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REVIEW

Looking Beyond the Fenceline: Assessing Protection Gaps for the World's Rivers

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Abstract

Protected areas are a cornerstone strategy for terrestrial and increasingly marine biodiversity conservation, but their use for conserving inland waters has received comparatively scant attention. In 2010, the Convention on Biological Diversity (CBD) included a target of 17% protection for inland waters, yet there has been no meaningful way of measuring progress toward that target. Defining and evaluating "protection" is especially complicated for rivers because their integrity is intimately linked to impacts in their upstream catchments. A new generation of global hydrographic data now enables a high-resolution, standardized assessment of how upland activities may be propagated downstream. Here, we develop and apply, globally, a river protection metric that integrates both local and upstream catchment protection. We found that "integrated" river protection is highly variable across geographies and river size classes and in most basins falls short of the 17% CBD target. Around the world, about 70% of river reaches (by length) have no protected areas in their upstream catchments, and only 11.1% (by length) achieve full integrated protection. The average level of integrated protection is 13.5% globally, yet the majority of the world's largest basins show averages below 10%. Within basins, gaps are particularly severe for larger rivers.

Introduction

The world's inland waters—rivers, lakes, springs, ground waters, and wetlands—contain exceptional numbers of species, provide critical ecosystem services, and are among the most threatened ecosystems globally (Dudgeon et al. 2005; Balian et al. 2008; Vörösmarty et al. 2010). Protected area (PA) coverage, in this article defined as all nationally designated PAs listed by the International Union for Conservation of Nature (IUCN), has rapidly expanded around the world in the last half century, and evidence suggests that well-managed PAs can achieve biodiversity conservation goals (Geldmann et al. 2013). Yet, the extent to which PAs can and do benefit inland waters has been little examined, with global assessments focusing squarely on terrestrial and marine systems (Watson et al. 2014).

Measuring the protection of inland waters is of more than academic interest. In 2010, for the first time, the Convention on Biological Diversity's (CBD) PA target (Aichi Target 11) required that "at least 17 percent of terrestrial and inland water areas ... are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas ..." (Convention on Biological Diversity 2010). Even putting aside the important qualifiers of management, representation, and connectivity, 6 years on there remains no globally comprehensive gap analysis of inland waters to provide information on where the numeric 17% target is unmet.

The extent to which existing PAs may protect inland waters has been poorly known due in large part to a lack of accurate, comprehensive spatial datasets of freshwater systems. One study has put coverage of lakes by PAs at

less than 2%, but spatial lake datasets have been unreliable for some parts of the world, and lakes comprise only one type of inland water (Chape *et al.* 2003). The Millennium Ecosystem Assessment (Finlayson & D'Cruz 2005) calculated that 12% of the world's freshwaters were included in PAs by overlaying PA polygons with inland water categories of the Digital Chart of the World. This simple overlay analysis confirmed only that freshwaters had not been intentionally excluded from PAs.

Evaluating the extent of river protection has been attempted in the past (e.g., Nel *et al.* 2007; Sowa *et al.* 2007; Stein & Nevill 2011) but has proven especially difficult as hydrologic flows, which originate upstream, are of critical importance for defining the connectivity, character, and integrity of rivers (Poff *et al.* 1997). In fact, it is a core feature of fluvial systems that they are shaped and affected not only by local circumstances but also by conditions in their oftentimes remote upland areas (Johnson & Host 2010). For large-scale assessments, a second challenge is posed by the requirement of adequate information regarding river networks and analytical tools to trace their connectivity. This challenge, however, has recently been addressed in the creation of new data and modeling frameworks. In particular, the HydroSHEDS database (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) now provides maps of the world's rivers at a high spatial resolution (500 m) and with associated information such as upstream topology and streamflow quantities, which enables complex analyses along river networks (Lehner & Grill 2013).

By overlaying the river and catchment information of HydroSHEDS with the World Database of Protected Areas (IUCN & UNEP-WCMC 2014), we calculated the extent to which rivers are captured within existing PAs ("local protection"), as well as the degree of upland protection for each river reach. Using this information, we propose a novel "integrated protection" metric that combines both local and upland river protection. While this first-of-its-kind metric does not encompass management effectiveness, it does offer a step toward assessing where protection gaps exist.

Methods

Data

We used the HydroSHEDS database (Lehner *et al.* 2008; Lehner & Grill 2013) to provide a consistent global river network at 15 arc-second spatial resolution (approximately 500 m pixel resolution at the equator). HydroSHEDS includes an estimate of long-term average "naturalized" discharge, derived by downscaling coarse-resolution (0.5°) discharge estimates of the global hydro-

logical WaterGAP model (Döll *et al.* 2003; model version 2.2 as of 2014). We assessed all river reaches—defined as stretches of rivers between consecutive tributaries—with a minimum average discharge of 100 l/second (0.1 m³/second). The resulting dataset encompasses 6.3 million reaches worldwide with an average length of 3.9 km each, amounting to a total of 24.3 million river kilometers. Smaller rivers have been excluded from the analysis, primarily due to increasing uncertainties in the underpinning global hydrographic and streamflow data.

