was subdivided into different elevation zones, and each of these unique com-
Combinations was then further subdivided according to geology, vegetation, etc. In the following section, we describe the parameters and thresholds that we applied. Examples of attributes that were tested initially but excluded from the final classification are slope and river channel slope as derived from elevation (both were highly correlated to elevation), and river density (highly correlated to runoff).

2.3.1. Type. As described above, we were able to delineate subbasins and stream reaches from the SRTM elevation data. Floodplains and wetlands were subsequently delineated based on SRTM plus additional remotely sensed imagery, as described later. We distinguished three basic types of streams and two basic types of subbasins. This classification is based on the size of streams and rivers in terms of their long-term average discharge, estimated via a hydrologic model as described later, because no measurements were available for this region. The thresholds were determined by consultation with hydrologists and local experts. "Pass-through basins" are adjacent to river channels and floodplains that receive most of their water from upriver.

Type of stream:
- **Stream.** Long-term average discharge ≤500 m$^3$/s.
- **River.** Long-term average discharge >500 m$^3$/s and ≤3000 m$^3$/s.
- **Mainstem.** Long-term average discharge >3000 m$^3$/s.

Type of subbasin:
- **Primary drainage basin.** Subbasin with largest stream ≤500 m$^3$/s.
- **Pass-through basin Subbasin with a river >500 m$^3$/s draining through it.

2.3.1.2. Elevation. We distinguished three elevation zones, representing the lowland plains, mid-elevation areas, and Andean mountain regions (Fig. 2a). The thresholds were again determined by experts, based on criteria to reflect both physical and biotic characteristics, including evidence that migratory catfish spawn in the mid-elevation zone. Average elevation values were calculated from SRTM data for each subbasin, and maximum elevations were calculated for each stream reach. The three elevation classes are:
- **Lowland.** <300 m.
- **Mid-elevation.** >300 m and ≤800 m.
- **High-elevation.** >800 m.

2.3.1.3. Geology. Geology can significantly influence the chemical composition of surface runoff and groundwater. In general, the geological formations within the region of analysis are highly correlated with elevation. Yet there are some

![Fig. 2](image_url) - Hydrogeomorphic characteristics of the Madre de Dios Basin: (a) elevation (SRTM data gridded at 90-m resolution); (b) stream reaches classified by % of upstream basin that occurs in the Andes (elevation > 800 m); (c) land cover (based on GLC2000: European Commission, 2003); and (d) model simulations of mean annual runoff (mm) per subbasin and mean annual discharge (m$^3$/s) per stream reach.
special geological layers within the higher-elevation Andean zone that appear to affect the hydrochemistry of their downstream drainages significantly (Barthem et al., 2003). Unfortunately, we could not reliably identify these layers from the best region-wide geologic map (Geologic Data Systems, 2003) and therefore introduced a simplified surrogate: we calculated the amount of high-elevation land area that drains to each stream reach (Fig. 2b) and classified the streams accordingly. Local experts recommended a threshold of 800 m as a suitable surrogate for Andean influence. The two surrogate classes for geology are:

- With parts of the basin above 800 m elevation (more than 0%).
- Without parts of the basin above 800 m.

2.3.1.4. Vegetation. We derived the dominant vegetation types per subbasin from the global GLC2000 land cover map (European Commission, 2003; 1-km resolution; Fig. 2c). From the detailed map legend we distilled four basic classes:

- Bamboo forest.
- Tropical forest.
- Montane forest.
- Grass- and shrubland.

2.3.1.5. Hydrology. Except for one known record of river stage measurements collected at the Centro de Investigación y Capacitación Rio de los Amigos (CICRA) field station above Puerto Maldonado, Peru (Goulding et al., 2003; Hamilton et al., in press), there are no relevant hydrological data on runoff formation or river flows available for the region of analysis. Under this constraint, hydrological information had to be approximated by employing data on precipitation and evapotranspiration to construct a hydrological model to simulate the spatio-temporal water balance. We utilized existing large-scale data from the Amazon-wide hydrologic modeling system known as IBIS-HYDRA, produced for the Large-Scale Atmosphere–Biosphere Experiment in Amazônia project (Kucharik et al., 2000; Coe et al., 2002). The IBIS component of this model provides long-term monthly estimates of runoff generation at a grid resolution of 0.5° (approx. 50 km). We disaggregated these values for the subbasin units to derive estimates of average long-term runoff generation for all subbasins (in mm/yr; Fig. 2d). We additionally accumulated the runoff amounts along the stream network to calculate long-term means of river discharge. Without existing discharge measurements the results of this modeling approach cannot be validated, but we believe that the estimates reflect at least the general hydrologic characteristics and trends of the study area. For the classification, we employed a simple division of “dry” and “wet” areas, based on consultation with hydrologists and experts familiar with the region:

- Dry. Average runoff generation within subbasin ≤1000 mm/yr.
- Wet. Average runoff generation within subbasin >1000 mm/yr.

