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Original research article

Mapping potential freshwater services, and their representation within Protected Areas (PAs), under conditions of sparse data. Pilot implementation for Cambodia

Leonardo Sáenz[a,*], Tracy Farrell[b], Annette Olsson[c], Will Turner[a], Mark Mulligan[d], Natalia Acero[a], Rachel Neugarten[a], Max Wright[a], Madeleine McKinnon[a], Cesar Ruiz[e], Jairo Guerrero[e]

[a] *Betty and Gordon Moore Center for Science, Conservation International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA*
[b] *Greater Mekong Program, Conservation International, Street 95 Sangkat Boeung Trabek, Khna Chamkar Morn, Phnom Penh, P.O. Box 1356, Cambodia*
[c] *Asia-Pacific Regional Office, 318 Tanglin Road, #01-30, Block B, Singapore 247979, Singapore*
[d] *Earth and Environmental Dynamics Research Group, Department of Geography, King's College London, Strand, London, WC2R 2LS, UK*
[e] *Conservation International Colombia, Carrera 13 No. 71-41, Bogotá DC, Colombia*

HIGHLIGHTS

- Protected Areas represent better Freshwater regulation than provisioning services.
- Due to Freshwater regulation importance The Prey Lang forest, should be protected.
- Riparian forests around Mekong's deep water pools should be better protected.
- Freshwater metrics framework proposed suitable for sparse data regions.

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ABSTRACT

Freshwater is arguably one of Earth's most threatened natural resources, on which more than 7 billion people depend. Pressures on freshwater resources from infrastructure, resource development, agricultural pollution and deforestation are mounting, particularly in developing countries. To date, conservation responses such as Protected Areas (PAs) have not typically targeted freshwater ecosystems and their services, and thus little is known about the effectiveness of these efforts in protecting them. This paper proposes and pilots an innovative freshwater services metrics framework to quantify the representation of potential freshwater services in PAs under conditions of scarce data, with a pilot application for Cambodia. Our results indicate that conservation actions have more effectively represented potential freshwater regulation services than potential freshwater provisioning services, with major rivers remaining generally unprotected. Results from the framework are then used to propose a series of context and region specific management options to improve the conservation of freshwater services in Cambodia. There is an acute need for such management options, as the country's food security depends largely on important freshwater ecosystems such as the Tonle Sap Lake and the deep water pools systems of the Mekong River. The framework proposed can be applied in other countries

* Corresponding author. Tel.: +1 703 341 2784.
E-mail address: lsaenz@conservation.org (L. Sáenz).

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or large river basins to explore the degree of representation of freshwater services within PAs systems, under conditions of sparse data.

1. Introduction

Freshwater is one of the most threatened resources sustaining human populations (Addams et al., 2009; Bourza, 2013; Foster et al., 2013; Lawford et al., 2013). Watershed and river degradation through deforestation, wetland degradation, river fragmentation, urbanization and pollution, are among the threats affecting the supply of this valuable resource (Vörösmarty et al., 2010; Hill et al., 2013; Winemiller et al., 2016). State-specific freshwater management strategies, including headwaters conservation through Protected Areas (PAs), have been proposed to more sustainably manage the supply of freshwater services (Vörösmarty et al., 2010; Green et al., 2015).

Freshwater services include the supply and regulation of freshwater in quantity and quality, which are fundamental for the survival of humans and biodiversity (Vörösmarty et al., 2005, 2010). However, we know little about the effectiveness of PAs in safeguarding freshwater services (Neil et al., 2009; Farrell et al., 2010). This is, in part, due to lack of appropriate methods, data and metrics to examine and monitor the cause–effect relationships between conservation policies and the state of freshwater services and their supplying ecosystems (Juwana et al., 2012; Hill et al., 2013; Ferraro and Hanauer, 2015). The evidence base that is needed to more adequately represent freshwater services in conservation plans is generally lacking (Neil et al., 2009).

However, part of the complication in deriving the evidence needed to better represent freshwater services in conservation programs may reside in our perception of what freshwater services are. According to the Millennium Ecosystem Assessment (MEA) freshwater is treated as a service as well as a system that supports other services (Vörösmarty et al., 2005). Indeed, freshwater can support, for instance, purification processes such as pollutants dilution in river streams; or it can support nutrient recycling processes, such as those that ensure healthy fisheries in the Mekong River basin (MEA, 2005; MRC 2013). Nevertheless, freshwater is also a final service that results from the interaction of several intermediary services working together (Mulligan et al., 2010). For instance, according to the MEA, forests, wetlands, lakes, flood plains and ground water aquifers are natural storages that help regulate the quantity and quality of the freshwater flowing out of watersheds (MEA, 2005). In contrast, rivers, lakes and other aquatic ecosystems are natural networks that provide access to gravity-driven freshwater flows for human consumption and biodiversity (Jones, 2011).

Due to these complexities in disentangling final from intermediate freshwater services, the literature has often categorized freshwater only in terms of its quantity, especially in global analysis of water resources (Vörösmarty et al., 2005), paying less attention to freshwater regulation and quality dimensions (Mulligan et al., 2010; Juwana et al., 2012; Hill et al., 2013). This knowledge gap in freshwater conservation requires attention in order to improve the design and planning of PAs, given that biodiversity and people are highly sensitive to changes in both the quality and the pulse of freshwater flows (Wallace, 2007; Constanza, 2008; Mulligan et al., 2010). Thus, before defining freshwater conservation priorities we must develop a clear understanding of (1) what type of freshwater services we are interested in protecting, (2) where and how those services are generated, (3) who receives the benefits, and (4) what types of indicators and safeguards are needed to diagnose and improve their status and track conservation progress (Thieme et al., 2007; Neil et al., 2009).

In this manuscript we take these perspectives forward to propose an innovative freshwater services metrics framework to quantify the representation of freshwater services in PAs, which can serve as a tool to help better inform conservation planning programs for freshwater at national or large river basin scales. The framework was designed to distinguish between the role of PAs in the regulation and provision of freshwater, both in quality and quantity. The distinction between these different freshwater services is important to make because their importance for people or biodiversity may vary between regions and can be context specific. Moreover, their effective management, conservation and monitoring may be service specific.

In this study we focus only on potential services (services irrespective of their use by humans) (Turner et al., 2013) and not on realized services. This choice of focus was made because the assessment of realized services requires additional analysis, especially at national scales, to effectively connect freshwater services with the corresponding set of service users, which was beyond the scope of the present study. Nevertheless, we believe that the analytical steps to assess potential services proposed in this study establish an adequate foundation for a subsequent assessment of realized freshwater services and their economic value. From now onward, when we use the term freshwater services we are referring to potential freshwater services and not realized freshwater services.

To develop the set of physical indicators that constitute the framework, we use a process-based eco-hydrological modeling approach implemented with the WaterWorld policy support system (http://www.policysupport.org/). Results are summarized spatially using a sub-watersheds hydrological network, according to Lehner and Grill (2013), to prioritize areas and river reaches important for freshwater service supply.

Finally, we applied the framework in the data-scarce context of Cambodia. We chose Cambodia because the Mekong River was one of the least modified in the world, until recently, and many fish species and human communities have evolved to exploit its flood pulse particularly in Cambodia's Tonle Sap Lake (Pearce, 2006; Kummu et al., 2008). Yet, this status is rapidly changing due to hydropower dams and other development pressures on the river, which could affect food security and income for four-fifths of Cambodia's population that, in one way or another, depend on the fish harvest during the flooding season (Kummu and Sarkkula, 2008). Cambodia's government is in the process of implementing its Green Growth Roadmap for Development, which is expected to tackle some of these freshwater challenges (Kingdom of Cambodia, 2009). The strategy requires that Cambodia develops sustainably and uses its freshwater resources wisely, but to achieve these goals freshwater protection efforts must be escalated (Yen et al., 2008; Kummu and Sarkkula, 2008; Kummu et al., 2008). However, more freshwater conservation research is urgently needed to better understand what freshwater services to protect and where.