We used all nationally designated PAs (DESIG_TYPE = "national"; STATUS = "designated") of all IUCN categories (IUCN_CAT = "I-VI," "not reported," or "not assigned") from the October 2014 World Database on Protected Areas (IUCN & UNEP-WCMC 2014) as our source data to describe the coverage of protected land surface areas globally (~160,000 polygons representing 19.2 million km^2, or 14.3% of the total global land surface area, excluding Antarctica). In cases where PA sites were only given as point data (~17,000 points representing 1.1 million km^2), we approximated their spatial extent as a circle with a size representing the reported area.

River protection metrics

The network topology of rivers means that upstream and downstream reaches are inherently connected and that local conditions may be influenced by upstream and upland activities. An assessment of a river reach's protection must therefore look both at local protection (whether a reach falls within a PA) and the degree of landscape protection within a reach's upstream catchment.

We propose a four-tiered approach to define the protection status of a river by calculating: (1) "local protection," which refers to all river reaches that lie within PAs; (2) "upland protection," which measures the percentage of protection of the upstream catchment area associated with each river reach; (3) "achieved target protection," which determines the deviation from a proposed upland protection threshold that represents sufficient protection; and (4) "integrated protection," which combines the requirement of local protection and achieved target protection.

Local protection

To determine local protection, we analyzed whether a river reach falls within a PA and assigned a binary protection status (0% or 100%). Reaches that cross PA borders were first split to allow for partial accounting. It is not uncommon to find rivers flowing along PA borders as they may be used to delimit the PA boundaries. We chose to consider these rivers as being inside PAs. However, the

Target upland catchment protection and measurement of protection shortfall

Figure 1 Calculation of "achieved target protection." Once an area-based target line has been defined (blue line), every individual river reach can be assessed as to how far it deviates from the target (based on its individual values for "upland protection" and catchment area). For example, a reach with an upland area of 10,000 km^2 of which 30% is protected achieves 50% of its protection target. Reaches that exceed the target line (anywhere in the blue area) are defined to achieve 100% of their protection target.
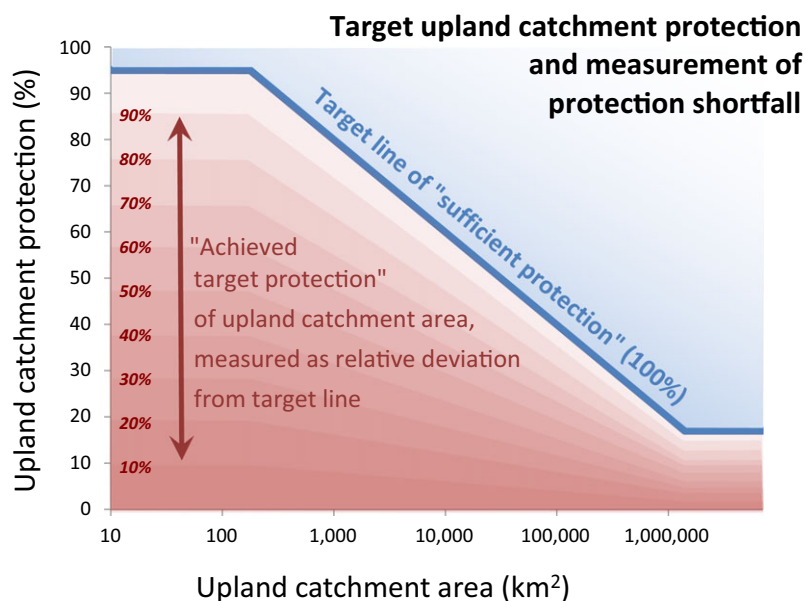
correct detection of boundary rivers is difficult as even small spatial inaccuracies inherent in the underpinning maps can lead to significant misalignments between river lines and PA polygons. To minimize errors, we added a 500 m buffer around all PAs before conducting the assessment as 500 m represents the spatial precision of the river network.

Upland protection

Using catchment delineations from the HydroSHEDS database, we quantified "upland protection" for each river reach as the percentage of PA coverage within the associated upstream catchment of the reach (0–100%). Following a particular river course from its headwaters to the ocean outlet, total upland protection can increase along the river network at confluences where tributaries with high protection ratios join, or it can decrease where tributaries with low levels of protection merge.

Achieved target protection

While "upland protection" provides a first-order proxy to characterize the degree of overall protection within a basin, the interpretation of this indicator is highly scale-dependent. For small headwater catchments, it has been shown that as little as 2% land cover change may affect the ecological status of small streams (Schueler *et al.* 2009; Cuffney *et al.* 2010). Thus, 100% upland protection is desirable and achievable for headwaters by putting the entire catchment under protection.

For larger scales, the correlation between spatial extent of PAs and its effect on aquatic ecology is less well studied. There is currently no scientifically derived minimum threshold that could be applied to all large basins globally, yet 100% upland protection is clearly unrealistic for the largest of rivers with millions of square kilometers in upstream area. While the CBD target of a minimum 17% coverage, derived through policy negotiations, could serve as an interim lower limit, considerably higher protection levels may be needed to achieve broad conservation goals (Woodley *et al.* 2012; Butchart *et al.* 2015).