2.3.1.6. Final hydrogeomorphic/ecological classification scheme for subbasins and streams. Based on the initial hydrogeomorphic/ecological classification scheme, we extracted a simplified classification scheme for subbasins and streams. A few outliers were manually adjusted (e.g., single units differing from their homogenous neighborhood due only to a slight excess of a certain threshold).

Subbasin classes:

- Pass-through basin (mainly along lowland rivers).
- Lowland wet tropical forest basin.
- Lowland dry tropical forest basin.
- Mid-elevation tropical forest basin (mainly wet).
- Mid-elevation bamboo forest basin (mainly wet).
- Mid-elevation montane forest basin (mainly wet).
- High-elevation montane forest basin (mainly wet).
- High-elevation grass- and shrubland basin (mainly dry).

Stream classes:

- Mainstem Madre de Dios River.
- Lowland river with drainage from elevations >800 m (i.e. with Andean influence).
- Lowland river without Andean influence.
- Lowland stream with Andean influence.
- Lowland stream without Andean influence.
- Mid-elevation stream with Andean influence.
- Mid-elevation stream without Andean influence.
- High-elevation stream (entirely Andean).

2.3.2. Floodplain classification

Floodplains are a dominant and biologically critical feature within the region of analysis as well as within the wider Amazon basin (Puhakka et al., 1992; Lewis et al., 2000), and the complexity of floodplain patterns cannot be captured sufficiently by the subbasin approach. We use the term “floodplain” broadly to denote areas along rivers that are subject to at least occasional inundation by overbank flow, as well as more distal areas that may not be subject to riverine inundation (Hamilton et al., in press). The latter may have been created by fluvial action but now lie on relatively uplifted terraces, or they may be areas subject to sheet flooding, often by water of local origin (i.e., rainfall or local runoff). Inundation or at least soil saturation results because they are level and poorly drained. They are nonetheless seasonally wet environments and in that respect would resemble floodplains that are inundated by riverine overflow, although their biota could be quite distinct.

We employed optical (Landsat ETM+) and microwave (JERS-1 synthetic aperture radar) remote sensing data as well as the SRTM topography to delineate floodplains and discern major habitats within them (for details see Hamilton et al., in press). We analyzed the different spatial data sets simultaneously with an object-oriented image analysis approach using the software package “eCognition” (Professional Version 4, Definiens Imaging, Munich). The object-oriented basis of this image analysis software proved to be superior in this case to traditional pixel-based image analysis for feature extraction and classification since contextual and topological rules can readily be incorporated into a knowledge-based classification algorithm. The maps made by image analysis were field-checked...
in a representative area along the Madre de Dios River, where over 100 observations of habitat types were made and diverse waters on the floodplain were sampled for analysis of major solutes to reveal water sources (Hamilton et al., in press). Most of the field observations agreed well with the floodplain classes as delineated from remote sensing data, and the observed differences were used to adjust the classification. Based on our field experience as well as published descriptions of the geomorphology and vegetation of floodplains of the Peruvian Amazon (Kalliola et al., 1991; Puhakka et al., 1992; Pitman et al., 1999; Kvist and Nebel, 2001), we manually interpreted the detailed classification of floodplain environments to distinguish six key classes of major floodplains and wetlands for conservation planning purposes. The three main floodplain classes (mainstem Madre de Dios, Manuripi River and braided river floodplains) include a mosaic of other floodplain environments such as palm swamps, meanderbelt forest, and herbaceous vegetation that were consolidated for the purposes of conservation planning at this scale (see Supplementary Map 1 for detailed floodplain classification).

Floodplain and wetland classes:

- **Mainstem Madre de Dios River floodplain.**
- **Manuripi river floodplain.**
- **Braided river floodplains.**
- **Palm swamps on fluvial terraces.**
- **Palm swamps along river courses.**
- **Pampas** (savannas subject to seasonal flooding, generally due to poor drainage of rainfall rather than overbank flow of river water; Hamilton et al., 2004).

### 2.4. Connectivity

Maintaining connectivity is a standard goal of conservation biology (Groves, 2003) and an essential and primary goal of freshwater conservation planning (Abell et al., 2002). Our aim was to develop a plan that, if implemented, would protect longitudinal and lateral connectivity over entire river systems (Ward, 1989) and thereby permit the dispersal and migration of aquatic species and the natural transfer of materials and energy (Federal Interagency Stream Restoration Working Group, 1998).

