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The Role of Tropical Forests in Supporting Biodiversity and Hydrological Integrity

A Synoptic Overview

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Abstract

Conservation of high-biodiversity tropical forests is sometimes justified on the basis of assumed hydrological benefits – in particular, reduction of flooding hazards for downstream floodplain populations. However, the ‘far-field’ link between deforestation and distant flooding has been difficult to demonstrate empirically. This simulation study assesses the relationship between forest cover and hydrology for all river basins intersecting the world’s tropical forest biomes. The study develops a consistent set of pan-tropical land cover maps, gridded at one-half degree latitude and longitude. It integrates these data with existing global biogeophysical data. We apply the Water Balance Model – a coarse-scale process-based hydrological model -- to assess the impact of land cover changes on runoff. We quantified these impacts of forest conversion on biodiversity and hydrology for two scenarios: historical forest conversion and the potential future conversion of the most threatened remaining tropical forests. A worst-case scenario of complete conversion of the most threatened of the remaining forested areas would mean the loss of another 3 million km² of tropical forests. Increased annual yield from the conversion of threatened tropical forests would be less than 5% of contemporary yield in aggregate. However, about 100 million people – 80 million of them in floodplains -- would experience increases of greater than 25% in annual water flows. This might be associated with commensurate increases in peak flows, though further analysis would be necessary to gauge the impact on flooding. We highlight basins in Southeast Asia, southern China, and Latin America that warrant further study.

Key words: Deforestation, biodiversity, hydrology, human vulnerability, agricultural conversion, tropical forest, annual water yield.

1. Introduction

Efforts aimed at articulating the value of biodiversity have been frustrated by a lack of scientifically based assessments of the functional contributions that biodiversity makes to rural livelihoods and economic development, and this has been particularly so in the wet humid tropics (Tomich et al 2004). One of the most frequently discussed is the contribution of biodiversity to maintaining hydrological functions, specifically, the provision of sustainable water yields, reduction of flood hazard, and erosion control. Conservation and integrated watershed management are intimately tied to the water cycle of humid tropical ecosystems. Oyebande (1988) estimated that half of the world's tropical forests were cut down since 1950 and that if current (at the time) trends continued, two-thirds of the remaining forests would be lost by the year 2000. Wet tropical ecosystems support important biodiversity resources. Structure and function of these forests are similar across the tropics, but there is spectacular variation in species composition, even across small distances. In a class by themselves as the richest terrestrial vegetation by far, conversion of these forests leads to the greatest species loss per unit area of any land cover change. Estimates are controversial, but these ecosystems may be home to 2/3 of the world's plant species and 90% of insect species (Gentry and Dodson 1987; Myers 1980; Osborne 2000). Less clear is the nature of their role and significance in providing reliable water supplies to humans and their agroecosystems, although much progress has been made in the past twenty years (Bruijnzeel 2004). From a sustainable development perspective, it is supposed – plausibly but without much evidence – that changes in upland land use practices could help poor hill-dwellers, conserve biodiversity, and provide tangible hydrological benefits for downslope urban-dwellers. However, domestic benefits of forest preservation vary greatly with location and with scale and the prospects of significant hydrological benefits from forest preservation may be much smaller than is popularly believed (Chomitz and Kumari, 1998). Basic science is still needed to address these issues, for the role of biodiversity spans an enormous array of phenomenon, from land productivity, soil physics, hydrology, nutrient biogeochemistry, and possibly weather and climate dynamics. The socioeconomics of land cover change, population dynamics, agricultural policy and sustainable development are all embedded in this dialogue as well.

Our study spans the pan-tropical domain. It assesses policy-relevant scenarios using biogeophysical data sets and hydrological models organized around river network topology (i.e. hierarchical organization of river systems that channel spatially-distributed runoff into regional water supplies). A drainage basin perspective is essential for understanding the upstream-downstream connectivity of water supplies, water demands, and emerging water problems. Many of the recent broadly spatial studies of tropical forests have been related either to the economics of forest alteration or its impact on carbon storage or greenhouse gas emissions (i.e., Barbier and Burgess, 2001; Maestad, 2001; Bazzaz, 1998; Tinker et al., 1996). Studies linking tropical forest conversion and hydrologic impacts are typically limited in spatial extent with a few notable exceptions (Giambelluca, 2002; Bonell, 1998; Bruijnzeel, 1991). The effects of forest conversion observed in small catchments (<1 km²) may be difficult to detect in large basins (>1,000 km²) due to the confounding effect of differing land cover types and spatial and temporal variability of rainfall patterns within these basins. In this study, we evaluate the impacts of landcover change (in particular, forest conversion to agriculture) across the pan-tropical domain. Our analysis is done at relatively coarse scale (30-min or 0.5 decimal degrees) but in a consistent manner so that cross-regional comparisons can be made.

1.1 Goals of this work

Our major goal was to assess the magnitude and location of hydrological benefits resulting from biodiversity-oriented forest conservation, where both watershed function and key biological diversity could be simultaneously preserved. This responds to a perception that biodiversity conservation actions will be easier to motivate, finance, and implement if it can be shown that those actions also reduce human vulnerability to hydrological disturbances.

2. The Pan-Tropical Assessment

The boundaries of our study area, which we call the pan-tropical domain (Figure 1), were delineated by selecting basins that contain tropical or sub-tropical moist, dry and coniferous forests (Biomes 1, 2 and 3, respectively) as delineated by the World Wildlife Fund (WWF) Terrestrial Ecoregions of the World potential landcover map (Olson et al, 2001). This is a global map of ecoregions containing more than 800 ecosystems which are classified into biogeographical realms and biomes. WWF defines ecoregions as ‘relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change’. The pan-Tropical study area encompasses approximately 55 million km². Moist forests make up 33% of this area and dry forests 16%. We included tropical and subtropical coniferous forests (Biome 3) for the sake of completeness, although this biome represents less than 4% of the total pan-Tropical area.

2.1 Representing Pan-Tropical Biodiversity

The two indicators that were of greatest value to the pan-tropical assessment and that were available for each of the WWF ecoregions were the biodiversity distinctiveness index (BDI) and the conservation status (see Sebastian et al., 2003 for details). The BDI is a scale-dependent attribute of biological richness that was determined based on 5 criteria: species richness; endemism; complexity of species distributions; uniqueness and rarity; and geographic uniqueness (e.g. areas that exemplify global rarity of their habitat type). Biodiversity measurements are often based solely on species richness (i.e. the number of species) but the BDI broadens the definition by incorporating ecosystem diversity and the ecological processes that sustain that diversity at varying biogeographic scales (Wikramanayake et al. 2002; Dinerstein et al. 1995). The BDI is premised on the assumption that, while all ecoregions are biologically distinct to some degree, some are exceptionally rich, complex or unusual. Ecoregions were ranked as Globally Outstanding, Regionally Outstanding, Bioregionally Outstanding, and Locally Important. Ecoregions are considered outstanding if they exemplify extraordinary levels of the first 4 criteria or if they meet the criteria for geographic uniqueness¹ (Dinerstein et al. 1995). It is important to note that the BDI was derived independent of threat and is thus a ‘pure’ (i.e. no human element) indicator of biodiversity. The influence of the human ‘element’ on biodiversity is embodied in the conservation status. Conservation status is specifically ‘designed to estimate the present and future capability of an ecoregion to meet three goals of biodiversity conservation: to maintain viable species populations and communities, sustain ecological processes, and respond effectively to short-and long-term environmental change

¹ For more specific information on the classification of the Conservation Status or the Biological Distinctiveness Index (BDI) please refer to the specific assessments by biogeographical realm: Dinerstein et al. (1995); Wikramanayake et al. (2002); Ricketts et al. (1999).

