HESS-2015-538 Response to reviewers

General: We appreciate the chance to respond to the two reviewers, as the original manuscript underwent major changes in splitting it in two parts. We're pleased that the current focus of both papers appears to work well. The further comments of reviewer 2 are of definite help in fine-tuning the manuscripts. Reviewer 1 still has major doubts or questions on the core of the method and concept we describe here – and we from our side are challenged to understand where and how we create the apparent misunderstandings that the reviewer articulates.

The core of the argument here seems to be:

> The manuscript states: $Q_t = F_p Q_{t-1} + Q_{a,t}$
>
> Reviewer states: Assuming that $Q_{a,t} = 0$ for now, then $Q_t = F_p Q_{t-1}$ and this can't be true for F_p restricted to the 0-1 range, so the equation can't be right…
>
> But, that's why there is the term $Q_{a,t}$. We've tried to understand whether in the text leading up to the first equation we've given the impression that $Q_{a,t}$ is 'negligible', but we don't see where we did set the reviewer on the wrong track.

Yet we have revised some of the text introducing the concept, and hope that a fresh look at this all by the reviewer could lead to more understanding of what we propose.

Detailed response to reviewer comments

Reviewer 1.	Response
I think the restructuring and responses to the reviewer comments on the previous submission have materially improved the MS relative to the previous one.	Thanks
I have only reviewed the first paper of the two though because I have encountered issues that need to be resolved.	
My overall comment is that much of the lengthy introduction on the various possible interpretations of flow persistence (Fp or the slope of the recession curve) adds little value and could even confuse readers. My preference would be reduce the lengthy detail and digressions, and focus on why and how catchments respond temporally to rainfall, what shifts in those responses may mean, and how an understanding of response mechanisms can lead to actions aimed at recovering catchment function.	There have of course been many discussions of the type reviewer prefers, and some are quoted here. Yet, it is not clear how the success of such interventions can be measured. Out focus here is what a stakeholder/observer who 'only' has access to data on the daily dynamics of river flow can infer about conditions upstream, and how he/she could interpret changes in the performance parameter that we propose. That's the stated purpose of the paper, and that's what we do. If reviewer wants to see a different paper, she/he may need different authors with access to different data.
It seems that the authors have failed to grasp a major comment I had on the previous version. In my opinion this MUST be addressed before this version can be taken any further. I thought my comment was straightforward and easily understood, but it seems the authors have	We have indeed failed to grasp this argument, because we think it is based on reviewer not grasping the argument we made. We hope reviewer can reconsider the perspective.

failed to grasp the issue so I will try again. The whole study is predicated on finding a simple index of flow persistence which can be measured over time to detect whether land-use changes are altering the responsiveness of a catchment to rainfall input. Fine and good. An examination of flow hydrographs will show that the flows out of a catchment initially rise after a rainfall event and then decrease again, with the decrease following what is known as a recession curve. The rise is typically more rapid than the recession or fall. With this as the context, I now take their equation (1) which is as follows: Qt =Fp Qt-1 + Qa,t Assuming that Qa,t = 0 for now, then Qt =FpQt-1 (i.e. the flow at time t is related to the flow at time t-1 by Fp). For this equation to be true for every rise or increase in flow (i.e. where Qt>Qt-1) Fp must be >1.	We concur that the rise in hydrographs is faster than the subsequent decline – and found (based on water balance logic) a way that the two are linked: the increase (at daily observation scale) is (1-F_p) times the effective rainfall, while the decrease is proportional to F_p What gives reviewer reason to make this assumption? Please, understand that if Q_t>Q_{t-1} the term $Q_{a,t}$ wont be zero, so your 'problem' doesn't exist.
Yet they only deal with values of Fp in the range from 0 to 1. So the Fp they are describing must only calculated on the falling flows. Yet this is not mentioned or described anywhere in the paper even though they explicitly note that Fp is equivalent to a recession constant (line 222). The authors provide data that show flow responses in a catchment (Figure 2 and assoc text) where the variability of flow (i.e. the magnitude of both the rises and falls) increases, yet there are no values of Fp>1. This needs explanation.	Please, the explanation is that there is also term Qa,t in the equation... The caption of Fig. 2 refers to "unimodal rainfall regime" – we have provided further detail on how a stochastic rainfall time series is used here to derive (P_t-E_{tx}), while increments in flow (the $Q_{a,t}$ term) are calculated as (1-F_p) (P_t-E_{tx}). If F_p = 1.0 we have a constant flow throughout the year, without any increments or decreases and 'perfect' buffering. Values of F_p above 1.0 are in our view not feasible within the equations we developed.
At some points they discuss the term Qa,t as though it were stochastic, at other points it seems that Qa,t is used to account for all flows greater than some level of base flow (implying that Qa,t is ≥0).	Yes, both statements are correct.
(BTW My understanding is that if Qa,t represents a proportion of the observed flow, it is not actually stochastic although there may be factors that give it a degree of stochasticity?)	Our use of "stochastic" is aligned with its common definition: https://en.wikipedia.org/wiki/Stochastic as "the physical systems in which the values of parameters, measurements, expected input, and disturbances are uncertain. "; it doesn't mean that stochastic terms are unbounded. The idea that a term can't be stochastic because it can be expressed as a fraction of the sum of that term and another one would, we think, not hold up to scrutiny. In that case stochasticity could not exist, as it can always be expressed as a fraction.