For longitudinal connectivity, we took an ‘all or none’ approach: connectivity is either maintained through a complete lack of large dams (height \( \geq 15 \text{ m} \) or volume \( \geq 3 \text{ million m}^3 \)), or it is lost where such barriers exist anywhere along a river. Large dams often affect the movements of fish and other organisms as well as disrupt key ecological processes such as flooding and sediment regimes (World Commission on Dams, 2000). We set a goal of maintaining longitudinal connectivity along the entire length of two major tributaries in the Madre de Dios Basin. As our region of analysis does not extend to the mouth of the Amazon, we extended this goal only as far downstream as the mouth of the Madre de Dios; however, if connectivity were disrupted downstream it would affect migrations of aquatic species into the region (Barthem and Goulding, 1997; Arajo-Lima and Ruffino, 2004).

Maintaining lateral connectivity requires protecting both the connection of the river to its tributaries, floodplain, and riparian zone, and the natural ability of a river channel to migrate laterally. The rich literature on riparian and floodplain buffers concludes that ideal widths are specific to individual systems (IUCN, 1992; Pringle and Benstead, 2001; Roux et al., 2002; Saunders et al., 2002). Bolivian and Peruvian forestry laws require 10–100 m and 50 m buffers, respectively, but these are not specific to the Amazon (Bolivia: Articulo 35 of the Reglamento General de la Ley Forestal; Peru: Articulo 26 of the Ley Forestal y de Fauna Silvestre). Along larger rivers identified as important for meeting representation goals, we recommended that all adjacent subbasins be appropriately managed to maintain buffer functions and connectivity and also to conserve contiguous smaller-stream environments, which may support certain life history stages of the riverine fauna (e.g., spawning and nursery habitat for fishes and prawns). The lateral width of our subbasins varies, but the effect was to create a buffer at least 1 km wide along these rivers.

### 2.5. Intactness assessment

Although the region of analysis currently has a relatively low human population density, there are several looming threats to the freshwater ecosystems of this basin. Among these, the most prominent is land conversion due to deforestation and agriculture (Goulding et al., 2003). Gold mining has had major impacts at a few sites, particularly at an area west of the Inambari River (Goulding et al., 2003). Smaller-scale gold mining also takes place in a more dispersed fashion along the rivers, especially on seasonally emergent bars. Mining-associated mercury contamination has caused concern, though the effects need further investigation (Guimarães et al., 1999; Lechler et al., 2000; Maurice-Bourgoin et al., 2000, 2003). Currently there are no large dams in the region of analysis; however, river impoundment to allow navigation through a reach of rapids on the Madeira River downstream from the mouth of the Madre de Dios River is under consideration. In addition to affecting the passage of aquatic animals through that reach, upstream effects on the natural flow regime might extend into the lower Madre de Dios and Orthon rivers.

To identify areas that remain relatively intact, we overlaid digital maps of population centers, roads, deforestation, and mining with drainage and subbasin maps (WWF Peru digital data, J.C. Riveros, unpublished data). Population centers and roads provide good indicators of where habitat conversion and loss are likely concentrated, since human activities affect the lands and waters surrounding these areas first (Sanderson et al., 2002). Subbasins without population centers, roads, land cover conversion, or mining activities were presumed to contain relatively intact freshwater ecosystems.

Additionally, we assumed that areas under formal protection support relatively intact freshwater. Few of these protected areas have been designed to conserve freshwater systems and species, but freshwater experts at a workshop held in Lima, Peru in July, 2004 asserted that many of the region’s large protected areas did confer protection to the freshwaters running through them. We mapped protected areas designated as IUCN categories I–VI (nature reserves, wilderness areas, national parks, natural monuments,
habitat/species management areas, protected landscapes, managed resource protected areas), under the assumption that these areas were most likely to be managed according to their conservation mandates. These areas cover 56,000 km², or 35% of the region of analysis (Fig. 3).

Indigenous lands and territorial reserves are also expected to contribute to the integrity of the basin. While these areas were not created with a biodiversity conservation goal, they represent formal barriers to the expansion of agriculture, cattle ranching and other forest conversion drivers. Recent evidence provided by Nepstad et al. (2006) working in the Brazilian Amazon supports this argument. These areas cover about 15,000 km², or 9% of the region of analysis (Fig. 3).