Conservation International has a strong relationship with the government of Cambodia and a vested interest in responding to these challenges in the Mekong River basin. As a result, it is currently participating in a series of freshwater research efforts in the country including Conservation International's conservation metrics project (http://www.metricsci.org/); MacArthur's food web and fisheries modeling project (http://www.bu.edu/cas/magazine/spring13/biology/kaufman/); and NSF Belmont's climate change and fish productivity project (https://igfagcr.org/funded-projects/maintaining-productivity-and-incomes-tonle-sap-fishery-face-climate-change-tlscc). The present study results from a collaboration among these different efforts, with an aim to support the implementation of the green growth strategies of the government of Cambodia.

2. Methods

2.1. Region of analysis

Our area of study is Cambodia, most of which (86%) lies within the lower Mekong River basin (Fig. 1(a)). The climate is heavily influenced by the Asian Monsoon regime, which brings approximately 65% of the total annual rainfall to the Mekong Basin. This significant water input causes the Tonle Sap River, which is located in the lower Mekong basin, to reverse its flow, leading to large variations in the natural flooded area of the Tonle Sap Lake (Fig. 1(a)) (Kummu and Sarkkula, 2008). Cambodia's iconic Tonle Sap Lake is thus very sensitive to the seasonal pulse of the Mekong River. Our assessment indicated that Cambodia is comprised of many diverse natural habitats and human land-uses (Fig. 3(a)), with around 57% of the country covered by deciduous and evergreen forest, including valuable hardwoods and rubber plantations. The center of the country, in contrast, is dominated by the Tonle Sap Lake floodplain, which is comprised by a mosaic of flooded scrubs, flooded forests and flooded grassland, together with rice paddies and human settlements. Coastal regions are generally covered by mangrove forests, rice cultivation, and aquaculture; often combined with urban uses and roads.

2.1.1. Delineation of hydrological region

To simulate Cambodia's hydrology, we defined a hydrological region contributing runoff to the country (Fig. 1(b) and (c)). The region consisted of the Tonle Sap River basin, the '3S' River basin, and other Mekong River reaches within Cambodia such as the Si Phan Don Riverine Archipelago to the north and the floodplain sections downstream of Phnom Penh to the south (Fig. 1(c)). The '3S' River basin is comprised of the Sekong, Sesan and Srepok Rivers, which contribute 25% of the total flow of the Mekong River (Arias et al., 2014) (Fig. 1(c)). The hydrological region also includes rivers draining from the Cardamom and Elephant Mountains into the Gulf of Thailand (Fig. 1(c)). All of these are hydrologically closed river basins that contribute runoff to Cambodia, and thus ensure that our assessment complies with the principle of hydrological closure (Fig. 1(c)). However, we did not attempt to model the whole Mekong River basin due to time, data and computational constraints. Instead, our focus was to provide insights into the potential freshwater services generated within Cambodia that are represented by the national PAs system. We nevertheless recognize the trans-boundary nature of the Mekong River Basin, and recommend that future studies apply the framework presented in this paper at the scale of the entire Mekong River and associated tributary countries.

2.2. Freshwater metrics framework

As indicated in the introduction, we propose an innovative freshwater services metrics framework for assessing the representation of freshwater services in PAs at national or large river basin scales. The method was designed to distinguish between the regulation and provision of freshwater in quantity and quality. For simplicity in distinguishing provisioning from regulation services, we assumed that freshwater quantity is naturally regulated in hillslopes by forests and other natural vegetation ecosystems as reported earlier by Bruijnzeel (2004). These ecosystems act as sponges and have the potential to regulate freshwater quantity through ecosystem functions such as fog capture and rain interception, as well as soil infiltration and evapo-transpiration (ET), among others (Bruijnzeel, 2004). In addition, these ecosystems act as filters to regulate the quality of freshwater, ensuring a natural dosage of sediments in freshwater flows through ecosystem functions such as sediment yield, water filtration, sediment transport and deposition, among others (Mulligan, 1998; Bruijnzeel, 2004; Sáenz et al., 2014).

In terms of freshwater provision, according to Vörösmarty et al. (2005) and Vörösmarty et al. (2010), our framework considers that this service is naturally supplied by rivers and water bodies as a result of gravity-driven water flows, which

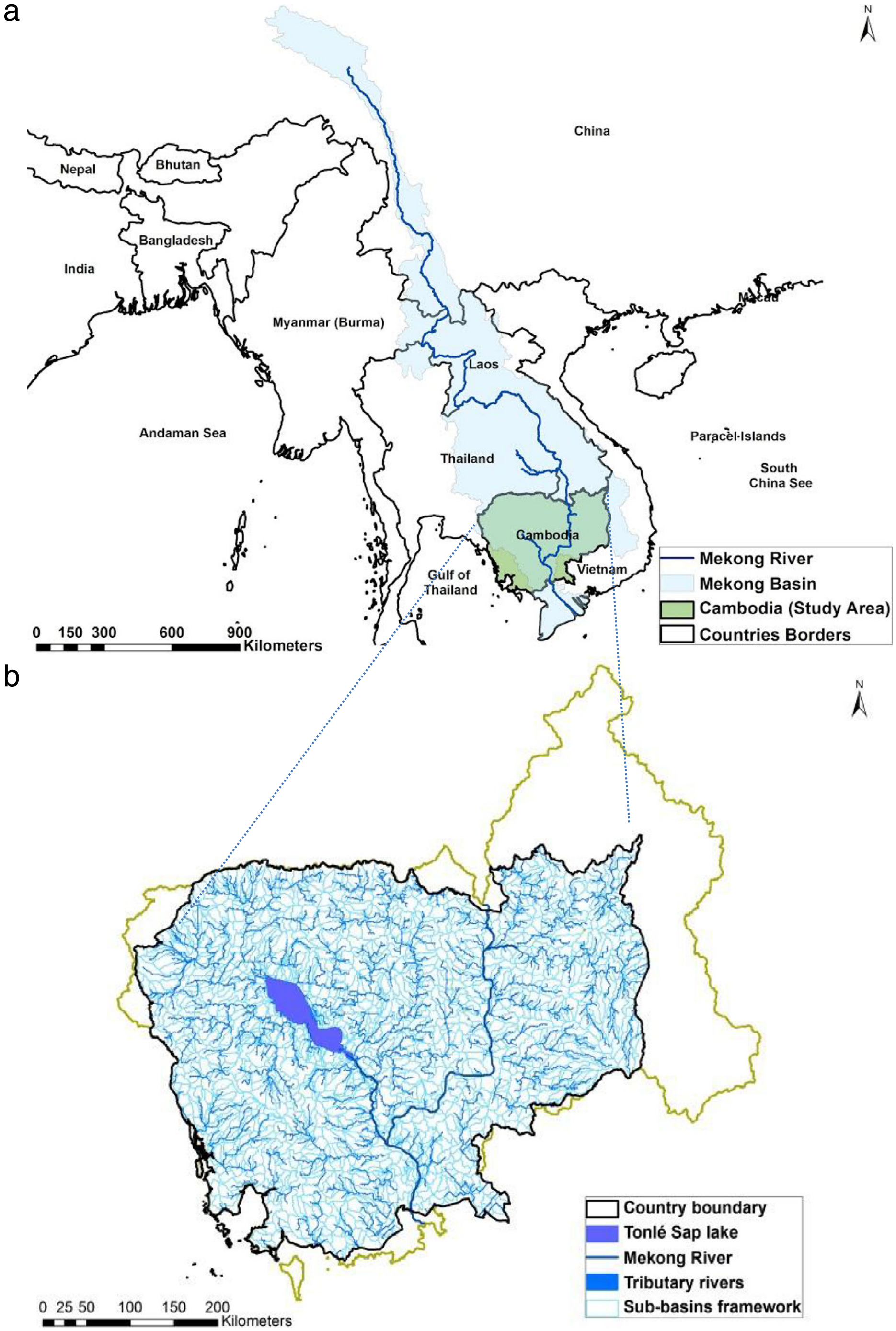

Fig. 1. (a). Map indicating the study area and the country boundary for Cambodia in the lower parts of the Mekong River basin. (b). Hydrological region and sub-watersheds hydrological network. (c). Major internal river basins in Cambodia used for delineation of the hydrological region for the study, together with the distribution of remaining forest zones and the location of major cities.