In the absence of more robust research, we here propose a sliding upland protection target by defining an area-based threshold line below which upland protection is considered increasingly insufficient. We derive this threshold line (Figure 1) as a piecewise function by setting upper and lower boundary conditions, two inflection points, and a logarithmic transition in between:

(1) We propose that the entire catchments of headwater streams should be protected; and we define headwater catchments as those below 100 km^2 in size. However, to accommodate minor land cover changes that may be considered acceptable, and to cover small spatial uncertainties in defining the boundaries of catchments and PAs, we set a target of 95% to provide "sufficient" upland protection.

(2) We propose that even the largest basins worldwide (e.g., the Amazon with approximately 6 million km^2) should reach at least 17% upland protection, as this value represents the minimum requirement for inland water protection according to the CBD.
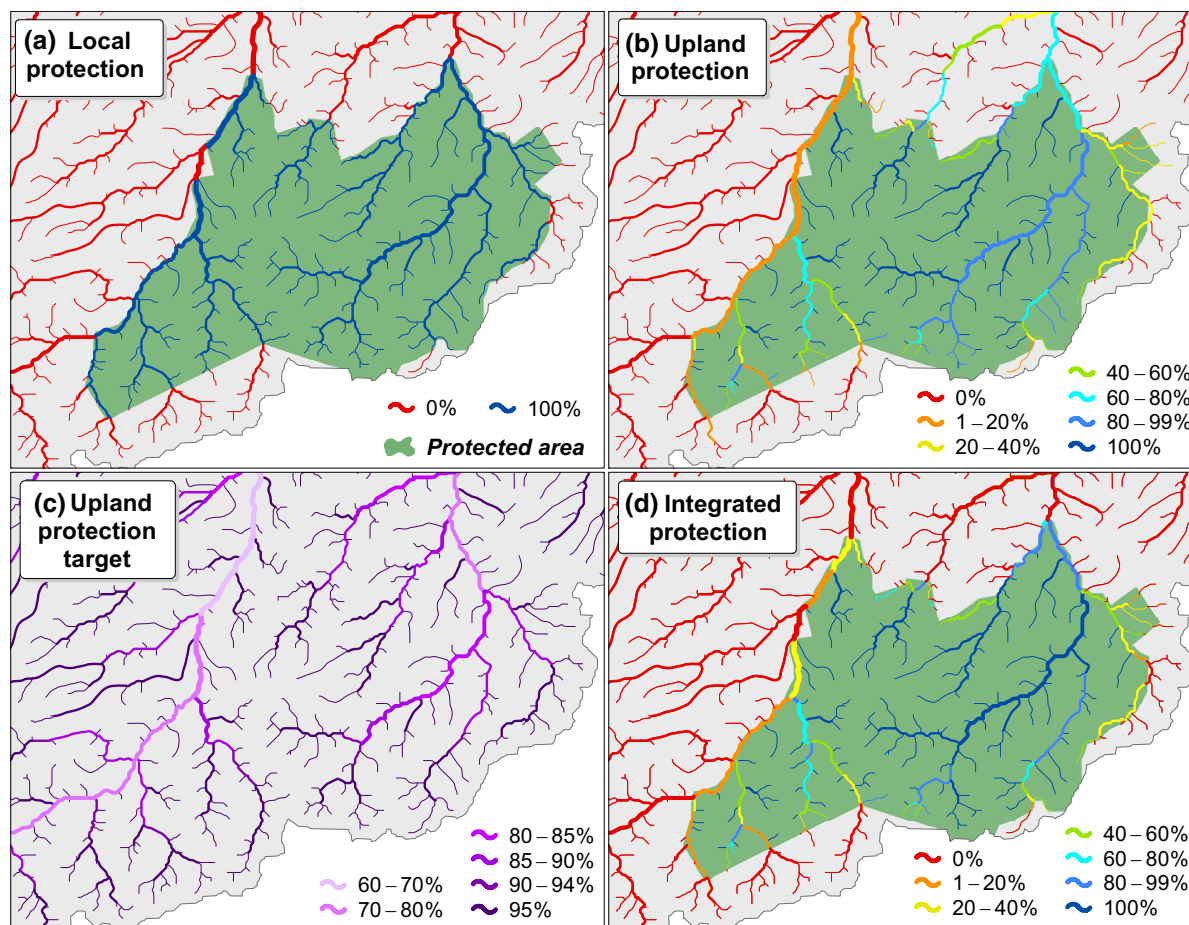
Figure 2 Conceptual approach of local versus integrated protection. Local protection (a) only distinguishes between 0% and 100% protection for each river reach. Upland protection (b) measures the percentage of protected area within the upstream catchment of each reach (0–100%). The upland protection target (c) assigns an area-based threshold of "sufficient protection" to each reach (17–95%). And finally, integrated protection (d) relates the upland protection of each reach to its protection target (0–100%). Reaches outside the protected area are considered unprotected (0%) in both local and integrated approaches. By design, integrated protection is equal or lower than local protection, and equal or higher than upland protection within the protected area.