(Wikramanayake et al. 2002 p.41).’ The conservation status is determined at the landscape level and is based on: loss of original habitat; number and size of habitat blocks; fragmentation/degradation; conversion rate and degree of protection. The global conservation status, which we used for this study, provides a ’30-year prediction of future conservation status given current conservation status trajectories (Olson et al., 2001)’ (see digital appendix Figure B.3). This variable is therefore used as an indicator of an ecoregion’s vulnerability to change.

2.2 Evaluating Pan-Tropical Land Use/Land Cover Change

Our assessment of land cover change focused on three different time periods: original (before large scale alteration by humans), contemporary, and a stylized future based on the conversion of the most vulnerable remaining tracts of tropical forest. This assessment required the generation of separate land cover surfaces for each of the specified ‘points’ in time and then the quantification of changes across two land use/landcover change scenarios which are described briefly below in the following sections. Specifics on the development of the land cover surfaces used in these scenarios can be found in Sebastian et al. (2003) and in digital appendix A.

2.2.1 Scenario 1: Historical changes in land cover

To examine historic change and the consequent hydrologic responses, three land cover datasets were created. The first, which for lack of a better word we call “original”, was based on the WWF ecoregions map and represents our best estimate of land cover prior to substantial human exploitation. The second, which we call “contemporary”, incorporates recent data on the current state of land cover (circa mid-1990s). The third, which we call “synthetic contemporary” focused specifically on the conversion of tropical forest to agricultural land uses. The objective of Scenario 1 was to provide a baseline for the analysis of potential future changes in land use. It also allowed us a means of testing the methodology from the hydrological perspective since the hydrologic model results from the contemporary dataset could be verified against observed flows.

The original land cover was derived from the WWF Terrestrial Ecoregions of the World (Olson et al., 2001). One of the benefits of using this source was that the ecoregions reflect ‘potential’ land cover and do not take into account human land cover conversions. Approximately 500 terrestrial ecoregions fall within the full basin extent of the pan-tropic study area. The contemporary land cover was based on the combination of existing datasets representing different aspects of contemporary land cover including natural vegetation, cropland and crop mosaic areas, pasture, irrigated areas and human settlements (Sebastian et al. 2003). The most frequently employed spatial reference for contemporary global land cover is the 1992/93 one-kilometer (1-km) resolution Global Land Cover Characteristics Database (GLCCD 2000; Loveland et al. 2000) interpreted using the International Geosphere-Biosphere Programme (IGBP) land cover classification scheme (IGBP 1998). The IGBP classification was best suited for this study since it maps easily into the hydrologic model’s input land cover classes, which were also based on IGBP classes. Cropland and cropland mosaic classes were determined based on the IFPRI Agricultural Extent database, which is a reinterpretation of the GLCCD v2.0 dataset. This exercise identified areas, at a 1km resolution, that contain 30 percent or more agricultural activity. For details on the creation of the IFPRI Agricultural Extent, see Wood et al. (2000) and IFPRI (2002). The Center for Sustainability and the Global Environment at the University of Wisconsin has developed a global pasture surface based also on a reinterpretation of the GLCCD v2.0 data. The pasture surface represents non-forest areas that are used for

grazing (Ramankutty 2003). The agricultural extent and pasture surfaces were superimposed on the IGBP classified GLCCD to create a combined land cover surface. This surface was then aggregated to the half degree resolution and the area shares of each class were calculated by cell. The shares were then adjusted to account for irrigated area and human settlements. The resulting cropland, irrigated and pasture totals per country were calibrated to the FAO totals for 1993 for arable and permanent crops and total pasture (FAOSTAT 2003). Each cell was then adjusted based on the weighted share of each agricultural land cover type.

The synthetic contemporary land cover was developed to eliminate the influence of classification differences between the original (based on WWF ecoregions) and contemporary (based on IGBP classifications) land cover surfaces. This dataset was derived by superimposing contemporary agricultural classes (irrigated and rainfed cropland and pastureland) onto the original land cover surface. In this way, the hydrologic response of tropical forest conversion to agricultural land use could be isolated and modeled without being confounded by errors due to differences in classification schemes. The hydrologic response of forest conversion to agriculture was further isolated by analyzing only synthetic land cover grid cells that were tropical forest in the original land cover surface. The hydrologic impacts for Scenario 1 (original forest to agriculture conversion) presented in this paper are based on the difference between the synthetic contemporary and the original land cover surfaces.

2.2.2 Scenario 2: Projected deforestation of tropical forest areas vulnerable to change

The focus in the second scenario was to gain a better understanding of the potential impacts of future tropical forest conversion. The objective, was to design a hypothetical , ‘worst-case’ land cover change experiment that explored deforestation in the most vulnerable tracts of remaining forest, and to measure what effect this conversion could potentially have on biodiversity, hydrological function and ultimately, on downstream human populations. The baseline for this scenario was the contemporary (not synthetic) land cover surface because the contemporary land cover surface was our best available representation of existing land cover. In Scenario 2, only existing forest area (circa 1992/3) within the tropical forest biomes was targeted for conversion; land cover in all remaining portions of the domain was held constant. The global conservation status from the WWF terrestrial ecoregions database was used to identify the areas most vulnerable to change within the tropical forest biomes; forest conversion was limited to these areas. As discussed in Section 2.1, the conservation status is an indicator of the degree and threat of change for each individual ecosystem. The key factors defining the conservation status are the degree of habitat loss, the level of fragmentation, remaining block size and level of conversion. The areas classified as critical or endangered were designated as those most threatened in terms of potential deforestation. Areas currently under protection, as identified by The World Conservation Monitoring Centre’s (UNEP-WCMC, 2003) protected areas database, were therefore not subject to conversion. As of the year 2000, there were 30,000 sites that were under national or international protection (UNEP-WCMC 2003). These data were made available through the Millennium Ecosystem Assessment (MA, 2005).