facilitate access for use by humans and other animals. Moreover, our framework accounts for the role of rivers and water bodies in ensuring the longitudinal flow connectivity necessary for sediment transport processes to take place, given that transport and deposition of water-borne sediments are a critical part of the quality of freshwater flows (Vörösmarty et al., 2003; Nilsson et al., 2010). No seasonal freshwater regulation was evaluated in this manuscript due to time and computational constraints. However, we argue that the annual time step used here is adequate to spatially distinguish the

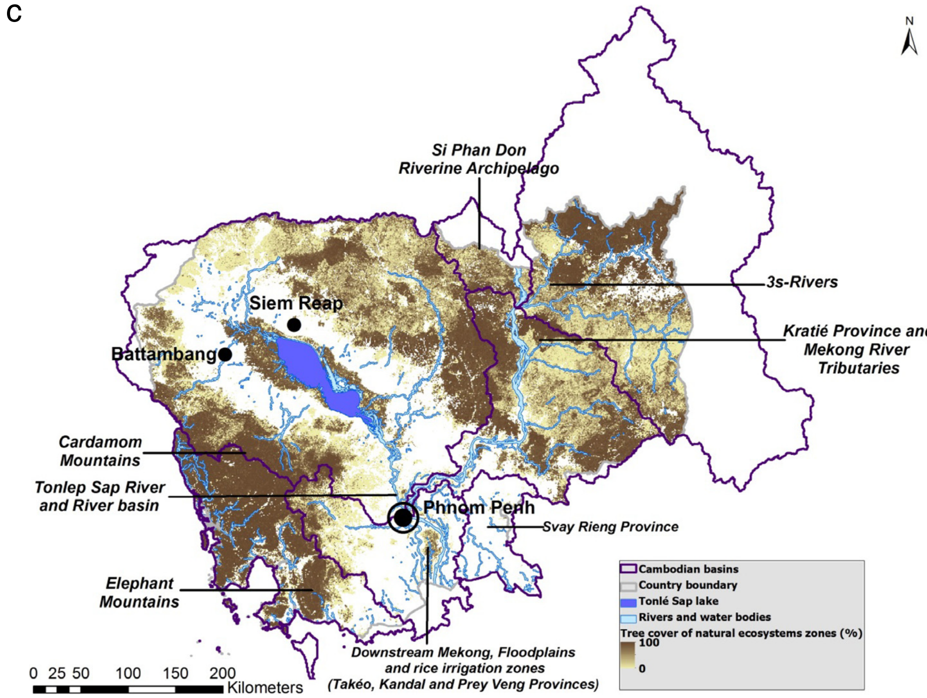

Fig. 1. (*continued*)

geographies important for freshwater regulation in the lower parts of the Mekong River, which tend to be less seasonal and exhibit lower elevation gradients than its Himalayan upper parts (Mulligan et al., 2011). Groundwater was also excluded from analysis due to lack of spatial data on aquifer volumes and recharge regimes.

To implement the framework we used the WaterWorld Policy Support System (http://www.policysupport.org/waterworld), a spatial eco-hydrological model designed to better understand hydrological processes mediated by vegetation ecosystems particularly in data-sparse tropical environments. The model is capable of simulating water quality, water balance, stream flow and the impact of climate and land use change on these variables at spatial resolutions of 1 km, 90 m and 30 m. The model operates with a monthly temporal resolution using a climatology representative of the period 1950–2000. WaterWorld includes significant innovations in our understanding of fundamental eco-hydrological controls in data sparse mountainous regions including wind-driven precipitation, cloud condensation frequencies, and fog and rain interception by forests in mountains. Moreover, the model produces improved evapo-transpiration (ET) estimates in areas facing high annual and seasonal ground level cloud, and has dedicated routines to calculate infiltration losses, and the melting of snow and ice in tropical river basins (Mulligan, 2013; Mulligan and Burke, 2005). WaterWorld also models soil erosion and sediment yield, using the runoff-wash erosion approach reported by Thornes (1990), and we model sediment deposition and transport using the method presented by Kirkby (1976) and Mulligan (1998). The model has been applied and tested widely, particularly in data sparse regions of the tropics (Mulligan, 2013; Sáenz et al., 2014). Model equations and model verification processes are outlined in detail in Mulligan and Burke (2005), Bruijnzeel et al. (2010) and Mulligan (2013).

To separate freshwater regulation from provisioning services, as described above, we derived a sub-watersheds hydrological topology from the vector river network of the HydroSHEDS database, at a resolution of 15 arc second (Lehner and Grill, 2013). In Cambodia, the dataset shows a population of 1500 sub-watersheds, with an average size of around 115 km^2, representing 24,000 km of Cambodia's rivers with stream flows above 0.1 m^3 s^{-1}. This granularity was chosen to provide optimal hydrological similarity for aggregation of indicators in headwater areas (where hydrological variables often vary largely across restricted elevation gradients) as well as in lowland river tributaries (where the slope of the terrain is lower but ET tends to be higher) (Fig. 1(b)).

The first two indicators in the framework describe the regulation of freshwater in quantity and quality (Fig. 2, Table 1). As an indicator for freshwater quantity regulation we use a spatial representation of the mean annual water balance (mm year^{-1}) in hillslopes at the sub-watersheds scale. Calculations are done with WaterWorld at a spatial scale of 1 km. The indicator provides an idea of the mean freshwater quantity regulated by each sub-watershed in a year. Rivers and their accumulated flow are not considered at this stage of the analysis. They are masked out from the spatial water balance. The rational for this procedure is to capture freshwater regulated at hillslopes only before it is accumulated downstream into rivers. Freshwater regulation controls considered in the calculation of the water balance include wind-driven rainfall and fog interception processes, mediated by vegetation and the underlying topography. We also simulated evapo-transpiration

Table 1
Freshwater service indicators developed to examine the representation of freshwater services in PAs.

Indicator	Unit	Normalized unit	Description
Water balance	mm $year^{-1}$	Index 0–1	Represents spatially the regulation of freshwater quantity in hillslopes, as modeled with WaterWorld, using a sub-watersheds hydrological network according to Lehner and Grill (2013).
Sediment yield	mm $year^{-1}$	Index 0–1	Represents spatially the regulation of freshwater quality in hillslopes, as modeled with WaterWorld, using a sub-watersheds hydrological network according to Lehner and Grill (2013).
River flows	m^3 $year^{-1}$	Index 0–1	Represents the quantity of freshwater provision along rivers, as modeled with WaterWorld, using a river network according to Lehner and Grill (2013).
Sediment transport	m^3 $year^{-1}$	Index 0–1	Represents the quality of freshwater provision along rivers, as modeled with WaterWorld, using a river network according to Lehner and Grill (2013).

losses driven by solar radiation, cloud cover frequencies, temperature and vegetation cover, among other hydrological factors.

