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Watershed services of tropical forests: from hydrology to economic valuation to integrated analysis

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'Watershed services' provided by forest ecosystems are receiving increasing attention in the research and policy arena. Changes in forest cover in tropical regions take many different forms and result in multi-dimensional changes in watershed processes: soil erosion rates, peak and low-flow levels, groundwater recharge rates, and water quality. These changes are in turn mediated by the socio-technical context to create a variety of context-specific human impacts, which constitute watershed 'services' (or 'dis-services'). Over the past decade, understanding of the biophysical linkage has generally become nuanced. But large gaps remain in regions like south Asia and Africa and on the question of how different types of forest transitions affect low flows, and the socio-hydrological links are inadequately studied. Economic valuation studies are still plagued with conceptual errors, oversimplified biophysical models, lack of social and technological context, and focus on lump-sum numbers. Greater integration of concepts, methods and latest results, and attention to context-specificity, are required for generating policy-relevant insights.

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Introduction

Forested ecosystems are said to provide a range of watershed services, including hydrological regulation in the form of low-flow augmentation, flood control and groundwater recharge, water quality enhancement, and soil conservation. These services are particularly important for communities in the tropics, either because rainfall is highly seasonal or locally limited, or because intensively cultivated and densely populated agrarian landscapes downstream are affected by soil-hydrological processes in the upstream forests [1,2]. They are also receiving

more global attention because tropical forests are major repositories of biodiversity [3], leading to interest in identifying win-win situations or trade-offs between biodiversity and watershed services [4]. Researchers have begun to extrapolate results from individual studies to national estimates of watershed service value [5,6], prepare global maps of watershed and other ecosystem service distribution [7,8] and even talk about 'hydrological hotspots' [9]. In parallel, national and international schemes involving payments for ecosystem services (PES) have already taken off in several countries, and most of them give watershed services of forests as the main rationale [10,11].

Unfortunately, "much of the current enthusiasm for ecosystem service projects . . . is an act of faith" [12]. It is based on a series of oversimplifications that are conventional wisdom, viz., that more and denser forest of any kind at any location will generate greater watershed services than any other land cover for all downstream communities. There are important nuances and complexities that, if not properly understood, may lead to failures of, if not adverse consequences from, policies and programmes that use the watershed service argument for tropical forest conservation.

This paper is a review of progress made and gaps that remain in understanding the socio-economic impacts of changes in watershed services induced by forest cover change¹ in tropical regions. In Section 2, the links between forests, watershed processes, and human well-being are described, the idea of 'watershed service' is clarified, and its implications for both biophysical and economic analysis are outlined. The first link is discussed in Section 3, where, given several recent reviews, only a brief overview and update is provided. The literature on economic valuation and analysis of watershed services is then discussed in Section 4. Given that previous reviews of this economic literature are either a decade old [13^{*}], are focused on sedimentation [14] or on temperate regions [15], covered economic valuation cursorily [16], or are brief [17] or inaccessible [18], this part of the review covers the last decade or so. It does not, however, cover the vast literature on PES, because these schemes take forest watershed service benefits for granted. I then use

¹ Not by non-forestry interventions in the hydrological cycle that often go under the name of 'watershed development or management' in the tropics, including bunding, terracing, or damming, diverting or lifting of water.

Table 1

Forest watershed processes and impacts: a framework ^a .		
Structural change ^b	Watershed process change	Possible human impact (Service or Dis-service)
Natural forest → Forest plantation, logged forest, shrub land, pasture, shifting cultivation, terraced agriculture, horticulture	Increase in erosion/Increase in sediment load	Reduced potability of water Increased fertility in downstream floodplain OR Decreased reservoir capacity downstream
	Higher flood or peak-flow levels	Change in flood severity and damage downstream
	Increases/decreases in total flow	Change in of agricultural production and availability for domestic users and livestock downstream
	Reductions in dry season flow or baseflow	
	Increases/decreases in groundwater recharge	Change in hydropower generation

^a Based on Table 1 in [18].

^b There is no easy correspondence between type of structural change and the change in watershed process; hence all types of changes are shown in a single box.

both the disciplinary and the interdisciplinary literatures to highlight the need for and the challenges in integrating the biophysical and socio-economic dimensions of such analyses.