2.6. Representation analysis

Representation is defined loosely as conserving the full spectrum of biological and environmental variation. Setting representation goals is intended to address the question of “how much protection is enough?” (Noss and Cooperrider, 1994; Groves, 2003). Without species or community data to inform our representation goals, we set goals based on those of similar exercises described in the conservation planning literature, recognizing that most of the literature describes conservation planning efforts in temperate environments. In terms of size, the subbasins that we delineated for our region of analysis (mean area, 250 km²) are smaller than many protected area size prescriptions for temperate freshwater headwater systems (Thomas et al., 1993; Noss et al., 2002; Oregon Department of Forestry et al., 2003). However, our goal of maximizing connectivity reduced the likelihood of recommending a single, isolated subbasin for protection.

We set a goal of capturing 20% of the area of each habitat type in our portfolio of recommended conservation areas. Although this goal is widely-used in conservation (Murray et al., 1999; Noss et al., 2002; Sala et al., 2002; Airame et al., 2003; Leslie et al., 2003; CSIR Environmentek, 2004), it is an important hypothesis to be tested over time with field data. Given that we have little understanding of the heterogeneity among system types within the region, we chose not to set differential goals at this time, even though a higher degree of beta diversity is suspected in headwater streams than other aquatic habitats based on general patterns seen elsewhere (Jacobsen, 2003). Similarly, we applied our habitat representation goal across the entire region of analysis, because we lack sufficient knowledge to subdivide the basin into biogeographically-informed stratification units (Ortega et al., in litt.).

To conduct a gap analysis of freshwater habitat types within the region, we overlaid existing and proposed protected areas with the maps of classified floodplains, subbasins, and streams, and then calculated the percent of each subbasin, stream, and floodplain class that was captured within those areas. Proposed protected areas for conserving terrestrial targets (Fig. 3) were those identified in WWF’s conservation plan for the terrestrial biodiversity of the Southwestern Amazonian Moist Forests ecoregion (World Wildlife Fund, 2004). For the river class calculation, all rivers were first buffered out on both sides by 10 km, and full protection status was assigned only to those river reaches with more than 75% of their

Fig. 3 – Current protected areas (IUCN categories I–VI) and indigenous territories in the Madre de Dios Basin. Los Amigos is a private conservation concession under management of the Asociación para la Conservación de la Cuenca Amazónica (ACCA).
buffered area under protection. This calculation is an attempt to adjust for the fact that river courses serving as the boundaries of protected areas are not necessarily well-protected themselves.

2.7. Selection of freshwater portfolio areas

Our selection of freshwater portfolio areas was an iterative, largely manual process, grounded in the goals of achieving...
representation, maximizing connectivity, and choosing the most intact systems where possible. We did not use decision-support software because no products were judged able to address longitudinal connectivity adequately. We assembled our portfolio of priorities using subbasins as building blocks, to ensure that no boundaries cut through subbasins.

Consistent with the terrestrial selection process, we gave first priority to areas that were adjacent to existing or proposed protected areas, and that appeared relatively intact based on interpretation of the threat data layers. From this core set of areas we were then able to build out the portfolio to meet our goals. This process included selecting the headwaters of existing and proposed protected areas to maintain longitudinal biophysical processes. We sought to minimize the size of the selected portfolio by choosing areas that met multiple goals, where possible.

To facilitate integration of our freshwater priorities with the existing terrestrial conservation plan for the region, we adopted a similar classification for priorities. Relatively intact areas selected to meet our representation or connectivity goals were identified as Level I. Level I protected areas or critical management zones could be defined by a range of interventions, including restrictions on use of the aquatic system, the designation of floodplain or riparian reserves, protection against instream barriers, or some degree of protection of the terrestrial landscape beyond the riparian zone. Priority areas that overlapped with indigenous territories were classified as Level II, recognizing that achieving conservation objectives for these areas would depend on collaboration with indigenous groups. Where it was necessary to select apparently disturbed areas to meet our representation and connectivity goals, we recommended these areas as Level III. Level III areas experience high use and will require active management and threat mitigation to contribute to conservation of the basin’s freshwater systems.

3. Results

3.1. Classification of stream reaches, subbasins, and floodplains

The subbasin and stream classification produced eight subbasin classes and eight stream classes (Fig. 4). The initial, detailed floodplain and wetland classification resulted in eight classes (Supplementary Map 1). Six major floodplain and wetland types were subsequently derived from the detailed classification for use in the representation analysis (Fig. 5). These major types likely underestimate the diversity of floodplains and wetlands in the region, but remotely sensed information

Fig. 5 – Major floodplain and wetland types within the Madre de Dios Basin. This map depicts current river floodplains as well as relict floodplains and other poorly drained lands below 400 m elevation that are likely to support wetland ecosystems. These broad categories were distinguished based on a detailed classification (Supplementary Map 1) using remote sensing information. The ‘Other floodplain and wetland’ category was not included in the representation analysis because these areas lacked distinguishing features based on the remote sensing information that was available.
confirms that these types are distinct in their geomorphology, hydrology, and vegetation. The remaining floodplain and wetland areas delineated in the detailed classification were not included in the conservation planning analysis because they lacked distinguishing features based on available remote sensing information.