As an indicator of freshwater quality regulation we use a spatial representation of the mean sediment yield (mm $year^{-1}$) in hillslopes at the sub-watersheds scale (Table 1). Similarly, calculations are done with WaterWorld at a spatial scale of 1 km and then presented as mean values per sub-watershed. The indicator provides an idea of the mean sediment production that each sub-watershed releases into rivers or water bodies in a year. Rivers are masked out during this analytical step to ensure that we capture sediment contributions from hillslopes only. The factors considered in the calculation of sediment yield include wind-driven rainfall, surface runoff, slope of the terrain, fraction of soil covered by vegetation and soil erodibility.

The final two indicators in the framework were selected to describe the provision of freshwater in quality and quantity (Fig. 2, Table 1). We used river flows (m^3 $year^{-1}$ $year^{-1}$) as an indicator of the potential amount of freshwater available for provision to both humans and biodiversity along river channels. To calculate the indicator, we model the accumulation of the water balance available from hillslopes into rivers using flow accumulation functions available in WaterWorld. Similarly, we use sediment transport in river flows (m^3 $year^{-1}$) as an indicator for quality of freshwater provisions, and calculate the indicator by modeling sediment transport and deposition processes both at hillslopes and river channels, as well as sediment accumulations along river channels.

All indexes described above are normalized by rescaling variable ranges from 0 to 1 using a feature scaling method (Juszczak et al., 2002). This unified scale is selected to facilitate comparisons between the level of representation of different freshwater services within PAs. Table 1 shows an enhanced description of the indicators incorporated into the framework.

A conceptual flow diagram summarizing our freshwater services metrics framework is also presented in Fig. 2. The diagram illustrates how rainfall, a function of the prevailing climate, is influenced by ecosystems and their functions once it reaches the terrestrial part of the water cycle, resulting in the water yield that is accumulated downstream, governed by a series of watersheds topological features including hillslopes, river channels and wetlands, among others (Fig. 2). Thus, the flow of freshwater from a given watershed integrates the outcomes of a series of regulation and provisioning service functions, in quality and quantity. The conservation status of these functions may vary depending on their degree of intactness and on the presence and location of PAs. The level of representation of these services in PAs can be used as a tool to illustrate the effectiveness of freshwater conservation responses in a given country or geographical region, and could offer the entry points for quantifying freshwater conservation priorities and highlight freshwater conservation gaps.

2.3. Parameterization of WaterWorld

WaterWorld was parameterized with quality-controlled global climate data available from its online databases. These data included WorldClim (Hijmans et al., 2004), which provides monthly means for temperature and precipitation for a period from 1950 to 2000. We also used a cloud frequency dataset based on an analysis of MODIS products, at a 1 km^2, provided by Mulligan (2013), in order to characterize atmospheric moisture and cloud condensing conditions. Elevation and flow lines data were extracted from HydroSHEDS (Lehner et al., 2008). However, it is important to mention that lack of locally available data for climate, including rainfall, temperature and relative humidity, made it necessary to implement the model with globally available datasets. Nevertheless, the application of WaterWorld with quality controlled global climate data has been reported to be sufficient to identify freshwater conservation priorities in data sparse conditions (Mulligan, 2013; Sáenz et al., 2014).

In terms of vegetation and land cover data, WaterWorld was implemented with fractional representations of forest, herbaceous and bare soil land cover groups according to Mulligan (2013). These categories were derived from several land cover classifications reviewed in our study including Cambodia's Forestry Administration forest cover change 2006–2010 (FA, 2011); JICA's (Japan International Cooperation Agency) National Topographic Map Mosaic of Cambodia 1:100,000 Scale (JICA, 2001); and the High-Resolution Global Maps of 21st-Century Forest Cover Change according to Hansen et al. (2013).

The forest functional group was produced using all available forest classes from FA (2011) and Hansen et al. (2013) and combining them into a continuous fractional category at a 1 km^2 spatial scale. The forest classes combined were

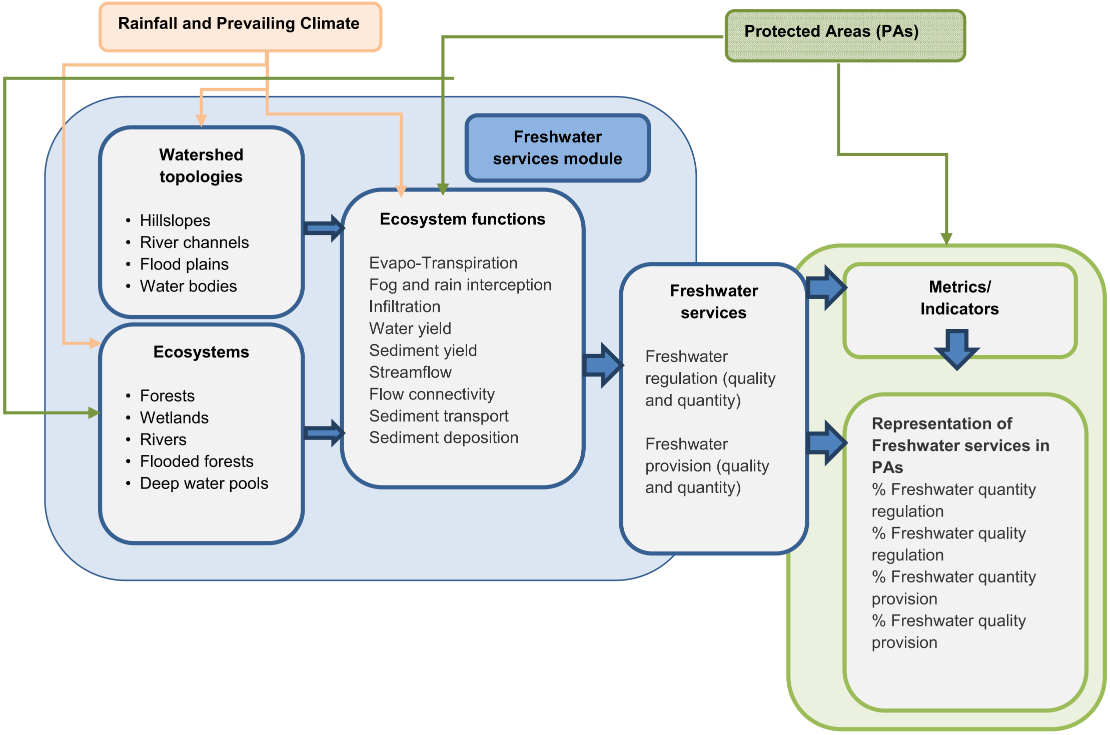

Fig. 2. Flow diagram of the freshwater services metrics framework designed to assess the representation of freshwater services in PAs.

deciduous, evergreen, flooded forests and high shrubs. The herbaceous functional category was assembled using agriculture, pastureland, shrubs, natural grassland and savannah classes according to FA (2011), Sexton et al. (2014) and Hansen et al. (2006). Finally, bare soil and water bodies were directly extracted from major urban, lakes and river categories according to FA (2011), Sexton et al. (2014) and Hansen et al. (2006) (Fig. 3(b), (c), and (d)). Soils data such as soil erodibility data were derived from global soils data from FAO (2009) available in WaterWorld.