(3) For a transition between these two boundaries, we propose a logarithmic decline in minimum upland protection targets. The proposed line is drawn in Figure 1 from 100% protection for a catchment size of 100 km^2 to 20% for a catchment size of 1 million km^2; thus, the protection target declines by 20% for each order of magnitude in catchment size, with the curve leveling off at 17%.

We consider basins below the target line to lack comprehensive protection because of the risk of significant impacts from modifications in the unprotected upstream catchment area. This risk grows proportionally with the deviation from the target line. We can quantify this deviation by calculating the "achieved target protection" of a river reach as the ratio (0–100%) between its actual upland protection and the assigned upland protection target, which depends on the reach's individual catchment size. All reaches that meet or exceed the line of sufficient upland protection receive a value of 100%.

Integrated protection

Finally, we propose an "integrated protection" metric as a double-criteria index assuming that true protection of a river requires that it lies within a PA (local protection) and that its upstream catchment is under some degree of protection as well (achieved target protection). The index is calculated at a reach level by applying the achieved target protection ratio to each river reach inside PAs (see Figure 2). In this approach, full (100%) integrated protection of a river reach is only achieved if the reach is

(1) locally protected and (2) meets or exceeds its area-based target of sufficient upland protection. Reaches that fall inside PAs but have less than sufficient portions of their upstream catchment protected achieve only partial (0–100%) integrated protection. Reaches outside PAs are considered unprotected (0%), even if some of their upland catchment is protected.

Like other traditional gap assessments, these metrics make no assumptions about the effectiveness of protection afforded to the upstream catchment or to the river reach. As such, they may be considered to represent maximum potential protection rather than actual protection.

Calculation and comparison of protection levels for different regions and river size classes

Based on the definitions above, we determined all four indices (local protection, upland protection, achieved target protection, and integrated protection) for each river reach globally. We then summarized the two main indices of local and integrated protection for a variety of spatial units: globally, by continent, for a selection of large river basins, and for six river size classes based on orders of flow magnitude (defined by logarithmic scaling of the long-term average discharge). The average local and integrated protection levels of a spatial unit (e.g., a basin or streamflow size class) were calculated as the average protection ratios of all reaches constituting the spatial unit, weighted by their individual reach lengths.

As the local protection ratio of a river reach is binary (either 0% or 100%), the resulting average local protection of the spatial unit (in %) automatically represents the length of rivers (in %) that are inside PAs. The average integrated protection level, however, is more complex to interpret: an average integrated protection of 40% may indicate that 40% of all rivers (by length) are inside PAs and all of them achieved 100% of their upland protection target; or that 80% of rivers are inside PAs yet they only achieved 50% of their upland protection target; or any other combination of local and achieved target protection that leads to the same average protection level. Given this complexity, measures of "average integrated protection" should only be interpreted as a general index of global, continental, or basin-wide riverine protection.

Results

Globally, 16.0% of the length of rivers are within PAs or form their borders and are therefore considered locally protected. There are, however, wide geographic disparities in local protection (Table 1 and Figure 3a) ranging from very high in the Amazon Basin (44.2%), which

alone contains 8.4% of global river length, to very low in the Euphrates-Tigris (1.4%).

In terms of upland protection, we found that 69.5% of rivers around the world (by length) have no PAs in their upstream catchments. While the remaining 30.5% of rivers have at least some kind of upland protection, this level varies between 0.1% and 100%. Only 10.9% of rivers (by length)—mostly smaller headwater streams with catchment areas of less than 100 km^2 and average flows below 1 m^3/second—achieve an upland protection of 95% or above. Including these headwater streams, a total of 11.5% of global river length meets or exceeds our defined target threshold of sufficient upland protection.

Combining local and achieved target protection, we found that 11.1% of global rivers (by length) are located within PAs and meet or exceed our defined protection target, i.e., the associated river reaches are under full integrated protection as defined by our proposed threshold line. When rolling up the results into different spatial units, the global average of integrated river protection is found to be 13.5% (Table 1). Results are substantially lower in many basins (Figure 3b), and within basins there can be high variation among river size classes (Table 1 and Figure 4). Small rivers show the highest averages of integrated protection, at around 14% globally. Medium to large rivers tend to be less well protected.

At the regional level, South America has by far the highest proportion of rivers under local and integrated protection (Table 1), yet the overwhelming influence of the Amazon on this result is apparent (Figures 3 and 4). The Middle East, Europe, and Asia, on the other hand, all have average levels of integrated protection below 10%.

Integrated river protection is, by definition, lower than local protection, and the discrepancy can reveal the appropriateness of PA design for inland water systems (Table 1). Europe, for instance, shows an especially high divergence between local (13.1%) and integrated (8.3%) protection levels, suggesting that many river reaches lie within PAs but lack sufficient headwater protection. At the basin scale, differences are even starker. For example, while local river protection in Australia's Murray-Darling Basin is 8.1%, integrated protection is much lower at only 3.5%. The spatial arrangement of PAs in the Mississippi Basin is similarly inadequate, with only 1.9% of integrated protection achieved basin-wide despite 5.6% of local protection.