If Qa,t represents all non-base-flows, then all the values where Fp would be >1 are used to estimate Qa,t (which is what I infer from lines 243-246)?	Almost correct, Qa,t indeed represents all non-base-flows – but there are no cases with $F_p > 1$, the way we have defined the terms of our equations.
Did they effectively vary Qa,t to get the results they present in Figure 1? If so, this needs to be explained.	Reviewer probably refers to Fig. 2 here. In that case: we have modified the figure to show both base flow and Qa,t
I also question then why they do not simply describe this approach as flow separation technique with the aim of quantifying the catchment responsiveness rather than the flow persistence.	Yes, the F_p is close to one of several flow separation techniques – but that terminology might come with strong perceptions on how it should be done. We prefer to present our method as following from what can be inferred from a time series of daily flow records, and then discuss where and how this differs from what has been done before. In the hope that it may help readers like reviewer 1, we have if it would help the reviewer we have used the flow separation language at an earlier point in the revised manuscript.
To my mind, they have not adequately explained these key points, so until I get an understandable explanation I cannot accept the paper.	We appreciate your 'persistence', but hope that the current version avoids the misunderstan-ding on which, we believe, your issues were based.
Some other points:	
Lines 119-138 provides a discussion of whether changes in land cover lead to changes in flows. They note that this has been shown in small catchments but not in large catchments. Yet they do not discuss the simple issue of detectability given the accuracy of the flow recording system. The design of most large weirs is simply not suitable for accurately measuring base-flows or relatively small changes in flows, which means that changes have to affect most of the catchment to be detectable and accurately quantifiable.	We added a brief reference to issues of detectability: "Detectability of effects depends on their relative size, the accuracy of the measurement devices, background variability of the signal and length of observation period."
In line 247-249 they describe Qa,t as being interpretable as effective rainfall. My understanding effective rainfall is that is this is simple a measure of how much rainfall is taken up by the soil. Only a daily time step (which is what they argue is logical to use) much of this water will not appear as flow over 24 hours unless the catchment is already saturated or has some rapid flow response mechanisms (i.e. rapid interflow). So it will not be adequately measured by Qa,t which needs to be made clear.	Reviewer is probably working in an environment where "events" are clearly separated, whereas we start from daily flow observations as such not knowing time-space details of rainfall. We thus don't know the time of rainfall relative to the time of observing river flow, nor the time it takes for rivers (at the point of observation) to respond. Effective rainfall is normally defined from the perspective of what reaches rivers. We are considering the statistical properties of the Q_a frequency distribution, rather than individual values.