2.4. *Representation of freshwater services in PAs*

Finally, we used a map of PAs for Cambodia in order to assess the representation of freshwater services in its existing protected area system. To implement the analysis we used the World Database of Protected Areas (WDPA) dataset (IUCN and UNEP-WCMC, 2014), which, for Cambodia, includes four main categories of areas managed for some conservation value. These categories are National Parks, comprising natural and scenic areas of significance for scientific, educational and recreational values; Wildlife Sanctuaries, harboring significant species of flora and fauna, including the Tonle Sap fish sanctuaries and Ramsar sites; Protected Landscapes used for recreation and tourism; and Multiple-use management areas established for sustainable use of natural resources (Fig. 3(e) and (f)).

In order to calculate the level of representation of freshwater services in PAs, we use zonal statistical analyses to identify the percentage of the country's total service units that are found within PAs. The procedure is repeated for all services and results are presented both spatially, in the form of maps; and graphically, in the form of basic comparative statistics using percentage bar diagrams. Basic statistics of the representation of these services are also presented for all natural terrestrial vegetation polygons beyond PAs, in order to highlight potential freshwater services that remain unprotected across the country. It is important to note that the natural vegetation polygons used in the analysis, either inside or outside PAs, represent terrestrial vegetation exclusively and no other types of natural vegetation, such as aquatic vegetation. The reason for this restriction is due to the fact that there are no comprehensive aquatic vegetation datasets that cover the whole of Cambodia to implement the country scale zonal statistical analysis described. From now onward, when we refer to natural vegetation we are referring to terrestrial vegetation only.

Fig. 3 shows the different land cover assessments included in our analysis for Cambodia. Fig. 3(a) shows Cambodia's land cover classes. Fig. 3(b)–(d) show different functional land cover groups used for parameterization of WaterWorld; and Fig. 3(e) and (f) show maps of natural vegetation and PAs across Cambodia.

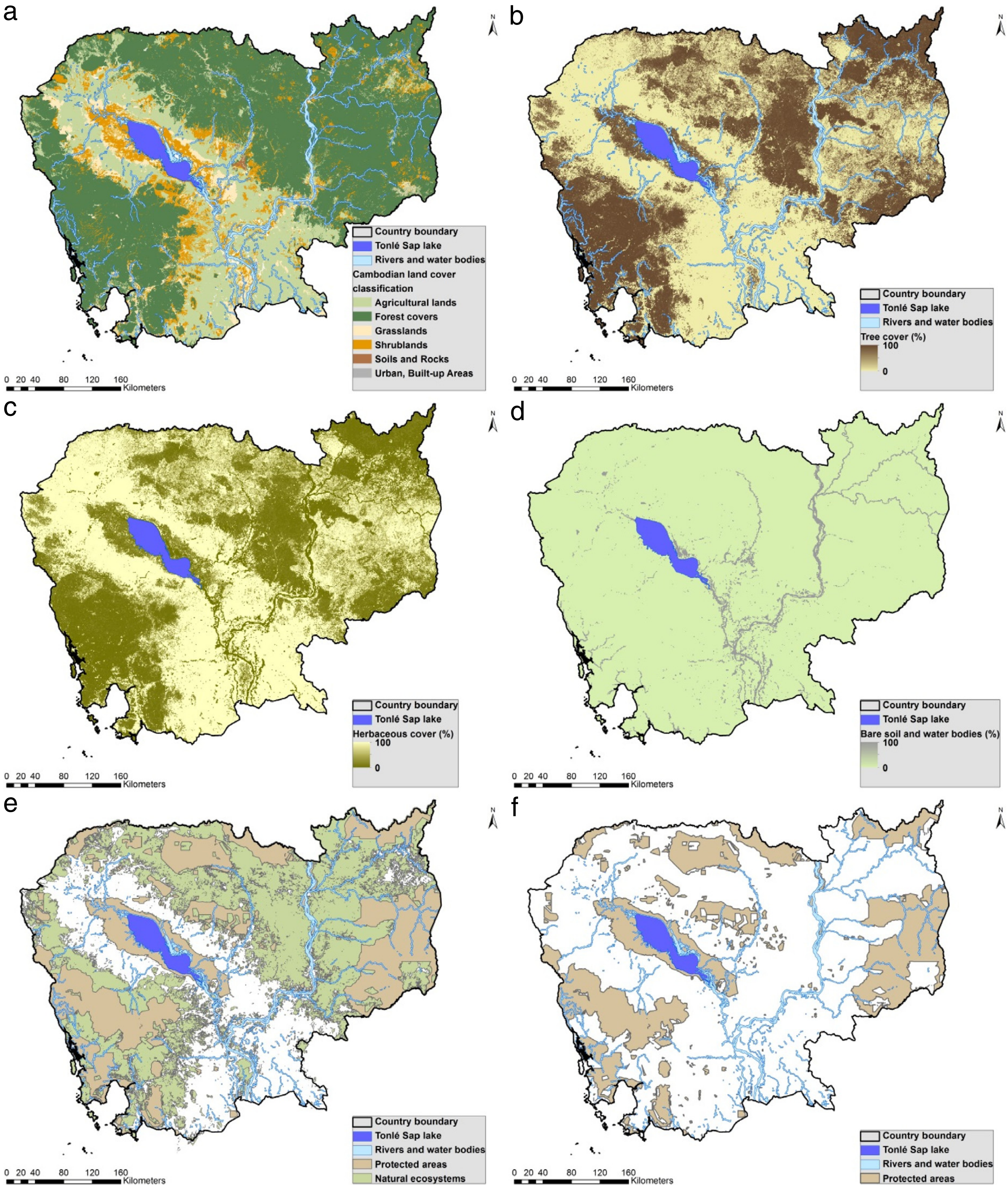

Fig. 3. Land cover types for Cambodia. (a). Land cover classifications. (b). Proportion of tree cover. (c). Proportion of herbaceous cover. (d). Proportion of bare soil. (e). Natural vegetation and overlay with protected areas according to WDPA for Cambodia. (f). Protected areas according to WDPA for Cambodia.

3. Results

Outcomes are first described spatially, in terms of the distribution of services across the country and within PAs. Indicators described include water balance, sediment yield, stream flow and sediment transport. Second, results are presented in the form of bar diagrams that compare basic statistics of the representation of different services within PAs and within natural vegetation areas more broadly. The latter representation could help to highlight the potential for additional freshwater service protection across the country.

3.1. Freshwater quantity

3.1.1. Regulation of freshwater quantity and representation in PAs

Results show that mountainous watersheds regulate a higher water balance per unit of land than the substantially drier lowlands where ET is highest (Fig. 5(a)); particularly those lowlands around the Tonle Sap Lake. By normalizing the water balance and applying zonal statistic analyses to land under natural vegetation and PAs (Figs. 4(b), 5(a) and Table 1) we can see that natural vegetation areas represent 76% of Cambodia's freshwater regulation services in 69% of the country's land; with PAs accounting for 31% of these services in just 26% of the country's area (Fig. 5(a)).

3.1.2. Provision of freshwater quantity and representation in PAs

Freshwater provision services are highest for sub-watersheds of river reaches along the Mekong River and its main tributaries, including the Sekong, Sesan, Srepok and Tonle Sap Rivers (Fig. 4(c)). Sub-watersheds of smaller rivers have a local freshwater provisioning role and also contribute to larger rivers (Fig. 4(c)). However, we calculate that the representation of freshwater provision services in PAs is substantially lower than the representation of freshwater regulation services. Only 24% of Cambodia's freshwater provision through rivers is found within PAs compared to 31% for freshwater regulation. Moreover, the representation of freshwater provision services in PAs is lower than the river length protected (29%); and the land protected (26%) (Figs. 4(d), 5(b)). Similarly, the representation of freshwater provision services in natural vegetation, beyond PAs, is also lower than the land area covered by natural vegetation (67%).