When stratified by flow quantities, local protection of the world's rivers is roughly equally distributed among river size classes (Figure 4). Slightly lower levels are observed for larger rivers (>1,000 m^3/second), which may be due to higher degrees of anthropogenic pressures around them, making PA designation more challenging. For smaller streams, average integrated protection is

Table 1 Average local versus integrated protection levels (%) calculated globally, by continent, and for a selection of large river basins. Asia excludes European part of Russia; North America includes Central America and the Caribbean.

| Spatial unit	Total protection	By streamflow size (m³/second)					
		0.1–1	1–10	10–100	100–1,000	1,000–10,000	> 10,000
Global	*Local*	*15.5*	*16.8*	*16.9*	*16.7*	*15.2*	*11.6*
	Integrated	**13.9**	**13.8**	**11.2**	**9.8**	**9.5**	**9.6**
	16.0 / **13.5**						
Africa	*Local*	*13.9*	*13.1*	*15.4*	*14.3*	*7.3*	*0.0*
	Integrated	**12.3**	**9.6**	**8.1**	**7.2**	**4.9**	**0.0**
	13.8 / **11.2**						
Asia	*Local*	*11.0*	*10.7*	*10.6*	*8.3*	*7.5*	*7.1*
	Integrated	**9.7**	**8.3**	**6.2**	**3.7**	**3.1**	**4.6**
	10.8 / **8.9**						
Australia	*Local*	*14.4*	*14.9*	*15.3*	*12.5*	*12.7*	
	Integrated	**12.5**	**12.1**	**10.4**	**6.9**	**9.5**	
	14.6 / **12.1**						
Europe	*Local*	*12.2*	*14.3*	*15.0*	*17.6*	*18.8*	
	Integrated	**8.7**	**8.1**	**6.1**	**5.9**	**8.9**	
	13.1 / **8.3**						
Middle East	*Local*	*9.8*	*7.6*	*6.0*	*7.3*	*0.0*	
	Integrated	**8.6**	**6.0**	**1.8**	**0.6**	**0.0**	
	9.2 / **7.6**						
North America	*Local*	*12.9*	*14.5*	*15.0*	*14.8*	*15.3*	*9.2*
	Integrated	**11.1**	**11.4**	**8.7**	**5.8**	**6.3**	**3.3**
	13.5 / **10.8**						
South America	*Local*	*28.8*	*30.4*	*29.5*	*30.5*	*27.3*	*17.6*
	Integrated	**27.8**	**28.4**	**25.3**	**24.2**	**20.5**	**16.2**
	29.3 / **27.5**						
Amazon	*Local*	*44.7*	*44.1*	*44.8*	*43.9*	*33.5*	*18.4*
	Integrated	**43.8**	**42.3**	**40.1**	**37.3**	**27.9**	**17.4**
	44.2 / **42.5**						
Yukon	*Local*	*33.2*	*34.2*	*36.1*	*19.5*	*29.0*	
	Integrated	**31.3**	**30.2**	**27.1**	**15.9**	**23.0**	
	33.2 / **30.2**						
Zambezi	*Local*	*25.7*	*23.3*	*28.4*	*37.1*	*30.6*	
	Integrated	**23.2**	**17.5**	**14.9**	**26.9**	**26.8**	
	25.7 / **21.5**						
Mekong	*Local*	*18.3*	*18.0*	*17.8*	*14.7*	*11.3*	*0.0*
	Integrated	**17.1**	**15.6**	**12.4**	**7.9**	**8.8**	**0.0**
	17.9 / **15.8**						
Danube	*Local*	*13.4*	*15.6*	*16.5*	*28.9*	*31.4*	
	Integrated	**9.3**	**8.8**	**7.7**	**10.2**	**18.1**	