There are a number of places where they abruptly introduce new symbols and fail to explain them e.g. line 237 QT and Qo are not explained.	We have made clear in the revised text that Q_T and Q_0 are equal to Q_t for t=T and t=0, respectively
There are still several basic typographical errors that would be found by a spell checker and should not be in a submitted MS.	Apologies (the spellchecker had been inadvertently switched off in part of the file)... We had further help in the current ms version
Reviewer 2	
Referee Report General Comments: Both of these articles are relevant and could provide contributions to decision makers, as well as those working with ecosystem services and flood risk. The authors adequately addressed all of my concerns within the original submission making the subsequent paper much more suitable for publication. The separation of the original article into two greatly strengthens the study.	
Specific Comments:	
Abstract: Abstracts need to be shortened. The abstracts are far too verbose as they stand. A more simplified abstract that excludes detailed discussions of equations/parameters will make them clearer and more engaging.	Addressed
PART I Figure 1: This figure is much improved and far easier to follow, however it seems a little blurry. Misspelling of pathways at line 727. No explanation of step 10 in figure description.	Addressed, explanation of step 10 added in the caption (consistent with its reference in the text)
Figure 4: This figure is blurry making the small text difficult to read. Avoid using contractions: For example, “don’t” should be “do not” Lined 158: change doess to does. Line 196: “it’s” should be “its”	Thanks, all corrections made
Line 212: “The probably simplest” to “A simple”	Thanks
Line 227-239: The wording of this sentence is confusing and requires some revisions.	Adjusted
Line 456: “en” should be “an”	Thanks
Line 534-536: Spell out authors’ full names.	Addressed
PART II An explanation of the general land cover characteristics for each watershed would be helpful.	
Table 1 provides an element of confusion regarding the proportion of forested land that needs to be acknowledged.	
Needs a conclusion section that summarizes the study, discusses implications, and acknowledges limitations and future research directions.	We have added a section “conclusions” that summarizes the discussion. Further research directions might be more appropriate in the discussion section.
Line 817: add comma after part	

Line 832: removed comma after intensity and response	Addressed
Line 841: add “the” after “we consider”	Addressed
Line 848: change patchlevel to “the patch level”	Addressed
Line 855 & 883: change “land-cover” to land “cover” (and throughout paper)	Addressed
Line 868: change “Fig.” to “Figure” (and throughout paper); “provides” to “provide”; and remove “are”	Addressed
Line 886: change “land-use” to “land use” (and throughout paper)	Addressed
Line 937: unsure what dace is supposed to mean	Addressed
Line 945: add “the” before “measuring”	Addressed
Line 987: no supplementary information given…	Addressed
Table 1: What is the differentiation between “forest” within land cover type and “natural forest” at the bottom of the table? For Bialo and Mae Chaem they are equal, but are different for the other two. An explanation for this must be given as the proportion of forested land is one of the primary drivers behind flow predictability.	Addressed
Figure 1: blurry	Addressed
Figure 5: Why are the water balance percentages different for the NatFor scenario when Figure App2 shows that the NatFor scenario is 100% for all watersheds?	The sites have different rainfall patterns, soils and landscape properties, all influencing the water balance.
Appendix 2: no proportions for Mae Chaem AgFor are given.	This land use type does not exist in Mae Chaem, according the data we used.

Flood risk reduction and flow buffering as ecosystem services: I. Theory on a flow persistence indicator for watershed health