3.2. Freshwater quality

3.2.1. Regulation of freshwater quality and representation in PAs

Results also show that mountainous sub-watersheds under natural vegetation play an important role in freshwater quality regulation. Undisturbed sediment loads transported from these areas determine the quality of freshwater that flows downstream to aquatic habitats such as the Tonle Sap Lake. These mountainous areas are generally covered by dense forests, but enjoy higher water balances and surface runoff than the lowlands. A log 10 transformation in Fig. 4(e) is used for visualization purposes only. In contrast, soil loss potential is much less significant in the floodplains. Sub-watersheds around the Tonle Sap Lake and the Mekong River delta, to the South of Phnom Penh, are examples of these areas, where sediments are likely to be deposited from upstream river reaches (Fig. 4(e)). By normalizing the production of sediments in hillslopes, and applying zonal statistic analyses to areas covered by natural vegetation and PAs, we estimated that PAs account for 34% of Cambodia's freshwater quality regulation services (Fig. 4(f)). This value is substantially higher than the percentage of land under protection (26%) (Fig. 5(a)). Also, natural vegetation areas account for around 92% of freshwater quality regulation services, which is much higher than the proportion of the country's area covered by these natural ecosystems.

3.2.2. Provision of freshwater quality and representation in PAs

Sub-watersheds of river reaches along the Mekong River and major tributaries including the Sekong, Sesan, Srepok and Tonle Sap Rivers, are critical for transport of undisturbed sediment loads across Cambodia (Fig. 4(g)). Other sub-watersheds that supply this important service are along the Aek Phnum and Siem Reap Rivers and, downstream, the Cardamoms (Fig. 4(g)). In general, sub-watersheds of smaller rivers in the lowlands show substantially lower sediment transport. We also found that a quarter (25%) of freshwater quality provision services can be found in PAs (Fig. 5(b)), again, lower than the proportion of rivers length under protection (29%). Finally, around 68% of freshwater quality provisioning services is found under natural vegetation (Fig. 5(b)).

Fig. 4 shows maps for Cambodia of regulation and provision of freshwater, both in quantity and quality, and filtered by PAs.

4. Discussion

The application of our framework for Cambodia shows that, in general, PAs represent freshwater regulation more effectively than provisioning services (Fig. 5). This can safely be explained by the fact that major rivers in the country, and perhaps their river flows, remain generally outside of PAs. Moreover, the representation of river flows in PAs (freshwater river volumes) is also lower than both the proportion of land and the combined length of rivers under protection. This finding may also indicate that PAs have tended to represent freshwater regulation service topologies better than provisioning topologies; but this is likely more a product of PA's being placed in hilly areas, where logging and development is more difficult. For instance, PAs better represent hillslopes, hilltops and headwaters in areas such as the Virachey National park to the north east, and the Cardamom Mountains to the south west (Fig. 6), than riparian buffers or river reaches in areas between Stung Treng, Siem pang and Krong Ban Lung, in the 3S system. The latter are important freshwater provisioning areas, both in terms of quality and quantity, for the deep water pools system of the Mekong River upstream of Kratie (Fig. 6). Thus, their protection should be strengthened.

Nevertheless, we identified existing areas according to the WDPA that could likely play critical freshwater provisioning services for Cambodia. Some of these areas are the Tonle Sap Man & Biosphere reserve and the Ramsar site located along

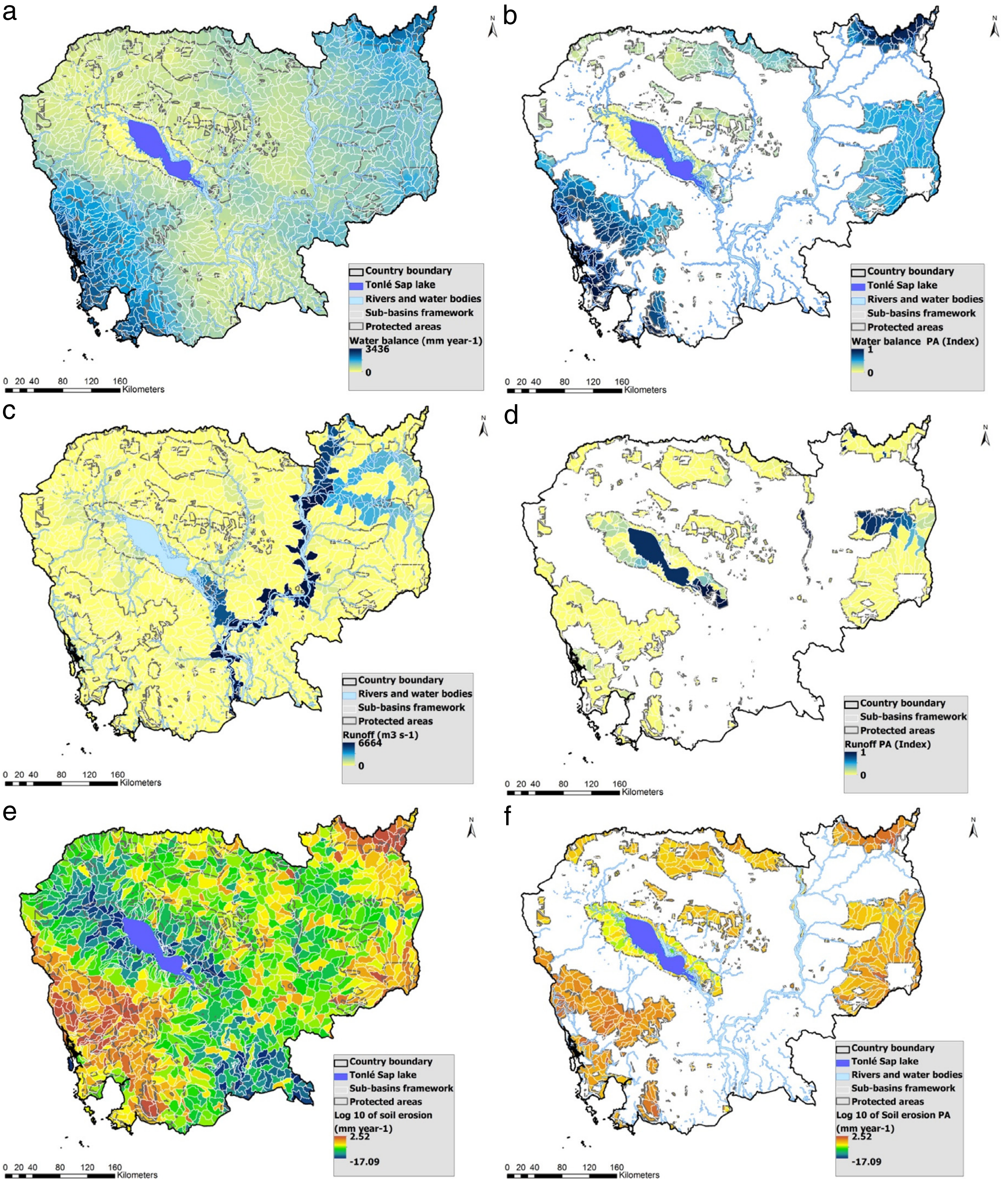

Fig. 4. (a). Water balance (mm year^{-1}). (b). Normalized water balance (index) extracted for PAs. (c). River runoff (m^3 s^{-1}). Sub-watersheds are used to highlight variability in river flows between river reaches. (d). Normalized runoff (index) extracted for PAs. (e). log10 of soil erosion (mm year^{-1}) used as a proxy for freshwater quality regulation. (f). log10 of soil erosion (mm year^{-1}) extracted for PAs. (g). log10 of sediment transport (mm year^{-1}) as a proxy for freshwater quality provision through rivers. (h). log10 of sediment transport (mm year^{-1}) extracted for PAs. A log10 transformation is used to improve visual interpretation for soil erosion and sediment transport indicators.

the Middle Stretches of the Mekong River north of Stung Treng (Fig. 6). These areas, if properly managed and protected, can contribute significantly to the conservation of the Tonle Sap Lake, and its associated floodplain, which sustain the most productive inland fishery in the world, as well as Cambodia's wet and dry season rice economy (Kummu and Sarkkula, 2008).