	14.9 / **9.2**						
Yangtze	*Local*	*16.0*	*13.5*	*12.3*	*12.1*	*10.4*	*8.7*
	Integrated	**14.5**	**10.7**	**8.3**	**8.3**	**4.5**	**8.7**
	14.7 / **12.6**						
Colorado	*Local*	*14.1*	*13.7*	*13.3*	*38.1*		
	Integrated	**8.1**	**4.2**	**3.3**	**13.0**		
	14.9 / **7.2**						
Congo	*Local*	*11.6*	*10.7*	*13.3*	*11.5*	*0.7*	*0.0*
	Integrated	**11.0**	**9.4**	**8.7**	**6.2**	**0.0**	**0.0**
	11.4 / **10.1**						
Niger	*Local*	*10.6*	*10.9*	*15.1*	*7.0*	*0.8*	
	Integrated	**8.9**	**6.3**	**6.1**	**2.1**	**0.5**	
	10.8 / **7.9**						
Amur	*Local*	*9.5*	*10.3*	*15.3*	*9.3*	*6.1*	*1.5*
	Integrated	**7.7**	**6.1**	**5.4**	**2.0**	**2.7**	**0.9**
	10.1 / **7.0**						
Volga	*Local*	*7.4*	*9.1*	*12.2*	*7.6*	*11.5*	
	Integrated	**4.7**	**3.2**	**2.4**	**1.0**	**3.3**	
	8.2 / **4.1**						
Murray-Darling	*Local*	*6.0*	*8.4*	*11.6*	*35.8*		
	Integrated	**3.4**	**3.1**	**2.5**	**10.1**		
	8.1 / **3.5**						
Rio Grande	*Local*	*5.1*	*7.5*	*7.4*	*23.3*		
	Integrated	**3.4**	**3.2**	**1.4**	**5.8**		
	6.1 / **3.3**						
Orange	*Local*	*4.1*	*6.1*	*14.7*	*12.2*		
	Integrated	**1.8**	**1.2**	**1.8**	**1.9**		
	5.7 / **1.7**						
Mississippi	*Local*	*4.6*	*5.7*	*9.3*	*13.9*	*15.2*	*1.2*
	Integrated	**2.1**	**1.5**	**1.1**	**1.4**	**2.5**	**0.2**
	5.6 / **1.9**						
Euphrates-Tigris	*Local*	*1.3*	*0.8*	*2.7*	*4.7*	*0.0*	
	Integrated	**1.1**	**0.6**	**0.3**	**0.4**	**0.0**	
	1.4 / **0.9**						
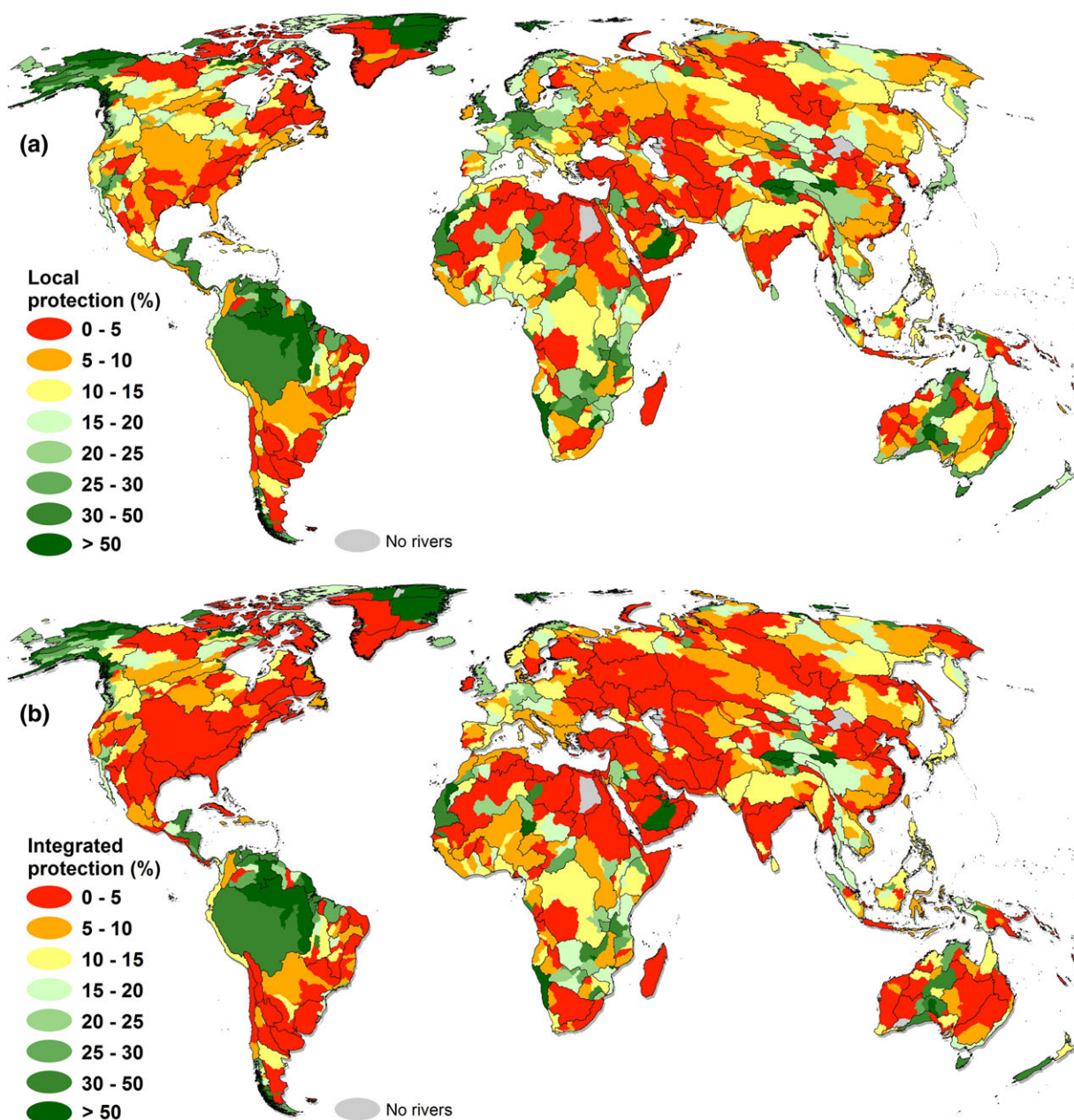
Figure 3 Global pattern of (a) local and (b) integrated river protection. High protection in river-rich areas is found in the Amazon Basin and in Alaska. Integrated protection levels are visibly lower in many places, e.g., in the Mississippi Basin and most parts of Europe. Figure shows a breakdown into subbasins of approximately 100,000 km^2 in average size, as well as black outlines for major basins.

similar to local protection levels, as local and upland protection are mostly coinciding in the associated smaller headwater catchments. Average integrated protection of the largest river class also tends to mirror local protection; this finding indicates that our chosen target of "sufficient upland protection" is often approached or exceeded and local protection represents the limiting factor. Mid-sized rivers (defined here as 10–10,000 m^3/second), however,

deviate the most between local and integrated protection; they are thus of high priority for improving the spatial alignment of local and upland protection.