Conceptualizing forest watershed 'services'

Since the emergence and popularization of 'ecosystem services' as a concept [19], it is common practice to list flood control, water regulation, soil erosion control and water purification under 'regulating services' and 'water' under 'provisioning services' of ecosystems. However, this approach has serious limitations [20,21]. It is necessary to distinguish between the structure of ecosystems, ecosystem processes, and impacts, outcomes or benefits.

In the context of tropical forests, 'structural change' takes many different forms—from intact natural forest to heavily hacked thickets, intact forest to selectively logged forest, natural forest to timber plantations, or forest to pasture, horticulture, shifting or perennial cropping. Each of these changes can influence several watershed processes – erosion rates, sediment load, water chemistry, peak flow levels, total flow, base flow, or groundwater recharge – in different ways. These changes can in turn result in different kinds of human impacts—increased cost of water purification, increased fertilization of floodplain lands, decreased reservoir capacity due to siltation, flood damage, changes in agriculture that is streamflow or groundwater-dependent, and so on (see Table 1). These impacts affect different 'stakeholders'—farmers, drinking water users, livestock owners, floodplain residents, or hydropower companies.

This framework has several implications for how one may understand and assess forest watershed services. First, a change in a process variable (say an increase in erosion) may have positive or negative human impacts

depending upon the context (such as presence of floodplain agriculture or presence of a dam). Therefore the process is not the 'service', the human impact is (and it can sometimes be a 'dis-service'). Functions or processes generate services only if there are humans that benefit from them; if streamflow changes but communities downstream do not use streamflow anyway, then *ceteris paribus* there is no change in ecosystem service [18,20]. Second, if services are context-dependent, then hydrologists and eco-hydrologists must choose or define (sometimes re-define) their 'variables of interest' and their models in ways that makes their analyses relevant to a particular context.

Third, the 'watershed service value' of a particular forest or land-cover type is meaningfully defined only in terms of the *changes* in human well-being downstream resulting from its replacement by an *alternative* land-use. Attempts to calculate the 'absolute value of the hydrological service' from a hectare of forest are meaningless.² It also follows that the value of *in situ* soil fertility of forests cannot be considered a service to agriculture or measured in terms of agricultural productivity or replacement cost (e.g., [6]), because forest soils (by definition) do not generate agricultural produce [13].

Fourth, generating human well-being from an ecosystem process invariably requires some investment of labour and/or man-made capital, technology and institutions (such as pumps to lift streamflow to fields and rules to decide who may pump how much). The service value is therefore crucially shaped by this socio-technical context.

² Calling 'water flow' a provisioning service of forest ecosystems [as in [19,22]] is misleading too, because water flows primarily because of rainfall, not forests.

Analyses of the process-impact link must therefore seek to understand the influence of this context [20*].

Fifth, with one type of structural change affecting several watershed processes and several stakeholders, understanding the distribution of impacts across space and time becomes at least as important as estimating the 'net change in aggregate economic welfare' that most economists focus on. So it would be crucial also to understand who wins and who loses, by how much and in what manner under alternative forest cover scenarios [14].

The forest-soil-water link

Following extensive debate and research in the 1980s and 1990s on the conventional wisdom of 'forests as sponges' and 'attractors of rain', a series of reviews [13*,23**] captured the consensus amongst forest hydrologists. In brief,

- a) Rainfall: The forest-rainfall relationship is tenuous in general and weaker in south and Southeast Asia, except for cloud forests.
- b) Floods: Conversion of forest to scrub land or pasture where soils get compacted is bound to lead to increases in peak flows locally. But deforestation is not primarily responsible for large-scale floods; other factors are more important.
- c) Erosion and sedimentation: Background erosion rates can vary tremendously by geology. Erosion effects of forest conversion depend significantly on what the new land-use is. Small-scale disturbances such as roads can have disproportionately large impacts. Catchment-scale sedimentation is lower than estimates based on plot-level erosion alone.
- d) Streamflow: Conversion of natural forest to plantations generally leads to increased evapotranspiration (ET) and therefore to reductions in total flows, groundwater recharge and dry season flows. Thinning of forests or plantations without disturbing soil infiltration properties has the opposite effect, as it reduces ET.
- e) Streamflow: The effects of forest degradation due to heavy use or conversion to horticulture, grasslands or agriculture are likely to be positive for wet season flows but the effects on dry season 'low flows' are highly context-dependent, as changes in ET and in infiltration capacity pull in opposite directions.