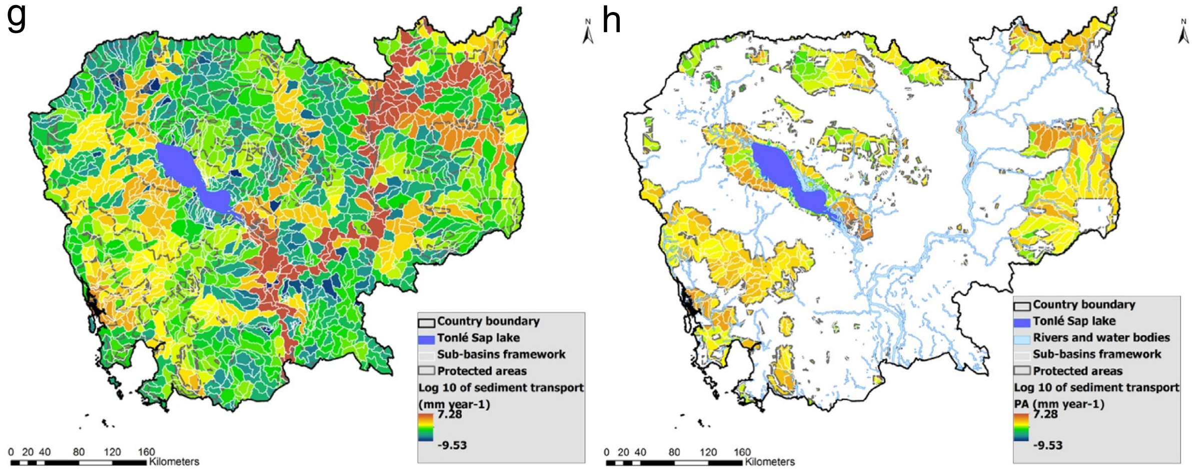

Fig. 4. (*continued*)

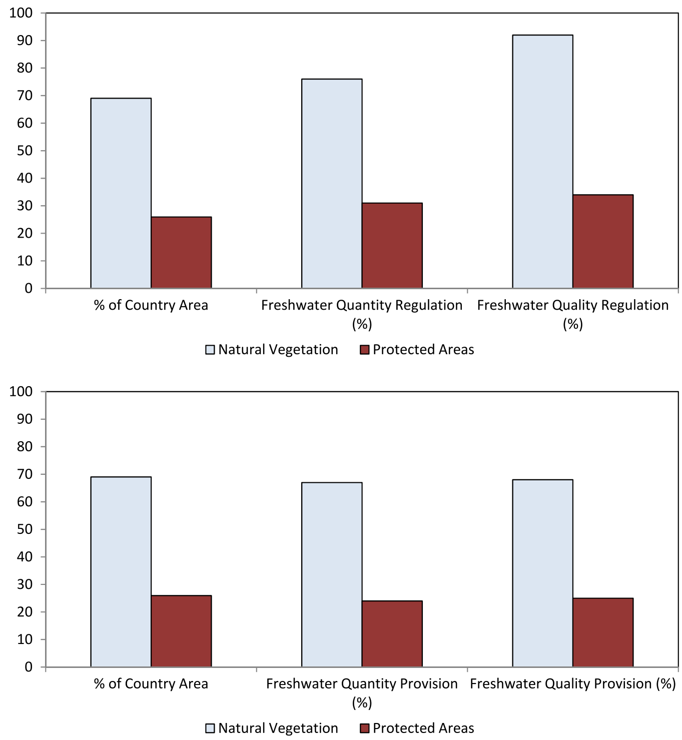

Fig. 5. Bar diagrams comparing the percentage of freshwater regulation and provision, in quality and quantity, found within PAs and under natural vegetation. (a). Freshwater regulation services both under natural vegetation and PAs. (b). Freshwater provision services both under natural vegetation and PAs.

They also can likely protect freshwater flows, in terms of quantity and quality, for the more than 50 deep water pools located along the Mekong River to the north of Kratie (Fig. 6), which are home to the iconic Mekong giant cat fish and the Mekong river dolphin (Mekong River Commission, 2013).

Unfortunately, none of these areas is well protected. For instance, only smaller parts of the Tonle Sap Man & Biosphere reserve receive some level of protection attention (Conservation International, 2014). These areas are principally the much smaller fish sanctuaries that have been designated within the lake to prevent any type of fishing; but for which our study did not have access. Thus, assuming the entire polygon of the Tonle Sap Man & Biosphere reserve as protected, according to the WDPA, may have clearly resulted in an overestimation of the already low level of protection of freshwater provisioning services calculated in our study.

Moreover, important areas for regulation of freshwater quality and quantity remain outside of formal protection across the country. One of these areas is the Prey Lang forest, located within Kampong Thom, Stung Treng and Kratie provinces

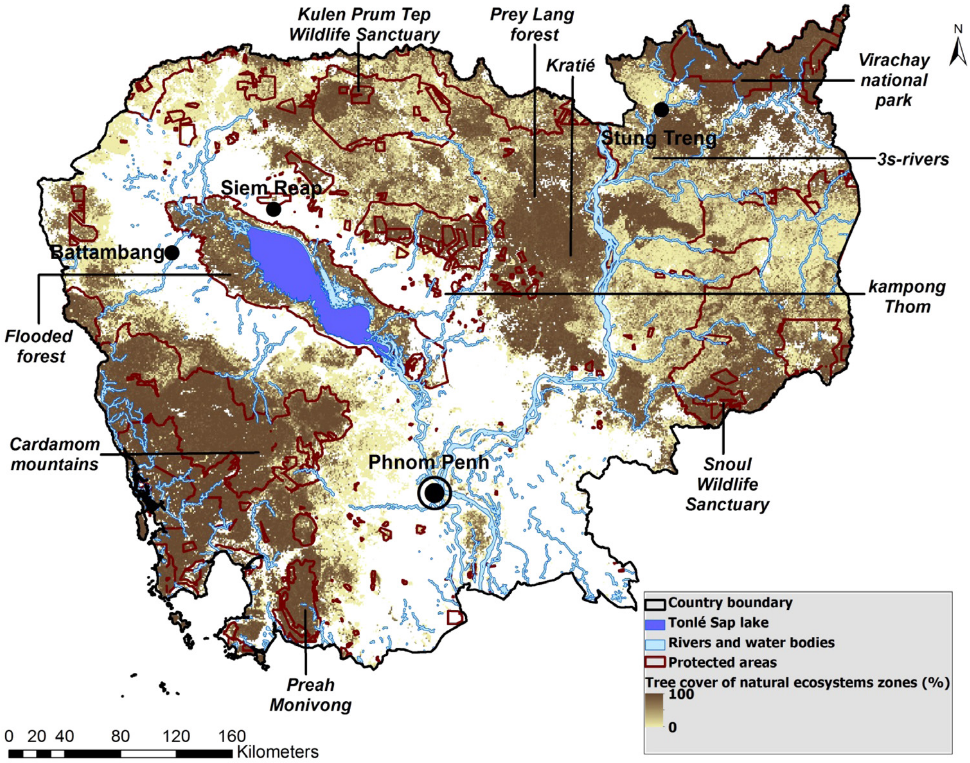

Fig. 6. Areas of importance for strengthening freshwater conservation planning and implementation across Cambodia.