2.4 Modeling the Hydrologic Effects of Land Use/Land Cover Change

Hydrological modeling was performed using the Water Balance Model (WBM) at a 30’ (lat x long) spatial resolution (Vörösmarty et al. 1998, Fekete et al. 2001, Federer et al., 2003). The WBM simulates monthly soil moisture variations, evapotranspiration, and runoff on single grid cells using biophysical data sets that include climatic drivers, vegetation, and soil properties. The state variables are determined by interactions among time-varying precipitation, potential

evaporation, and soil water content. Potential evapotranspiration (PET) was computed using a modification of the well-known Penman-Monteith surface dependent method (Monteith, 1965; Shuttleworth and Wallace, 1985; Federer et al., 1996) which was found to perform best for global-scale land cover and climate modeling studies (Federer et al., 1996; Vörösmarty et al., 1998). Simulated “actual” evapotranspiration is distinguished from PET through limitations imposed by soil water deficit. Interpolated gridded surfaces of climate observations developed by New et al. (1998) were used as model forcings. Land cover inputs were developed specifically for this study as described in Section 2.2. Dominant soil type and texture were taken from the FAO/UNESCO (1995; Global Soil Data Task, 2000) soils data bank. Runoff for land cover mosaics was computed by generating separate runoff surfaces for all land cover types and then apportioning the runoff for each cover type within a grid cell according to the share (or fraction of area) occupied by that cover type. Details regarding model parameters and performance are presented in Digital Appendix A.

3. Results and Discussion

3.1 Pan-Tropical Overview of Changes in Landcover & Hydrology

Table 1 summarizes the proportions of land cover types aggregated across the entire pan-tropics and illustrates our best estimate of aggregate land use change. Assuming that the WWF ecoregions offers a reasonable representation of the state of land cover prior to significant human alteration, tropical forests accounted for as much as 53% (29 million km²) of the pan-tropical area. Of the forested area, about 62% was moist forest, 31% was dry forest and 7% was coniferous forests. Fully one-half of the tropical forests disappeared between the original and contemporary states, with 32% of the forests directly converted to agriculture (most of which has occurred since 1950, according to Oyebande, 1988). The remaining 18% of original forested area was classified in the contemporary land cover as other types of natural vegetation such as grassland and savanna. This apparent ‘loss’ could be due to the differences between the hypothetical and real land cover surfaces, or it could represent historical forest systems that have given way to grasslands and savannas for other reasons, either natural (i.e., climate variability) or anthropogenic (i.e., logging, fuel). Although the magnitude of loss in moist and dry forest areas were nearly identical in Scenario 1, the percent change in dry forest (~50%) was more than twice that of moist forest (22.5%). This finding supports field studies such as Laurance et al. (2002) who found that drier deciduous forests in the Amazon were more vulnerable to agricultural conversion than moist forests; our analysis suggests that this holds true over the pan-tropics as a whole.

Moist broadleaf forests comprise 36% of the pan-tropic domain (i.e. the area within all basins that have a share in the tropical forest biomes) and 82% of the three tropical forest biomes (see Figures A.1 and A.2 in digital appendix A for delineation of realms and Table B.1 in digital appendix B for a summary of forested and threatened areas and population by biome and realm). This biome has a high area share of globally and regionally outstanding biological distinctiveness (83% compared to only 56% of the dry broadleaf forest). The share of the moist broadleaf forest classified as critical or endangered (44%) is low in comparison to the shares for the dry and coniferous biomes (64% and 78% respectively). Scenario 2 of this study was predicated on the assumption that if an area is protected then it will not be converted. Although this is an extreme assumption it helps highlight the regions that are likely to be more vulnerable due to a lack of protection. Approximately 16% of the total study area is protected (this

percentage is the same on average for the tropical forest biomes and those areas outside of these biomes) with most of the protected area (43%) falling in the Neotropical realm (Central and South America). This is not surprising since a large portion of the Amazon basin is protected through both international and national initiatives. The Indo-Malay realm (South and Southeast Asia), which has the highest share of the population for the study area (53% - of which about two-thirds reside in the moist broadleaf forest biome), also has the lowest area share of protected forests (9%). And sadly, while the Indo-Malay realm shows the highest level of global or regional biological distinctiveness (74% compared to a study area average of 58%), the majority of the forests in this realm (66% of the moist forests and 75% of the dry forests) are classified as critical or endangered. We found that the Indo-Malay realm suffered the highest amount of tropical deforestation, accounting for 41% of the agricultural conversion within the pan-tropical domain while occupying only 29% of the pan-tropical area. Conversely, the Neotropics (Central and South America) account for almost half of the tropical forested area but only one-third of the area converted for agricultural and urban use.

3.1.1 Scenario 1: the effect of past land cover change

Table 2 summarizes the changes in average annual basin water yield (or discharge, Q) in response to Scenario 1 and 2 land cover changes. In scenario 1, representing historical forest cover loss, the 32% conversion of forests to agriculture (both cropland and pasture) has yielded an aggregate 10% increase (approximately 2000 km³) in annual yield. This is a noteworthy change at the global scale, insofar as pan-tropical runoff exceeds 20,000 km³/yr, representing more than half of the global continental runoff (Fekete et al., 2002). Interestingly, the 2000 km³ increase in annual yield due the agricultural conversion of tropical forests represents about three-quarters of global annual agricultural water withdrawals (approximately 2700 km³ according to the World Resources Institute; <http://earthtrends.wri.org/>). The largest proportion of both forest conversion and increased yield has occurred within the Indo-Malay realm, where a 44% forest conversion has yielded a 23% increase in annual yield. Basin aggregated modeling results (see Figure B.3 in digital appendix B) showed the generally linear increase in basin yield with forest lost noted by others (Oyebande, 1988; Bruijnzeel, 1996) although there is a great deal of scatter indicating that other factors influence this relationship as well. Figure 2 shows that forest clearing in dry locations has a much larger impact (relative to annual precipitation) than in moist locations. Where annual average rainfall is between 750 and 1800 mm/yr, the increase in runoff (relative to annual precipitation) is as much as 2 to 4 times higher than in basins with annual rainfall greater than 1800 mm/yr. This illustrates the principle reported by van Noordwijk et al. (2004), that forests will generally evapotranspire similar amounts of water across climates, but the additional water available after deforestation will be greater relative to total precipitation in dry climates than in wet.

Contemporary land cover (circa 1992/93) contained only about 12 million km² of tropical forests. The conversion of the most vulnerable remaining forests (Scenario 2 land cover change) would result in an additional loss of 3 million km² (about 25% of contemporary tropical forests), leaving just 9 million of the original 29 million km² tropical forests intact. After conversion of vulnerable forests in Scenario 2, the proportion of agricultural area in the tropics would increase from 13% to an estimated 18%. Interestingly, while this scenario was predicated on threats to biodiversity as a result of deforestation, the total area of our hypothetical forest conversion is within the range of land expansion needed to meet the growth in food demands over the next few decades (Bruinsma 2003). In other words, although Scenario 2 is hypothetical, the possibility of it becoming reality is quite high.