These reviews highlighted substantial ambiguities and gaps, especially in research on ET, infiltration and the 'low-flow problem'. They also pointed to the general thinness of research in south Asia and Africa.

Subsequent research has

- a) largely confirmed but also contextualised the hydrological effects of plantations [24–26],

- b) pointed out large differences in dry season ET within natural forests in southeast Asia, depending upon their deciduousness [27*],
- c) identified potential mechanisms that may imply a stronger forest-rainfall relationship at the meso-scale [28], especially for convective precipitation ([29], but see also [30]), and
- d) suggested that direct hydrological interventions (pumping and diversions) might in some cases be contributing much more to streamflow changes than forest cover change [31].

But comprehensive studies that clarify the infiltration question and the low-flow problem are still few (as pointed out for China by [32]). In fact, most studies in the tropics still have methodological problems [33,34*], and ecologists continue to argue for the flood control benefits of forests [35] but without convincing evidence [36]. While more studies have been taken up in Latin America and southeast Asia, south Asia and Africa continue to be inadequately investigated.

Economic impact of change in watershed services of forests

While the literature on ecosystem service valuation in general is booming, as also that on PES, economic analyses of watershed services of tropical forests in the past two decades have been scanty. Dropping those that are not based on site-specific economic data,³ the rest have been summarised in Table 2 in terms of their main features. Of these, some do not clearly spell out what alternative land-use scenario is being considered; these have been listed at the end.

Several patterns emerge from this review. First, the geographic distribution of these economic studies mirrors that of the hydrological studies, i.e., largely concentrated in south-east Asia and Latin America, with poor coverage of south Asia and Africa.

Second, the type of forest cover transition (logging, reforestation, degradation) or conversion (forest to agriculture or swidden) that is relevant varies from site to site, as does the type of 'service': power generation, urban water supply, irrigation, or health. Trying to come up with one value or even a range of values for watershed services of tropical forests is therefore meaningless. Even within a single type of impact the range is enormous—from \$4/yr/ha to \$2000/yr/ha in the case of sedimentation effects on hydropower generation [13*]. Thus, we are not in a position to offer benchmarks for extrapolation to other sites.

Third, and perhaps most important, even the direction of impact is different from conventional wisdom. The con-

³ Those that use the so-called 'benefit transfer approach' [e.g., [37,38,39]].

Table 2
Main features of recent economic valuation studies of watershed services in tropical forests.