(Fig. 6). Prey Lang is a large, evergreen, lowland forest containing also significant fauna and flora, and holding a large carbon stock. Thus, formal conservation of this forest, through PAs establishment or the designation of special catchment management zones, should be promoted to safeguard its important freshwater regulation services.

Therefore, Cambodia would benefit from exploring a number of watershed management strategies to ensure better protection of freshwater regulation and provisioning services. Some of these strategies should include design and implementation of PAs in headwaters that are currently unprotected. The Prey Lang area, as well as sub-watersheds in the 3-S rivers system (including trans-boundary parks), should be high priorities (Fig. 6). Moreover, Cambodia should explore other strategies for reducing deforestation threats, and foster restoration of degraded landscapes, including flooded forests. Such strategies could take the form of payments for watershed services (PWS) or water funds (Asbjornsen et al., 2015), where compensation is made by watershed service users, such as water utilities or existing hydropower plants, to upstream land owners for changing land uses to more environmentally friendly ones. Such mechanisms should be explored in areas around the Virachey National park in the north east of the country, and the Cardamom Mountains to the southwest, where these types of service users can be found (Killeen, 2012) (Fig. 6).

Additionally, Cambodia should explore the development of other methods that directly protect river courses and aquatic systems, such as fish sanctuaries and catchment conservation zones. These strategies can more directly safeguard freshwater flows provisioned through rivers from in-river pressures such as sand dredging and construction of hydropower and irrigation dams (Bravard et al., 2013). Particularly, protection of river corridors in the 3-S rivers system can enable Cambodia to expand its current protection of riparian systems and corridors, which are key habitats for both aquatic and terrestrial biodiversity (Fig. 6) (Conservation International, 2014).

However, the designation of formal protection status, in countries like Cambodia, is not enough to ensure the conservation of these important freshwater service supply areas (Neil et al., 2009; Farrell et al., 2010; Mascia and Pailler, 2011). Where PAs are the solution, they must not only be declared but well managed and secured from concessions, downgrading, downsizing and degazettement, among others (Mascia and Pailler, 2011). This is very relevant in Cambodia, where large proportions of protected areas are not managed well, or not managed at all, and have in fact been substantially degraded (Conservation International, 2014). Nevertheless, Cambodia has started to recognize the importance of riparian zones and to include them within national protection designations, which is good news for conservation of aquatic systems, biodiversity and freshwater services (Conservation International, 2014).

Some shortcomings of our study that should be improved in future freshwater service studies are, first, that this paper focuses exclusively on the spatial assessment of potential freshwater services at national scales rather than on realized freshwater services. Assessing realizable services would require a significant assessment of service benefits such as fisheries, rice or hydropower production; and beneficiaries such as fishermen communities, farmers or hydropower operators, which were beyond the scope of this study. Moreover, a better discrimination of freshwater services supplied by aquatic habitats including wetlands, floodplains and flooded forests, as well as consideration of groundwater, would be required in order to identify the corresponding set of service users that depend on these freshwater service sources. Thus, additional analyses are required to select those places most important in supporting current human uses in Cambodia.

Second, our study does not evaluate the impacts of existing or proposed dams on freshwater services. This decision was made first, due to limited reliable data on river fragmentation and flow alteration resulting from dams during the time frame of this study; and second, because our focus was primarily on assessing the representation of freshwater services within PAs. We recognize that dams can prevent downstream aquatic ecosystems, such as the Tonle Sap Lake, from enjoying the freshwater services supplied by PAs. Therefore, integration of results from our study with parameters such as the level of river fragmentation or flow alteration caused by dams to Cambodia's rivers, as documented by Kummu et al. (2008) and Arias et al. (2012), would be a valuable next step.

Third, our study does not evaluate correlations between the services of PAs with issues such as fish catch or ecological food webs in the Tonle Sap Lake, and thus does not provide implications for the sustainability of fisheries in Cambodia. Nevertheless, our results could effectively complement current research efforts exploring some of these issues in Cambodia, including the MacArthur's food web modeling project led by Boston University (http://www.bu.edu/cas/magazine/spring13/biology/kaufman/), and the NSF Belmont's climate change and fish productivity project led by Conservation International (https://igfagcr.org/funded-projects/maintaining-productivity-and-incomes-tonle-sap-fishery-face-climate-change-tlscc).

5. Conclusions

In spite of several PAs in place in Cambodia, little was known about their effectiveness at representing freshwater services until now. Much needs to be done in Cambodia to correct this, bearing in mind its significance to food security and economic dependence on critical freshwater habitats such as the Tonle Sap Lake. By developing and testing an innovative freshwater services metrics framework, this paper moved these perspectives forward for Cambodia by presenting the first spatial and high resolution national scale assessment of the representation of freshwater regulation and provision services within the existing PAs system.

This is also one of the first studies for the country, to the knowledge of the authors, in which quality and quantity of freshwater provisions are distinguished. This discrimination is important to improve the targeting of freshwater conservation planning efforts, since protecting each of these different service dimensions may require context and habitat specific interventions. For instance, this type of improved knowledge is likely to be essential to better assess where and how the placement of proposed dams along the Mekong River in Cambodia can result in greater flow alteration or sediment retention. If dams continue to disconnect the highly productive fisheries or rice fields in and around the Tonle Sap floodplain, from important sediment production areas upstream, such as those identified in this study, floodplain fertility and productivity may decline with disastrous consequences for Cambodia's food security.

In terms of amplification of this work to other regions, we point out that the framework proposed can be applied in other countries or large river basins under conditions of sparse data. This is because first, most of the data used for implementation of the framework were obtained from quality controlled globally available climate and remote sensing databases available from WaterWorld; and second, because the methodologies suggested can easily be used or adapted to identify both important freshwater provisioning areas, and freshwater conservation gaps. In addition, the framework can be expanded to evaluate the representation of realized freshwater services from PAs, by including beneficiaries' data; and its results can be coupled with economic valuation approaches such as those developed by the InVEST model team (http://www.naturalcapitalproject.org/invest/). Results can also be coupled with other measures of ecosystem value including biodiversity, carbon sequestration and storage, food provision, and ecosystem-based adaptation such that conservation options with multiple benefits can be defined in Cambodia and beyond. Conservation International is currently developing this exercise for Cambodia and Madagascar through its institutional metrics project, where natural capital status for multiple benefits is a key component of the assessment (http://www.metricsci.org/).

Finally, the proposed freshwater services metrics framework can be developed into a new dynamic tool that interoperates dynamically with WaterWorld, which already possesses an Application Protocol Interface (API) (http://www.policysupport.org/). With this integration, WaterWorld can be called to provide the hydrological data needed by our framework to build and summarize the necessary indicators to describe the conservation status of freshwater services for specific countries or watersheds of interest. The framework can also be integrated to more detailed national scale web-based tools such as Tremarctos Colombia (http://www.tremarctoscolombia.org/). Tremarctos has been recently developed by Conservation International to provide early warnings of the impacts of mining and development pressures, including dams and roads, on Colombia's biodiversity. Thus, interoperation with our framework can help data rich national scale tools like Tremarctos to decouple the particular impacts on biodiversity that may result from impairment of freshwater services beyond specific project sites.

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