A full 72% of the original but now converted tropical forest was classified as either globally or regionally outstanding; an even greater percentage (82%) of the area hypothetically conversion in Scenario 2 was classified as such. Approximately 2.1 billion people -- 1/3 of the world's total-- reside within the boundaries of the WWF tropical forest biomes with 1.7 billion (or 70%) living in areas classified as having globally or regionally outstanding biological distinctiveness (see Table B.2 of digital appendix B). Approximately 500 million people (28% of the pan-tropical population) are living in existing (circa 1992/3) tropical forest. Of these forest dwellers, nearly one-half (200 million) are living in the vulnerable forest areas targeted for conversion in scenario 2, highlighting the intense human pressure on what little forest remains. Furthermore, in Scenario 2 each different forest BDI class loses 20-25% of its forest to agricultural conversion (see Table B.3 of digital appendix B). Many of the threatened areas are biologically rich but not currently under protection. Within the most threatened areas, there is a high degree of biological distinctiveness and so as these areas are converted, we stand to lose an even higher percentage of biological richness than occurred in the past.

3.1.2 Assessing the spatial patterns of hydrological changes

A common perception in the forest-hydrology link is that deforestation increases human vulnerability to floods. The issue is much debated, especially with respect to large river basins that link large downstream populations to forested uplands. A literature review by Kiersch and Tognetti (2002) found little evidence for effects of land use change on flooding in basins great than 100 km². There is some agreement, on theoretical grounds, that the most catastrophic floods in large basins result from storms so large and persistent that peak flows are unaffected by land cover (Calder, 1999, p.30; Bruijnzeel 2004). On the other hand, Costa et al (2003) present empirical evidence that large scale savanna clearance in the Tocantins basin (175,360 km²) has been associated with increases of 24% in mean annual flows and a 28% in wet season flows, though not necessarily with flooding.

Because the WBM operates at a monthly (rather than daily or hourly) scale, we cannot directly simulate the impact of land cover change on flooding. However, as a first step in understanding hydrological impacts of land cover change, we assess the impacts on mean annual flows. We assume that cells experiencing substantially greater annual flows due to deforestation are at increased risk for flooding (though not necessarily for catastrophic flooding, following the argument of Bruijnzeel and others). This assumption was supported by the fact that we found a very strong correlation (Pearson correlation coefficient = 0.92, p-value= 0.000) between increased mean annual runoff and increased maximum monthly runoff aggregated to the basin scale, indicating that changes in hydrologic behavior that effect the extremes are reflected in the mean annual flows as well.

One of the key factors in examining the effects of land use change, loss of biodiversity and hydrological function on human vulnerability is the recognition that the populations affected by these changes are linked to disturbance through river networks. Thus affected populations could be living both in the areas where the land use change takes place and in areas far downstream. The hydrological response can be propagated far downstream of the actual point of disturbance (as illustrated in Figure 3), and become both intensified and/or diluted depending on the character of the influent tributaries, and where the land use change takes place. For example, historical forest conversion in the upper half of the Ganges basin (Figure 3a) created an accumulation of hydrologic disturbance (in this case, increase in annual Q), which is diluted in the lower half of the basin as the mainstem joins with other less disturbed tributaries. In the case of the Mekong (Figure 3b), hydrologic effects are relatively low until the confluence with the

Mun River sub-basin, approximately 750 km from the mouth. This basin is the most impacted sub-basin within the Mekong basin (Richey, J., University of Washington, personal communication, December 2003) and the increase in annual Q from this sub-basin nearly doubles (from 10% to 20% of contemporary Q) the overall impact of forest conversion in the Mekong basin.

3.1.3 Scenario 2: the effect of the loss of critical high-biodiversity forest areas

Figure 4 shows the spatial distribution of increased annual Q relative to contemporary Q ($\Delta Q/Q$) from the Scenario 2 tropical forest conversion to agriculture. Aggregated across the pan-Tropics, the total increase Scenario 2 annual Q was less than 5% of contemporary Q (see Table 2), however the impacted areas were much more spatially focused than in Scenario 1. The highest annual yield increases ($\Delta Q/Q > 1$) are focused in southern China, western Mexico and the Yucatan peninsula, with more localized areas in Paraguay and Bolivia, and in Kenya. Like Scenario 1 (historical conversion), the largest impact is in the Indo-Malay realm, which has an increase of 411 km³/yr or 7.1% of contemporary Q. But unlike Scenario 1, the neo-Tropical realm (Central and South America) takes a close second, showing an increase of 294 km³/yr or 2.9% of contemporary Q. Because the areas targeted for conversion in Scenario 2 tend to be more spatially focused than in Scenario 1, the impact of hydrologic changes on human populations is potentially greater. Populations that reside along floodplains can be particularly vulnerable to changes that increase river flows. We developed a human vulnerability index (HVI) for assessing the potential hydrologic impact to floodplain populations (N_{imp}) from upstream deforestation, which we describe here briefly. See digital Appendix A for a more detailed description and a numerical example.

The change in runoff due to Scenario 2 deforestation in each gridcell (i) was converted to local yield ($\Delta Q_{loc\ i}$ = change in gridcell i runoff multiplied by grid cell i area) and then ΔQ_{loc} was summed along the digital river network (Fekete et al., 2001) resulting in an upstream accumulated change (ΔQ_{acc}) for each grid cell i. The relative contribution of $\Delta Q_{loc\ i}$ to downstream cells can be computed by dividing $\Delta Q_{loc\ i}$ by ΔQ_{acc} in each downstream grid cell, and summing the results for grid cell i and all grid cells downstream of cell i. An indicator of the number of people living on floodplains potentially affected by grid cell i (per unit ΔQ) was obtained by dividing the floodplain population (N_{fp}) in by ΔQ_{acc} and then summing in the downstream direction. The number of people impacted by ΔQ_{loc} in grid cell i ($N_{imp\ i}$) was then computed as :

$$\begin{aligned}
 N_{imp_i} &= \Delta Q_{loc_i} \cdot \frac{N_{fp_i}}{\Delta Q_{acc_i}} + \Delta Q_{loc_i} \cdot \frac{N_{fp_{i+1}}}{\Delta Q_{acc_{i+1}}} + \Delta Q_{loc_i} \cdot \frac{N_{fp_{i+2}}}{\Delta Q_{acc_{i+2}}} + \dots + \Delta Q_{loc_i} \cdot \frac{N_{fp_{mouth_i}}}{\Delta Q_{acc_{mouth}}} \\
 &= \Delta Q_{loc_i} \cdot \sum_{j=i}^{mouth} \frac{N_{fp_j}}{\Delta Q_{acc_j}}
 \end{aligned} \tag{1}$$