The example of the Mississippi Basin given in Figure 4 reveals big discrepancies between local and integrated protection across size classes; the smaller headwater streams are not well protected and this limitation is propagated downstream to affect larger rivers,
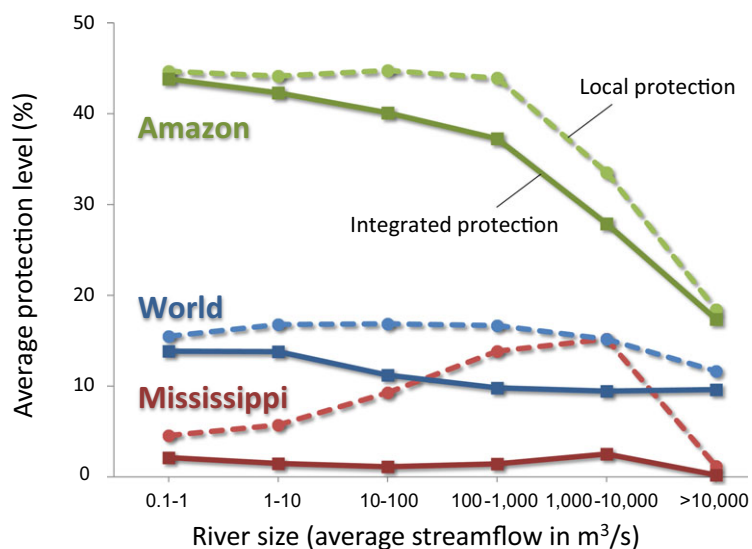
Figure 4 Local versus integrated protection for rivers of different streamflow sizes (flow values represent long-term averages). The global distribution shows that integrated protection is significantly lower than local protection, in particular for middle- to large-sized rivers.

which show increasing local protection while their integrated protection remains small. The Amazon Basin is an example of high protection, both locally and integrated, although the largest rivers remain less well protected.

To gain some insights into the sensitivity of the results regarding the chosen shape of the target line (Figure 1), we tested the effect of shifting the line by an entire order of magnitude to the left (i.e., making the target easier to achieve). As a result, the global average of integrated protection increased by only 0.3%, with the strongest increase of 2.3% found for larger rivers (1,000–10,000 m^3/second). Based on this finding, we conclude that the general approach is fairly robust and not highly susceptible to the chosen inflection points of the target line. We recognize, however, that results for larger rivers are sensitive to the definition of the lower boundary (here set at the CBD target of 17%).

Discussion

This study represents the first comprehensive assessment of the extent of integrated river protection worldwide. Not only is local (i.e., traditional) protection accounted for, but each river segment is also evaluated in the context of its landscape position. Our results of integrated river protection suggest that even if all existing PAs were well managed to conserve riverine targets inside them, many of the world's rivers are poorly protected in their respective upland areas. Average integrated protection levels remain significantly below the CBD's 17% target when assessed globally, regionally, and by streamflow size class.

We have also produced traditional protection results (inside PAs) that can be used for comparisons with similar analyses for terrestrial and marine systems. We find that globally 16.0% of the length of river reaches with an average flow of at least 100 l/second are located within or along the border of PAs, suggesting that local river protection is higher than protection in both terrestrial (14.3%) and marine (3.2%) realms (our own calculations using the same PA coverage). The slight exceedance over the terrestrial value is indicative of global PA distribution being biased toward areas with higher river density as compared to deserts. When our new measure of integrated protection is applied, the global average of river protection drops to 13.5%, i.e., below terrestrial protection, due to locally protected rivers with insufficient upland protection. Only 11.1% of all rivers (by length) are under full integrated protection.

Parsed by region, the results tell a more differentiated story. Unsurprisingly, the patterns for rivers across geographic regions mirror those seen in terrestrial gap analyses, with hotspots of low protection in the Middle East, parts of Central and South Asia, North America, southern South America, northern Africa, and parts of Australia. Given that riverine protection gaps are as important to address as those for terrestrial and marine systems, new or expanded PAs in underprotected regions should be designed with a landscape view of the river network and associated species and ecosystems (Abell *et al.* 2011; Hermoso *et al.* 2015).

Globally, smaller headwater streams dominate (by length) the world's running waters. These streams provide important sources of water, sediments, and biota (Meyer *et al.* 2007; Clarke *et al.* 2008) and thus are

vitally in need of comprehensive protection (Freeman *et al.* 2007). We found that smaller headwater streams in many basins have levels of integrated protection below the CBD's 17% target; this is a worrying gap, but also one that might be addressed more easily than similar gaps for larger systems. The lack of integrated protection of mid-sized to large rivers, on the other hand, raises concerns about the representativeness of different habitat types within PA networks (Linke *et al.* 2011).