Study	Region	Type of forest cover change	Watershed effect analysed	Biophysical model/method used	Type of impacts and stakeholders	Method(s) used for valuation
<i>Studies with clearly specified alternative land-use scenarios</i>						
[52]	Philippines	Natural forest to logged forest	Increased downstream sedimentation	Paired catchment study	Damage to coral reef and hence decline in tourism and fishing	Gross revenues from tourism and fishing before and after logging
[53]	Malaysia	Natural forest to selectively logged forest	Decline in water seeping out of the peat swamp forest	Threshold model of storage-seepage relationship	Loss of agricultural production (second paddy crop)	Ex-ante simulation: assume 10% crop loss for each year that threshold is exceeded
[40**]	Chiang Mai, Thailand	Natural forest replaced by pine	Decline in streamflow	Analysis of time-series of streamflow and forest cover data	Water scarcity for urban users, and loss of agricultural production	Ex-post analysis, direct estimation
[50*]	Madagascar	Forest to swidden agriculture	Increased flood frequency	Analysis of time-series of streamflows and forest cover data	Loss of agricultural (paddy) production	Ex-ante simulation, using average profitability of paddy cultivation
[42*]	Costa Rica	Forest to pasture	Increased sedimentation but increased water yield	USLE & water balance model from other studies	Changes in hydropower generation	Ex-ante simulation, direct estimation
[54]	Indonesia	Natural forest to two logging regimes	Increased downstream sedimentation	Paired catchment study	Loss of hydropower generation and increased cost of water treatment	Ex-ante simulation: direct loss of economic production
[47]	Western Ghats, India	Regeneration of degraded forest to dense natural forest	Higher soil erosion in degraded forest (plus changes in many other forest state and process variables)	USLE for soil erosion, linear model converting sedimentation to irrigation reduction and then crop loss	Increased siltation in downstream reservoirs reduces frequency of irrigated paddy crop	Ex-post analysis: time-series on forest cover change coupled with cross-sectional data on forest use, and average crop production values
[51]	Kumaon region, India	Reduction in forest cover (presumably replaced by agriculture)	Decrease in streamflow	Water balance model—not validated	Loss of agricultural production	Contingent valuation
[55]	Hawaii	Natural to degraded forest	Decline in groundwater recharge	Assumed that change forest quality will reduce recharge by 31%	Reduced urban water availability	Ex-ante simulation, average values, backstop technology
[43,56*,57,58]	Indonesia	Forest to agriculture	Decline in baseflow	Pre-existing water balance model for study catchments used to generate baseflow estimates	Loss of agricultural production (2001), increased water collection costs (2004), increase in diarrhoea (2007)	Ex-ante simulation: cross-sectional analysis across 37 watersheds; different studies use different techniques (production function, contingent valuation, consumer surplus approach or averting expenditure)
[46*]	Western Ghats, India	Degraded forest to natural forest	Decline in surface runoff	Paired catchment study	Reduced frequency of irrigated crop in command area of irrigation tank	Ex-ante simulation: net income from irrigated and unirrigated agriculture through sample plot monitoring and survey

Table 2 (Continued)

Study	Region	Type of forest cover change	Watershed effect analysed	Biophysical model/method used	Type of impacts and stakeholders	Method(s) used for valuation
[44*]	Sumatra, Indonesia	Natural forest to degraded forest or to selectively used forest	Increased erosion rates in agricultural lands, decreasing streamflows, increased floods, plus changes in many other forest state and process variables	From anecdotal evidence and guesstimates	Decline in agricultural productivity, increase in price of domestic water & flood damage	Ex ante simulation: secondary data from various sectors and sources; TEV changes presented sector wise, stakeholder wise, county-wise
[41]	Valdavian eco-region, Chile	Natural forest to pine plantation	Decrease in streamflow	Model relating streamflow to water supplied was generated from secondary data	Decline in quantity of water supplied to city	Price x change in quantity supplied.
[45]	Central Sulawesi, Indonesia	Dense natural forest to degraded forest	Decrease in streamflow	Observed streamflow data with model relating land-cover to flow (calibrated)	Decline in water available for irrigated paddy crop in dry season	Choice experiments, after converting scientific model results into local perception data
[59]	Tapanti NationalPark, Costa Rica	Part deforestation, part conversion to agriculture	Increase in sediment load, water quantity (and also biodiversity)	Experts input on erosion rates (zero sedimentation assumed in forested catchment!)	Increased water purification cost, increased hydropower generation cost (apparently due to dredging)	Cost data from water purification plant and hydropower plant
[60]	Peru and Equador	Conversion of forests to agriculture/pasture/coffee/swidden/restoration	Increase in sediment load, increase in total flow, decrease in dry season flow	Soil & Water Assessment Tool (SWAT) model with local soil data, calibrated with flow data	Decreased water treatment costs, increased water supply cost to urban consumers	<i>Did not study economic benefits to downstream stakeholders, only opportunity costs (of not cultivating) to upstream landholders</i>
<i>Studies where alternative land-use scenario is not clearly specified (hence '?' below), or absolute value is sought to be estimated</i>						
[61]	Xingshan county (Yangtse river) China	No forest to complete forest?	Increase in water regulation capacity (defined as water stored in forest canopy, litter, & soil)	Detailed physical model with local data but no validation; GIS-based land-cover map	Increased hydropower generation because of regulated release of water	Model relating river flow to power generation; constant electricity price
[62]	Xingshan county, China	No forest to complete forest?	Increase in water regulation capacity, decrease in soil erosion and sedimentation, plus all other components of TEV	Detailed forest cover data, soil erosion rates assumed, forest productivity data source not given	Increased hydropower, agricultural production, oxygen production, timber production	Direct economic valuation, travel cost method (crude), replacement cost of oxygen
[6]	Entire India	No forest to complete forest?	Increase in soil conservation, flow augmentation, flood prevention	Avg. value of soil loss prevented and groundwater recharged by forests from literature	Soil fertility increases production [but actually in forest!]; more water available for all types of consumers	Replacement fertilizer value of nutrients lost in soil erosion; opportunity cost of water at a steel plant
[63]	18 countries in the Mediterranean region	No forest to complete forest?	Sediment load, flow regulation (and all other components of TEV)	Not clear, most probably expert opinion	Decreased cost of water purification and flood damage	Not clear: direct valuation, avoided cost, defensive expenditures for structures