The HVI essentially maps the affected floodplain populations within a basin to deforested grid cells, based on the relative magnitude of hydrologic impacts within the basin. For two deforested grid cells, each with the same number of potentially affected people downstream of them, the grid cell with the higher ΔQ_{loc} relative to ΔQ_{cum} , would yield a higher number of impacted people due to a larger hydrologic disturbance. Because not all people living on floodplains are potentially impacted by upstream deforestation, total N_{imp} will always be less than or equal to total N_{fp} within a basin. . Although the units of the HVI are the same as population,

it does not quantify the exact number of people downstream of any single grid cell nor does it quantify the actual number of people that will be affected by a specified hydrologic event (i.e., a flood of a particular magnitude). However, we believe it offers insight into the potential “human cost” from the hydrologic effects of deforestation within each basin, as illustrated in Figure 5. Within the Ganges River basin, the grid cells that could have the greatest potential impact on downstream populations are those in which Scenario 2 forest conversion occurs along the southern edge of the Himalayan Mountains. As used here, the HVI does not allow for comparison of human vulnerability across basins; however, normalization methods are currently being tested for this purpose.

Table 3 summarizes the potential vulnerability of populations within and downstream of forest areas converted in Scenario 2 to increasing levels of hydrologic disturbance (in the form of $\Delta Q/Q$). Of the 3.6 billion people living in the pan-Tropics, about 1.6 billion (44%) live outside of areas affected by the targeted forest conversion, leaving about 2 billion people potentially affected to some degree by the Scenario 2 forest conversions. About 600 million of these people live on floodplains according to our delineation of floodplain populations (detailed in digital appendix A). Using a somewhat arbitrary threshold of a 25% increase in average annual Q (for this purpose, the total amount of water flowing through the cell, including accumulated upstream flows) as an indicator of potential threat, we delineated “hydrologic hotspots” as those grid cells where the ratio of increased Q to contemporary Q ($\Delta Q/Q$) was equal to or greater than 0.25 (or 25%). About 104 million people (approximately half of the total number of people living within the target areas) are potentially at risk from the effects in these “hydrologic hotspots”. More than three-quarters of these people (80 million) live on floodplains affected by these hotspots, which makes them particularly vulnerable to both immediate and long-term changes in the hydrologic regime due to Scenario 2 deforestation.

3.2 Biodiversity-Hydrology-Population Nexus

The pan-tropic assessment at 30' resolution, while limited in articulating the full dimension of hydrologic change and human vulnerability is nonetheless useful in expressing broad patterns of cause and potential effect. As noted previously, while the Scenario 2 forest conversion is strictly hypothetical, the intense human pressure on remaining forest tracks as well as the continuing need for agricultural land to feed ever increasing populations makes the results of this scenario both realistic and pertinent. The results of this analysis were combined to identify ‘priority’ basins that warrant future examination and protection. The spatial coincidence of four indicators (Table 4) was used to identify the priority basins shown in Figure 6. Again Southeast Asia, and in particular the Zhujiang, Menjiang, Chang Jang, Fuchun Jiang, Hanjiang, Menjiang and Hong basins of southern China, are identified as requiring more detailed study in linking forest conservation with maintenance of hydrological functions. Western Mexico shows a series of very small watersheds along the Pacific coast which were categorized as priority basins because of high vulnerability in terms of hydrology, biodiversity and populations. In South America, the Parana basin, which covers parts of Argentina, Paraguay and southern Brazil, received much of the projected deforestation in scenario 2 primarily due to the lack of protection and its vulnerability to future change. The small number of priority basins in Africa does not imply a lack of concern for basins in Africa; to highlight target basins in Africa it may be necessary to set a regionally derived $\Delta Q/Q$ threshold because of the larger size of river basins in much of tropical Africa. Within the priority basins shown in Figure 6, approximately 40 million

people are potentially at a higher risk from the effects of forest conversion in our so-called “hydrologic hotspots”.

4. Summary and Conclusions

This study was predicated on the existence of significant tracts of tropical forest that provide both havens of biodiversity richness and socially beneficial watershed services. The goal of this study was to identify the location and extent of such tracts within the tropics globally and to generate evidence of the nature and scale of the biodiversity and hydrological services they deliver, and to provide some sense of the importance of those services to the human populations they help support. We developed land cover surfaces to represent three important “snap shots” in time: 1) Original, based on the WWF Ecoregions of the World, which represented land cover prior to substantial alteration by human activities; 2) Contemporary, based on a combination of existing maps and classification schemes, which represented the state of land cover/land use in the mid-1990s; and 3) a ‘worst-case scenario’ future landcover, which was developed to represent the conversion of the most vulnerable tropical forest tracts to agriculture. We then evaluated the impacts to biodiversity, hydrology and human populations for two scenarios: Scenario 1 (historical land cover/land use change) and Scenario 2 (future conversion). Our key findings are summarized as follows.

- Assuming that the WWF Terrestrial Ecoregions of the World (Olson et al., 2001) map offers a reasonable estimation of land cover prior to substantial human alteration, the Earth was once home to 29 million km² of tropical forests, comprised of moist broadleaf (62%), dry broadleaf (31%) and tropical/subtropical coniferous forests (7%). Over 80% of the moist forests and nearly 60% of the dry forests were within areas classified as globally or regionally outstanding in terms of biological distinctiveness. By the mid-1990s, only half (15 million km²) of the original forests remained; approximately 32% of the original forests were directly converted to agriculture (most of which has occurred since 1950, according to Oyebande, 1988). While the magnitude of loss was near identical for both moist and dry forests, the fraction of dry forests lost (50%) was twice that of moist forest (22%). The future of the remaining tropical forest appears uncertain: 44% of the moist broadleaf forests, 64% of the dry forests and 78% of coniferous forests are classified as critical or endangered.
- Over the entire study area, the historical conversion of forests to agriculture (as of the mid-1990s) has yielded an approximate 10% increase in annual basin yield (a ratio of 1% water yield increase for every 3% forest area lost). The largest proportion of both forest conversion and increased yield has occurred in southeast Asia, where a 44% forest conversion has yielded a 23% increase in annual basin yield. Using a somewhat arbitrary threshold of a 25% increase in average annual discharge for delineating “hydrologic hotspots”, about 100 million people could be vulnerable to the hydrologic effects of our hypothetical but feasible future tropical forest conversion; 80 million of these people live on floodplains within or downstream of these hotspot areas.
- Southeast Asia, and in particular the Zhujiang, Menjiang, Chang Jang, Fuchun Jiang, Hanjiang, Menjiang and Hong basins of southern China, are identified as priority areas for further study with respect to the risk of loss due to changes in hydrological function and biological distinctiveness. Small watersheds along the western coast of Mexico were also highlighted as having increased vulnerability in terms of hydrology, biodiversity and populations. In South America, the Parana basin which covers parts of Argentina, Paraguay and southern Brazil contains several sites of interest as well. This basin received much of the

projected deforestation in scenario 2 primarily due to the lack of protection and its vulnerability to future change. As many as 40 million people could be vulnerable to the hydrologic impact of forest conversion in these target basins.