3.2. **Intactness assessment**

Deforestation, mining, and human population centers are unevenly distributed across the basin and are clustered around major roads and rivers outside of protected areas and indigenous lands (Fig. 6). The road connecting Mazuco with Puerto Maldonado and then Ñapunay is a particularly disturbed corridor that cuts across the mainstem Madre de Dios and its floodplain. This area is due to come under far greater pressure, as the currently unpaved road is being upgraded to a major highway under the Regional Infrastructure Integration Process of South America (IIRSA) initiative. Deforestation appears most intense along this corridor, whereas mining and agriculture occur both here and in more upstream areas. These observations concur with those from other parts of the Amazon Basin, where large-scale forest destruction has been linked with the construction of major new highways (Laurance, 2000). Intensive gold mining continues along the Madre de Dios upstream from Puerto Maldonado and along the Inambari River about 145 km upstream from that same point; during our field visits we observed disturbances of the Madre de Dios river banks by placer mining. Agriculture also occurs in upstream portions of the Inambari Basin and between the Inambari and Madre de Dios rivers. With the exception of some agricultural encroachment in the Tambopata National Reserve and along the southwestern edge of Manu National Park, it appears that the protected areas have done relatively well at limiting intensive resource exploitation.

3.3. **Representation and connectivity gaps**

Despite the high level of protected area coverage within the region of analysis, several freshwater habitat types are underrepresented (Tables 1–3). One of the eight subbasin classes, five of the eight stream classes, and one of the six floodplain classes are underrepresented under both the current and proposed terrestrial protected area systems. An additional two subbasin classes (lowland dry tropical forest and pass-through basins) would only be fully represented if the proposed terrestrial priority areas were implemented. Mid-elevation habitat types are well represented, but several of the low- and high-elevation classes are substantially lacking in protection.

Longitudinal connectivity along the main rivers is fairly high within the region. However, there are a few major gaps. The section of the Madre de Dios mainstem that flows downstream from its confluence with the Las Piedras River to Manuripi National Reserve currently lacks management or protection. Downstream from Manuripi to its confluence with the Madeira River, the mainstem Madre de Dios also suffers from a longitudinal gap in protection. A shorter gap exists along the Rio Tambopata from Puerto Maldonado to the northern edge of the Tambopata National Reserve. The largest longitudinal gap occurs along the mainstem Madre de Dios.
from Manu National Park downstream to the Manuripi National Reserve.

Lateral connectivity gaps occur along many of the main rivers that form the border of existing or proposed protected areas. These include the northern and southern edges of Manuripi National Reserve (bounded by the Manuripi and Madre Dios Rivers, respectively), the northern side of the Las Piedras River (although the southern side is also only bordered by a proposed protected area), and the northern edge of the Tambopata National Reserve (Inambari and Tambopata rivers).

There are also several “headwater gaps” – unprotected subbasins containing the most upstream headwaters of exist-

<table>
<thead>
<tr>
<th>Subbasin habitat type</th>
<th>Total area (km²)</th>
<th>Existing protected area (km²)/(%)</th>
<th>Terrestrial nominated area (km²)/(%)</th>
<th>Freshwater nominated area (km²)/(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-elevation grass- and shrubland</td>
<td>10,645</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2164 (20)</td>
</tr>
<tr>
<td>High-elevation montane forest</td>
<td>20,166</td>
<td>9522 (47)</td>
<td>0 (0)</td>
<td>2481 (12)</td>
</tr>
<tr>
<td>Lowland dry tropical forest</td>
<td>44,829</td>
<td>7974 (18)</td>
<td>3694 (8)</td>
<td>3003 (7)</td>
</tr>
<tr>
<td>Lowland wet tropical forest</td>
<td>11,997</td>
<td>6364 (53)</td>
<td>574 (5)</td>
<td>629 (3)</td>
</tr>
<tr>
<td>Mid-elevation bamboo forest</td>
<td>11,291</td>
<td>9006 (80)</td>
<td>1814 (16)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Mid-elevation montane forest</td>
<td>14,332</td>
<td>10,003 (70)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Mid-elevation tropical forest</td>
<td>32,196</td>
<td>11,523 (36)</td>
<td>4552 (14)</td>
<td>2777 (9)</td>
</tr>
<tr>
<td>Pass-through basin</td>
<td>13,824</td>
<td>1938 (14)</td>
<td>1123 (8)</td>
<td>5964 (43)</td>
</tr>
<tr>
<td>Total</td>
<td>159,280</td>
<td>56,330 (35)</td>
<td>11,697 (7)</td>
<td>17,018 (11)</td>
</tr>
</tbody>
</table>

Percentages are calculated as a proportion of the total area of that habitat type. Those habitats that are underrepresented for existing protected areas are highlighted in italic. Those habitats that are underrepresented when both existing and nominated terrestrial protected areas are considered together are highlighted in bold.