version of natural forest to pine plantations consistently shows reduced flows [40^{••},41] whereas a rare study integrating flow and sediment load effects [42[•]] predicts net positive impacts of forest conversion to pasture because benefits from increased flows exceed sedimentation impacts. While deforestation is expected to cause reductions in agricultural incomes in Indonesia because of reduced baseflow [43–45], forest regeneration is expected to reduce agricultural incomes in Western Ghats, India [46[•]] because agriculture there depends upon surface runoff filling downstream tanks.

Fourth, there are only two studies where watershed services were part of a larger total economic valuation (TEV) and where stakeholder-wise analyses were done [44[•],47]. They show clear trade-offs between different forest ecosystem benefits and beneficiaries. Additional hydrological benefits come at a cost, sometimes to local forest users [47] and sometimes to timber companies [44[•]].

Reaching an integrated understanding

While several interesting studies have emerged in the last decade, we are some distance from a clear understanding of the links between tropical forest cover-watershed process and socio-economic impact. Apart from gaps in regional coverage mentioned above, there are key weaknesses that appear to stem from lack of a shared and rigorous conceptual framework and methodology within and across disciplines. At the outset, the tendency to equate process with service and to estimate absolute economic value rather than difference with respect to specific (and realistic) alternative land-use scenarios persists (as in the last four studies in Table 2). In fact, such conceptually flawed studies seem to dominate the policy discourse (e.g., [48], which is based on [6]). Changing the framing of the problem is the first challenge confronting researchers of tropical forest watershed services.

Even if correctly framed, addressing the problem by collecting and analysing adequate amounts of both biophysical and socio-economic data is a major challenge. Consequently, economists continue to depend upon the simplistic Universal Soil Loss Equation (USLE) [see critique in [13[•]]] or guesstimates of erosion rates and hydrological change [44[•]], while hydrologists are actually measuring sediment load and using sophisticated SWAT models. Only a few economists have had access to robust hydrological models [e.g., [56[•]]]; others have done the analysis themselves [40^{••}]. Similarly, hydrologists venturing into valuation end up using the benefit transfer approach [e.g., [49]] rather than generate primary site-specific data. Collaborations between hydrologists and economists are slowly increasing [41,45,46[•],50[•],51], although some times the inter-linkages remain weak [e.g., [51]]. Without rigorous models and tight integration, the findings will be highly uncertain.

The 'socialization' of the hydrological variables remains a challenge. Barkmann *et al.* [45] demonstrated the importance of properly identifying and representing socially relevant hydrological variables and their changes, especially in contingent valuation studies; this requires extensive qualitative pre-studies and interaction with hydrologists. But also required is an understanding of the agro-hydrology [46[•]] that links streamflow to water in the field, viz., the functioning of irrigation systems or well technology and groundwater institutions, which requires involving engineers as well [21].

Finally, economists will have to move beyond generating single monetary values of aggregate economic welfare to understanding their distribution and different ways of aggregation [47]. Showing the statistical significance of a hydrological variable in the econometric analysis only shows that 'hydrological services matter'. But more place-based and realistic analyses of what institutional, cultural and political factors shape impacts, and how ecosystem users respond to these impacts, both downstream and upstream, are required for making a meaningful contribution to environmental policy.

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