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Table 1: Comparison of the aggregate areas of land cover types and land use changes in Scenario 1. Original represents land cover prior to substantial exploitation from humans while contemporary represents the state of current land cover. The synthetic landcover was derived by overlaying shares of contemporary agricultural classes (rainfed and irrigated cropland and pastureland) onto the historic surface. This intermediate land cover surface was used for isolating the hydrologic signal resulting from the historical conversion of tropical forest to agricultural land uses.

	Original		Synthetic ¹		Contemporary		Scenario 1 Change ³	
	Area (000 sq km)	Share of total area (percent)	Area (000 sq km)	Share of total area (percent)	Area (000 sq km)	Share of total area (percent)	Area (000 sq km)	% (percent)
Coniferous forest	2,066	3.8	1132	2.1	350	0.6	-935	-45.2
Moist forest	18,299	33.3	14179	25.8	12,449	22.7	-4,121	-22.5
Dry forest	8,949	16.3	4485	8.2	2,107	3.8	-4,464	-49.9
Total Forest²	29,315	53.4	19,795	36.0	14,906	27.1	-9,519	-32.5
Savanna	15,078	27.5	15078	27.5	10,490	19.1	0	0.0
Grassland	1,456	2.7	1456	2.7	1,927	3.5	0	0.0
Other	9,076	16.5	9076	16.5	5,884	10.7	0	0.0
Agriculture / Urban	0	0.0	9519	17.3	21,719	39.5	9,519	
Total land cover	54,925	100.0	54,925	100.0	54,925	100.0		

¹ Synthetic contemporary is the agricultural classes from the Contemporary surface overlaid onto the Original landcover surface. The agriculture total includes both cropland and pasture.

²The Forest total includes all forest within the pantropic study area and is not limited to the forests within the tropical forest biomes.

Table 2: Changes in Annual Basin Yield for Scenario 1 (historical) and Scenario 2 (projected future), summarized by biome and realm.

	Original:	Original to Synthetic		Contemp:	Contemporary to	
	Annual Q	(Scenario 1)		Annual Q	Scenario 2	
	km ³ /yr	km ³ /yr	%	km ³ /yr	km ³ /yr	%
<i>Change in Q by Tropical Forest Biome</i>						
Tropical and Subtropical Moist Broadleaf Forest	12868	1478	11.5	15608	927	5.9
Tropical and Subtropical Dry Broadleaf Forest	613	322	52.4	1052	63	5.9
Tropical and Subtropical Coniferous Forest	280	19	0.0	242	19	7.7
Other Biomes	5876	196	3.3	5803	0	0.0
<i>Change in Q by Realm</i>						
Neotropical	9070	473	5.2	10086	294	2.9
Afrotropical	3922	393	10.0	4510	73	1.6
Indo-Malay	4428	1017	23.0	5765	411	7.1
Australasia	1271	118	9.3	1471	182	12.3
Other Realms (within study area)	947	13	1.4	873	49	5.6
Total	19638	2014	10.3	22705	1008	4.4

Table 3: Number of people (total population and those living on floodplains) exposed to increasing levels of hydrologic disturbance (in the form of increase annual discharge, Q) from Scenario 2.

dQ/Q	Total Pan-tropic Population (millions)	Percent of total (%)	Population on floodplains (millions)	Percent of total (%)
No change	1575.5	43.5	215.4	26.2
0 to 0.1	1529.1	42.2	381.0	46.4
0.10 to 0.25	411.3	11.4	144.6	17.6
0.25 to 0.50	78.4	2.2	56.6	6.9
0.50 to 1	17.8	0.5	8.8	1.1
>1	8.0	0.2	14.4	1.7
Total	3620.3		820.9	

Table 4: Criteria used to identify ‘priority’ basins shown in Figure 6 that warrant examination at a finer scale.

Variable	Criteria
Biological Distinctiveness Index (BDI)	Globally or regionally outstanding
Global Conservation Status	Critical or Endangered
Land cover	Forest areas within the tropical forest biomes
Change in annual yield relative to contemporary basin yield ($\Delta Q/Q$)	≥ 0.25
Downstream population	Downstream population as a percentage of the total population for the basin 1: 30-70%; 2: 15-30%; 3: 0-15%

Figure 1: Extent of tropical forest biomes pan-tropical modeling domain. The pan-tropical boundary includes river basins within which one of the three tropical forest biomes reside. River basin boundaries were determined using network topology (Vörösmarty et al. 2000 a,b) and contemporary runoff (Fekete et al. 2002).