<table>
<thead>
<tr>
<th>Stream habitat type</th>
<th>Total area (km² inside 10 km buffer area)</th>
<th>Existing protected area (km²)/(%)</th>
<th>Terrestrial nominated area (km²)/(%)</th>
<th>Freshwater nominated area (km²)/(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-elevation stream (Andean influence)</td>
<td>12,650</td>
<td>1259 (10)</td>
<td>0 (0)</td>
<td>1916 (15)</td>
</tr>
<tr>
<td>Lowland river (Andean influence)</td>
<td>7475</td>
<td>651 (9)</td>
<td>0 (0)</td>
<td>1858 (25)</td>
</tr>
<tr>
<td>Lowland river (no Andean influence)</td>
<td>6328</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2394 (38)</td>
</tr>
<tr>
<td>Lowland stream (Andean influence)</td>
<td>6578</td>
<td>3958 (60)</td>
<td>0 (0)</td>
<td>191 (3)</td>
</tr>
<tr>
<td>Lowland stream (no Andean influence)</td>
<td>33,770</td>
<td>3037 (9)</td>
<td>0 (0)</td>
<td>4613 (14)</td>
</tr>
<tr>
<td>Mainstem Madre de Dios</td>
<td>8625</td>
<td>69 (1)</td>
<td>522 (6)</td>
<td>3661 (42)</td>
</tr>
<tr>
<td>Mid-elevation stream (Andean influence)</td>
<td>16,768</td>
<td>9960 (59)</td>
<td>0 (0)</td>
<td>160 (1)</td>
</tr>
<tr>
<td>Mid-elevation stream (no Andean influence)</td>
<td>12,815</td>
<td>4086 (32)</td>
<td>2111 (16)</td>
<td>2977 (23)</td>
</tr>
<tr>
<td>Total</td>
<td>105,009</td>
<td>23,020 (22)</td>
<td>2633 (3)</td>
<td>17,770 (17)</td>
</tr>
</tbody>
</table>

Percentages are calculated as a proportion of the total area of that habitat type. Those habitats that are underrepresented when both existing and nominated terrestrial protected areas are considered are highlighted in bold. For all calculations, rivers were first buffered out on both sides by 10 km, and full “protection” or “nomination” status is assigned to a river reach when its protected or nominated area exceeds 75% of the buffered area (see also text).

<table>
<thead>
<tr>
<th>Floodplain habitat type</th>
<th>Total Area (km²)</th>
<th>Existing protected area (km²)/(%)</th>
<th>Terrestrial nominated area (km²)/(%)</th>
<th>Freshwater nominated area (km²)/(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainstem floodplain</td>
<td>7981</td>
<td>1577 (20)</td>
<td>424 (5)</td>
<td>3087 (39)</td>
</tr>
<tr>
<td>Manuripi floodplain</td>
<td>799</td>
<td>438 (55)</td>
<td>0 (0)</td>
<td>345 (43)</td>
</tr>
<tr>
<td>Braided floodplain</td>
<td>644</td>
<td>157 (24)</td>
<td>0 (0)</td>
<td>3 (0)</td>
</tr>
<tr>
<td>Palm swamp on terraces</td>
<td>305</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>65 (21)</td>
</tr>
<tr>
<td>Palm swamp-riverine</td>
<td>211</td>
<td>102 (48)</td>
<td>35 (17)</td>
<td>49 (23)</td>
</tr>
<tr>
<td>Pampas</td>
<td>2810</td>
<td>537 (20)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Total</td>
<td>12,750</td>
<td>2811 (22)</td>
<td>459 (4)</td>
<td>3549 (28)</td>
</tr>
</tbody>
</table>

Percentages are calculated as a proportion of the total area of that habitat type. Only the “palm swamp on terraces” habitat type (highlighted in bold) proved to be underrepresented when both existing and nominated terrestrial protected areas are considered together. Nevertheless, nominated areas would afford greater protection to the larger river floodplains.
ing protected areas. Four subbasins upstream of the Bahuaja Sonene National Park were added to the portfolio to close this gap.

3.4. Portfolio areas

In total, we highlighted 86 subbasins that require new or additional protection to fulfill our representation and connectivity goals. The areas we have recommended cover about 17,000 km² in total. Of these areas, 44% are recommended as Level I, 29% are recommended as Level II, and 27% are recommended as Level III (Fig. 7).