Significant improvements in PA design could be achieved by designating as new PAs those unprotected headwaters that sit upstream of existing PAs. Alternately, where headwaters are already well protected, they may provide some degree of downstream protection even when no local PA exists there. In fact, these locations may offer a primary avenue for optimizing PA networks by adding downstream PAs for river corridors that already exceed the upland protection target. Our approach can highlight where strategic planning for upstream protection (Linke *et al.* 2007; Moilanen *et al.* 2008) and systematic approaches to catchment zoning (Abell *et al.* 2007; Nel *et al.* 2011) have the most potential to improve the condition of rivers and other inland waters.

While this study provides proof-of-concept of the suggested approach, both technical and methodological challenges remain. Our accounting of local and upland protection hinges on the quality of both the World Database on Protected Areas and the underpinning hydrographic data. We believe, however, that these technical issues are less problematic than the uncertainties introduced by the definitions and decisions required for the gap assessment. For example, it remains conceptually ambiguous whether to consider a river at the boundary of a PA as being locally protected or not.

We also acknowledge that there is a lack of existing evidence of successful river protection for testing the shape and inflection points of our proposed target line of "sufficient protection," yet we consider it a reasonable placeholder until such evidence emerges. We recognize that local geomorphological characteristics, hydrological connectivity, species distribution ranges, or varying runoff contribution can render some areas of a catchment more important than others, and optimized protection should focus on these critical landscape and ecological elements rather than relying on generalized percentage thresholds (Higgins 2003). As well, to the extent that PAs serve to mitigate riverine impacts originating outside PA boundaries, issues of size and configuration will be tied to the scale and intensity of those impacts. However, the required level of catchment protection remains a largely unresolved question (Gergel *et al.* 2002). Our sliding target line, based on increasing upland area, is intended to

integrate some of these scale issues, but as a global approach it can only cover broad patterns.

To provide stronger support for the validity of our approach and the chosen settings, it is of paramount importance to improve the monitoring of actual effects of PAs on ecosystem and hydrological integrity both locally and downstream. Depending on the outcomes, the method and settings should be adjusted accordingly. As for now, there is ample evidence that the proposed target line is already met or exceeded today in many river basins and throughout all streamflow size classes worldwide, demonstrating its general achievability.

As noted in our results, global figures mask regional and basin-level trends, with a significant bias due to the Amazon's very high protection levels (44.2% local protection and 42.5% integrated protection). A large proportion of the Amazon's PA network is composed of IUCN Category VI reserves, designed to "conserve ecosystems and habitats, together with associated cultural values and traditional natural resource management systems" (Dudley 2008). There is a history of debate around whether such reserves qualify as "true" PAs due to the range of activities allowed within them (Dudley *et al.* 2010). We included them in our analysis to be consistent with terrestrial accounting systems (Watson *et al.* 2014). Studies into how well each of the PA categories confers protection to inland waters both within their boundaries and downstream would be a valuable research direction.

In the meantime, protection results should be interpreted cautiously, given the focus of the gap assessment on extent of coverage and our inability to evaluate management effectiveness. Permitted developments in PAs of less strict protection may compromise the health of a river, yet a well-managed category VI PA may still provide better protection to inland waters than a poorly managed category III or IV PA. In general, we know that many PAs are not managed with riverine systems in mind, so the conservation picture is undoubtedly worse than our results suggest (Thieme *et al.* 2012). The location of threats relative to PAs may be a larger driver of the status of ecosystems within the PA than the proportion of upstream basin under protection. On the other hand, in the increasingly few remote areas of the world, such as many of the Amazon's headwaters, *de facto* protection of inland waters may occur without the presence of formal PAs at all (Joppa *et al.* 2008).

Conclusions

We have demonstrated that our proposed indicator of "integrated river protection" is a viable alternative to the

traditional "within the fenceline" approach to gap assessments, in which systems are counted as protected or not based on whether they fall within PA boundaries. This binary approach is clearly inadequate for inland water systems, which sit at the lowest points in their landscapes and integrate hydrologically mediated impacts from their catchments. Because rivers are shaped by these complex processes, PAs alone will rarely ensure their conservation, but with effective design and management they can make important contributions. Identifying gaps in the extent of river protection is a first step, and we believe that our indicator can illuminate gaps from the small scale of individual subbasins to any aggregated ecological or political unit.

If our approach is adopted as an improvement over current indicators, or receives consideration by the CBD-mandated Biodiversity Indicators Partnership, we propose that a next-generation indicator be explored that incorporates other inland water types as well. To account for the effectiveness of protection, additional work could be pursued to combine the gap assessment with information on existing anthropogenic disturbances, ranging from dam construction to aquatic pollution. Some of this information is readily available at a global scale and could be used to assess how different types of upland activities (such as hydropower development, mining, or timber harvesting) may compromise the protection status of rivers. Regardless, we strongly believe that the proposed indicator method of measuring the extent of integrated protection can elevate the profile of inland waters within PA discussions and, consequently, take accounting of the protection of these systems to a higher level.

Acknowledgments

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