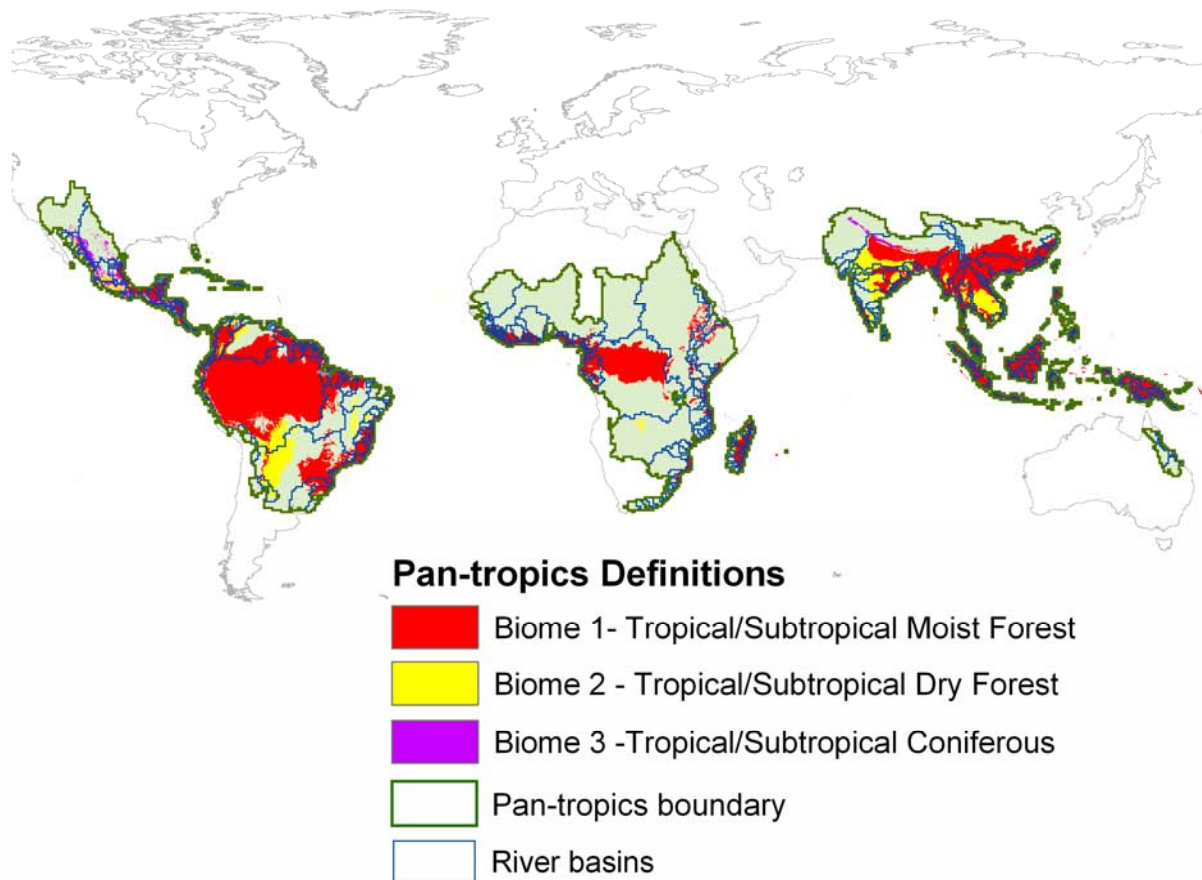


Figure 2: Relationship between ratio of increased runoff to annual rainfall ($\Delta RO:Rainfall$) to annual rainfall for individual grid cells (small symbols) and averaged over river basins (larger diamonds). Locations with average annual rainfall between 750 and 1800 mm/yr show a dramatically higher relative increase in runoff than those with rainfall > 1800 mm/yr.

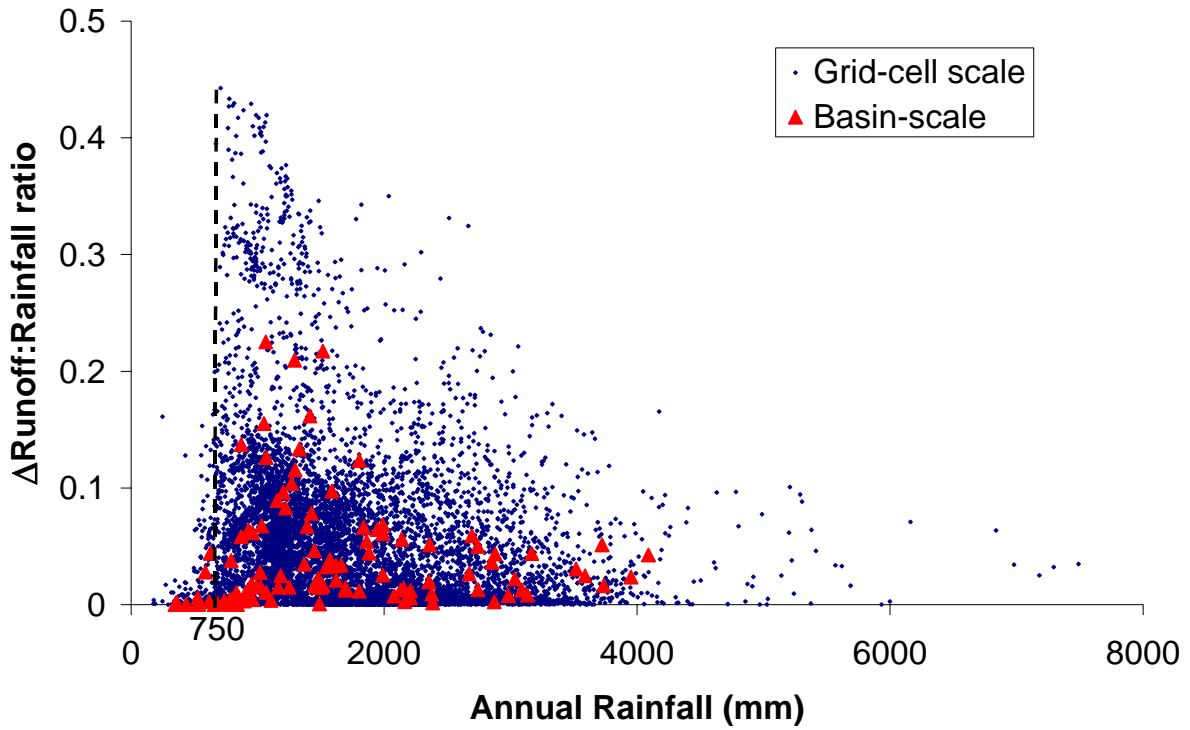


Figure 3: Propagation of hydrologic response (ratio of ΔQ to contemporary Q) from forest conversion along the mainstems of a) the Ganges and b) the Mekong river.

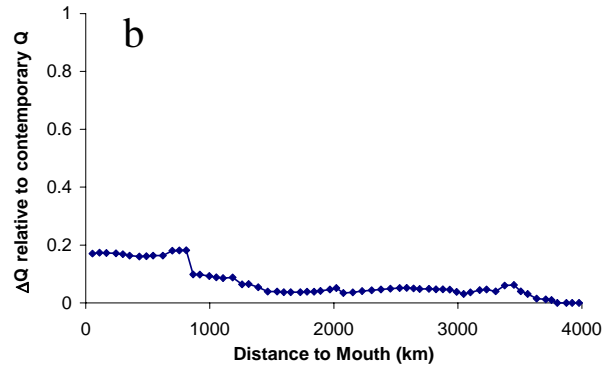
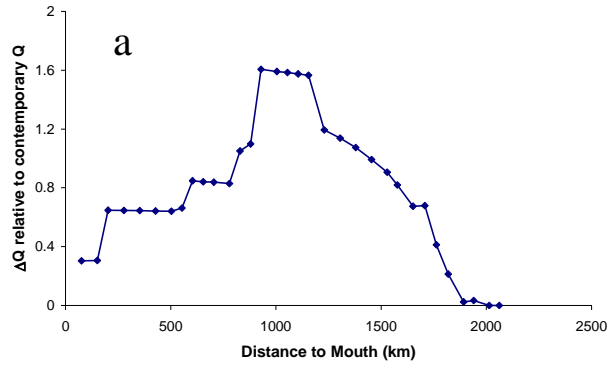


Figure 4: Change in annual discharge (ΔQ) as a fraction of contemporary Q for Scenario 2 (projected future forest conversions). Insert compares the changes in basin-average runoff between the two scenarios.