The result is a preliminary integrated plan for the freshwater and terrestrial systems of the Madre de Dios Basin (Fig. 7). At least 20% of each freshwater habitat type is represented in this plan. Major corridors along the Las Piedras and Tambo-pata rivers also connect the most downstream reaches of the Madre de Dios to its headwaters in the Alto Purús Reserved Zone and to its headwaters in the Bahuaja Sonene National Park, respectively. As new data become available within the region, this preliminary set of portfolio areas should be revisited and revised if necessary.

4. Discussion

4.1. Coarse-filter approach

Our coarse-filter habitat representation approach is intended to capture the majority of the more common freshwater species within an area that is extremely data poor. Because the purpose of this exercise was primarily to test the creation and analysis of the coarse filter, we did not apply a parallel and complementary fine-filter approach, intended to capture special elements-like rare and endemic species. In large part, these data are unavailable for the region, though some data exist for a few flagship species such as otters and side-necked turtles. It may be a decade or more before the ranges of endemic or rare fish species are known throughout the region of analysis, and likely even longer for other freshwater taxa. When better species-level data become available in the future, they may be added to the analysis, thereby helping to identify habitats of particular importance as well as assist in setting more habitat-specific representation goals that capture differences in beta-diversity. In the meantime, a subsequent iteration of freshwater planning for this region might incorporate measures of habitat complexity, derived from remotely sensed imagery, to begin to identify areas of higher potential biodiversity. This information would not substitute for fine-filter data, but could add a level of discrimination for areas within the same habitat class.

4.2. Habitat classification

We present our habitat classifications as hypotheses that serve as a starting point for conservation planning in this remote region. Carefully designed stratified sampling in the field will be required to validate the classifications, and corrections would have the potential to change the resulting
map of priorities considerably. We underscore, therefore, the highly provisional nature of our results. Nevertheless, this study is of broader interest because it illustrates an approach to freshwater conservation planning that was previously not possible. Our ability to generate a high-quality drainage map from the new, high-resolution SRTM elevation data was the critical starting point for a series of model applications that culminated in the classification of subbasins and river reaches. In a region with no river discharge data and no pre-existing fine-scale subbasin maps, we believe that our results represent an important advance in freshwater conservation planning that can be replicated elsewhere. Similarly, the mapping of floodplain and wetland habitats represents an unprecedented combination of remote sensing observations and new image-analysis techniques. Hydrologic models and computer classification of remote sensing data should never supersede field observations and data, but their outputs can be used to design targeted sampling strategies, which are especially needed in vast and remote areas like the southwest Amazon.

4.3. Applicability to other basins and ecoregions

The tools and approaches that have been developed to delineate subbasins and stream networks, as well as to attribute these units with physical parameters, have been designed to work within a data-limited environment. The essential core layer of SRTM elevation data at 90-m resolution is available at near-global coverage and thus enables applicability in virtually all ecoregions or river basins globally. The tools we have developed will soon be available from the authors as extensions within a standard GIS software package (ArcView, Version 3.2, ESRI, Redlands, CA) and can thus be instrumental in further analyses.

The classification framework and the required auxiliary data sets have been designed and selected in a generic manner and should therefore be transferable to other regions beyond our region of analysis. The final classification scheme can be adapted to suit local requirements. The mapping of floodplains and wetlands based on globally available, spaceborne remote sensing observations also can be extended to other basins within the southwestern Amazon region and, with appropriate calibration and validation, to other extensive floodplain systems.

4.4. Gaps in protection for freshwaters

Freshwater systems appear to be moderately well-protected in the region of analysis, particularly when proposed terrestrial priority areas are considered. The combined size of protected areas in the region and the fact that many were originally designed to capture entire watersheds means that rivers should receive some degree of protection no matter what the configuration of areas. However, despite the fact that existing protected areas, as defined in this assessment, cover 35% of the region of analysis, we found some notable gaps in protection of the region’s freshwaters. These gaps took three main forms. First, there were representation gaps in protection of certain broad habitat classes. Second, there were lateral and longitudinal connectivity gaps. Last, there were what we have termed ‘headwater gaps’ – that is, populated catchments that are upstream of existing and proposed protected areas. These areas present special challenges for conservationists because of their potential impacts on downstream quality.

The two main gaps in habitat class protection were for high-elevation systems in the southern part of the Madre de Dios Basin, and for nearly all of the lowland river classes, including the mainstem Madre de Dios River and its floodplains. Gaps in lowland river protection are in fact a universal problem for aquatic conservation, even though these systems provide critical habitats for both resident and migratory species (Peres and Terborgh, 1995) and their floodplains in particular comprise unique aquatic environments not found along lower-order rivers and streams (Frisell, 1997). Much of the disturbance in the region is concentrated in these lowland gaps because the larger rivers of the Amazon have supported the transportation system of the region for hundreds of years. Our freshwater plan, by recommending different types of protection, attempts to address these gaps in a practical fashion.