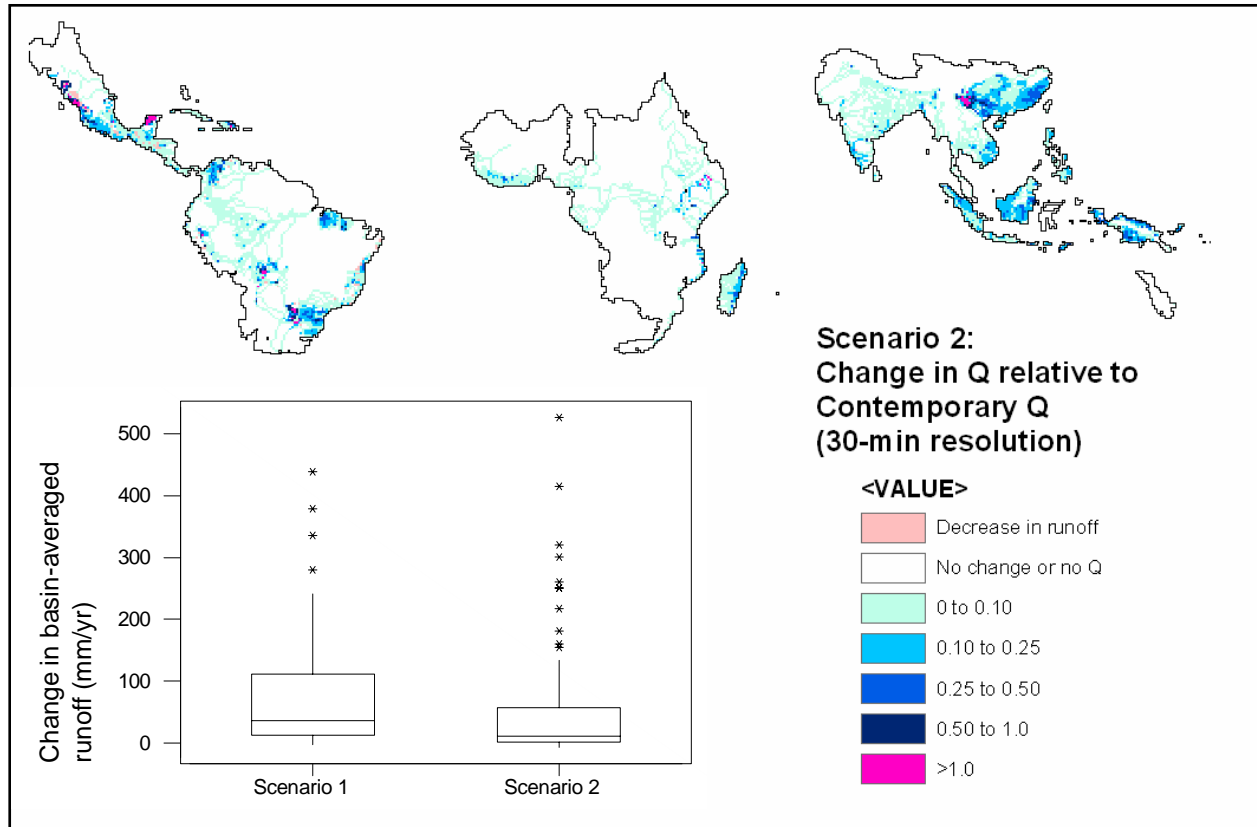


Figure 5: Example of downstream floodplain population exposed to Scenario 2 changes in annual basin Q in Southeast Asia. The total number of people living on floodplains downstream of a grid cell is weighted by the magnitude of the increase within that grid cell relative to the increase as it is accumulated along the flow network. In other words, if two grid cells had the same number of downstream population, the one with the greater increase in Q would be shown to affect a higher number of people.

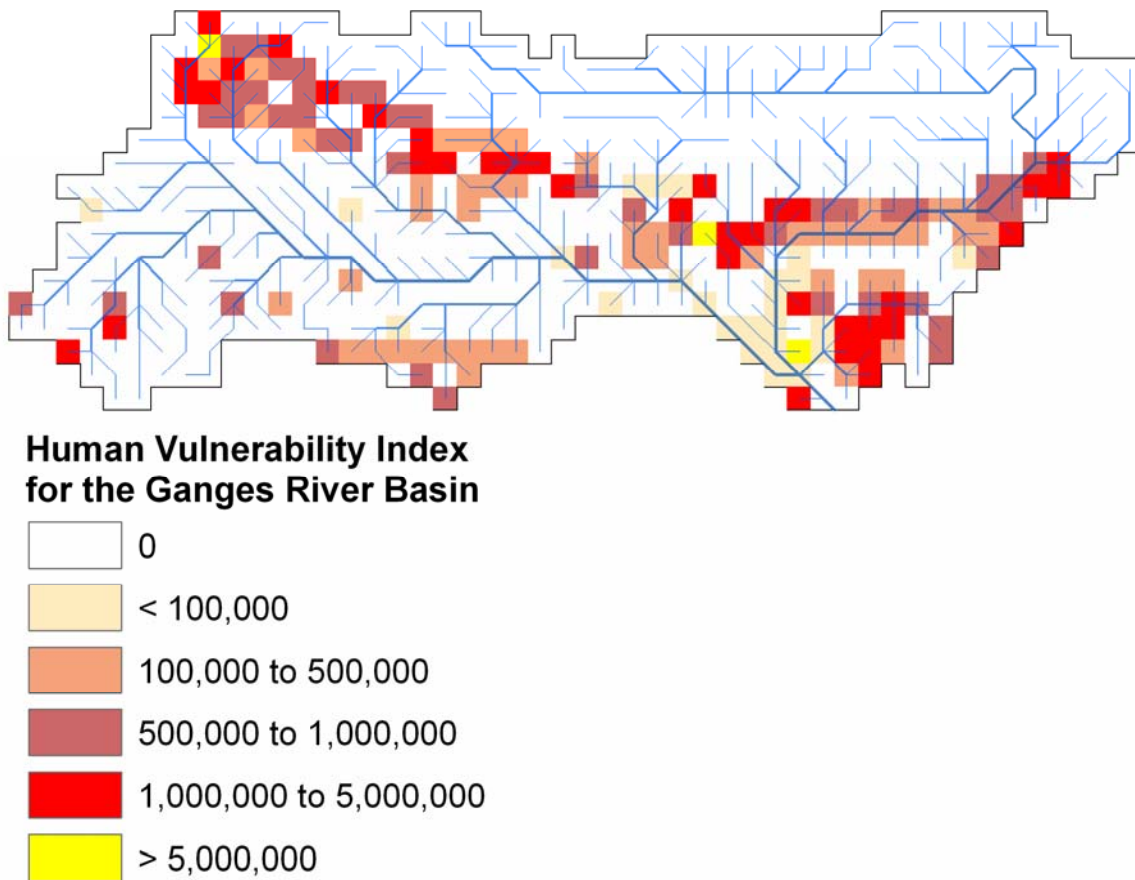


Figure 6: Locations of priority basins worthy of further study and future protection, as determined by the intersection of biodiversity, hydrologic impact and human vulnerability (described in Section 3.2).