The most obvious problem in terms of lateral connectivity stems from the common practice of using rivers as the boundaries of protected areas. Protecting one bank is certainly preferable to no protection at all, but implementing floodplain or riparian management on the unprotected side would go far toward creating a buffer and providing habitat, both for aquatic and some terrestrial species (de Lima and Gascon, 1999). On a related note, the practice of designating rivers as protected area boundaries is questionable in a region where rivers may provide the only or best access points to these areas; Peres and Terborgh (1995) argue for maximizing the defensibility of Amazon nature reserves by using drainage basins as the basis for delineating boundaries.

Longitudinal connectivity gaps were surprisingly few, if we assume that rivers flowing through or alongside protected areas are free from instream barriers. Those gaps that we found, however, are critical ones. For example, the mainstem Madre de Dios downstream of Manu National Park is unprotected for about 150 km. Protecting the longitudinal connectivity of priority rivers, both inside and outside protected areas, would require a commitment by decision makers not to construct instream barriers on these systems. While the risk of hydropower development may presently be low for rivers in the region of analysis, a commitment by the governments of Peru and Bolivia to protect migration corridors from the headwaters of the Las Piedras and Tambopata rivers down to the mouth of the Madre de Dios could serve as a strong argument to Brazil to reconsider plans for large-scale hydropower and navigation projects directly downstream (Fearnside, 2005).

The final category of ‘headwater gaps’ highlighted instances where protected areas failed to achieve their full potential for conserving the freshwater systems running through them, because relatively small pieces of upstream headwater catchments fell outside the areas. In some cases, remedying this problem could be accomplished by extending the protected area boundaries. In other situations, the window of opportunity for protecting an entire intact drainage basin has passed, and attention must shift to management within a human dominated landscape. The importance of...
implementing best management practices in headwaters, though, should not be underestimated, as these areas can have disproportionately large influences on downstream water quality, nutrient regimes, and flow (Meyer and Wallace, 2001).

4.5. Selection of portfolio

The process that we used for selecting priority areas allowed us to meet representation and connectivity goals while also taking into account existing threats and terrestrial nominated areas. In total about 11% of the region of analysis was nominated for some level of protection, 57% for representation and 43% for connectivity. In the future, the development of a decision-support software that explicitly addresses longitudinal connectivity could allow for the generation of multiple optimum sets that meet specific area requirements while minimizing area.

5. Conclusions

Our proposed plan is built on a combination of common sense, expert opinion, and sophisticated spatial data analysis and modeling. The implementation of these recommendations will require extensive stakeholder involvement and considerations of social and economic tradeoffs. We recognize that creating additional protected areas in this already well-protected area would be challenging, and that much of the land outside protected areas and indigenous lands is already settled to various degrees. Consistent with the terrestrial plan for this region, we have designed a plan that recognizes that protected areas are only one of several important and complementary strategies. In this region where people directly depend on healthy freshwater systems and the services that they provide for their sustenance (Kvist and Nebel, 2001), there are strong arguments to be made for mitigating disturbances that impair freshwater systems and for working with communities to develop multiple-use management zones. Relatively simple measures to safeguard migratory fish corridors and the floodplains that nourish countless species and valuable fisheries are also well-justified from an ecosystem services perspective.

Key to creating an effective conservation plan is being able to visualize water and land together. Terrestrial conservation planners have more often than not created blueprints without undertaking the simple act of overlaying rivers with their land cover and land use maps. To be fair, in some cases only very poor river maps have been available; a new global drainage map (Lehner et al., 2006) will help address that problem. Even where no freshwater classifications are available, applying simple rules of thumb, like encompassing entire drainage basins and promoting lateral and longitudinal connectivity along rivers, can make any plan more ‘freshwater friendly.’ Truly integrated terrestrial-freshwater conservation planning would require simultaneous identification of priority systems in the two realms, and subsequent recommendations based on the most efficient intersection of the two priority sets. In this example of partial integration, we have been able to take planning substantially further than was previously possible to produce a scientifically grounded map that, while provisional, can nonetheless be used to catalyze conversations about how to protect freshwater biodiversity in the Amazonian headwaters and in other data-poor systems. The data sources used to complete our analysis are now available for most of the globe, which means that with a few relatively simple GIS and image-analysis tools, coarse filter conservation planning for freshwater biodiversity is virtually a universal possibility.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2006.10.054.

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