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Abstract 1

We present and discuss a candidate ~~here~~ for a single parameter representation of the complex concept of watershed quality that does align short and long term responses, and provides bounds to the levels of unpredica~~t~~aibility. Flow buffering in landscapes is commonly interpreted as ecosystem service, but needs quantification, as f~~. F~~lood damage reflects insufficient adaptation of human presence and activity to location and variability ~~(inherent plus induced)~~ of river flow. Increased variability and reduced predictability of river flow is a common sign, in public discourse, of degrading watersheds, combining increased flooding risk and reduced low flows. ~~Flow buffering in landscapes is commonly interpreted as ecosystem service, but needs quantification.~~ Geology, landscape form, soil porosity, litter layer and surface features, drainage pathways, vegetation and space-time patterns of rainfall interact in complex space-time patterns of ~~riverflow~~river flow, but the anthropogenic aspects tend to get discussed on a one-dimensional scale of degradation and restoration. A strong tradition in public discourse associates changes on such degradation-restoration axis with binary deforestation-reforestation shifts. ~~changes in tree cover and/or forest quality~~E~~, but the e~~mpirical evidence for such link that may exist at high spatial resolution may not be a safe basis for securing required flow buffering in landscapes at large. ~~. Capturing the relationship between the space-time patterns of rainfall and riverflow in a single buffering indicator can help the way empirical evidence is summarized and projected change in land use change scenarios is evaluated. Where space-time details of rainfall remain unknown, a simpler approach is needed. We present and discuss a candidate here for a single parameter representation of the complex concept of watershed quality that does align short and long term responses, and provides bounds to the levels of unpredicatibility.~~ We define a ~~The~~ dimensionless FlowPer parameter F_p that ~~(F_p)~~ represents predictability of river flow in a recursive flow model. Analysis suggests that buffering has two interlinked effects: a smaller fraction of fresh rainfall enters the streams, and flow becomes more persistent, in that the ratio of the flow on subsequent days has a higher minimum level. ~~It is defined through a recursive model of river flow,~~ $\cancel{Q_t = F_pQ_{t-1} + (1-F_p)(P_t - E_{tx})}$~~, that relates the flow Q on day t to that on the previous day~~ $\cancel{(Q_{t-1})}$~~, and a term that reflects precipitation P on the day itself and evapotranspiration E in a preceding time period, with Q, P and E expressed in~~ $\cancel{mm\ d^{-1}}$~~. When summed over one or more~~

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~~years, this recursive model reflects the water balance ($\sum Q = \sum P - \sum E$), once changes in the storage term that can dominate short term dynamics become negligible. F_p varies between 0 and 1, and can be derived from a time-series of measured (or modeled) river flow data. In a parsimonious interpretation that aligns with data sets that only exist of (daily) records of riverflow, the spatially averaged precipitation term P_t and preceding cumulative evapotranspiration since previous rain E_{tx} are treated as constrained but unknown, stochastic variables. Without knowing when peak flows occur, the balance equation suggests that a decrease in F_p from 0.9 to 0.8 means peak flow doubling from 10 to 20% of peak rainfall (minus its accompanying E_{tx}). Flood duration has a nonlinear response to increases in F_p, as low F_p values lead to high peak flow of short duration, and at high F_p values thresholds of flooding may never be reached. In a numerical example a decrease in F_p led at most to an increase in expected flood duration by 3 days.~~ As a potential indicator of watershed health (or quality), the F_p metric (or its change over time from what appears to be the local norm) matches local knowledge concepts, captures key aspects of the river flow dynamic and can be unambiguously derived from empirical river flow data. Further exploration of responsiveness of F_p to the interaction of land cover and the specific realization of space-time patterns of rainfall in a limited observation period is needed to test the interpretation of F_p as indicator of watershed health (or quality) in the way this is degrading or restoring through land cover change and modifications of the overland and surface flow pathways, given inherent properties such as geology, geomorphology and climate.

1 Introduction

Degradation of watersheds and its consequences for river flow regime and flooding intensity and frequency are a widespread concern (Brauman ~~et al~~et al.~~.~~, 2007; Bishop and Pagiola, 2012; Winsemius ~~et al~~et al.~~.~~, 2013). Current watershed rehabilitation programs that focus on increasing tree cover in upper watersheds are only partly aligned with current scientific evidence of effects of large-scale tree planting on streamflow (Ghimire ~~et al~~et al.~~.~~, 2014; Malmer ~~et al~~et al.~~.~~, 2010; Palmer, 2009; van Noordwijk ~~et al~~et al.~~.~~, 2007, 2015a; Verbist ~~et al~~et al., 2010). The relationship between floods and change in forest quality and quantity, and the availability of evidence for such a relationship at various scales has been widely discussed over the past decades (Andréassian, 2004; Bruijnzeel, 2004; Bradshaw ~~et al~~et al.~~.~~, 2007; van Dijk ~~et al~~et al.~~.~~, 2009). Measurements in Cote d'Ivoire, for example, showed strong scale dependence

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of runoff from 30-50% at 1 m^2 point scale, to 4% at 130 ha watershed scale, linked to spatial variability of soil properties plus variations in rainfall patterns (Van de Giesen ~~et al~~et al., 2000). The ratio between peak and average flow decreases from headwater streams to main rivers in a predictable manner; while mean annual discharge scales with $(area)^{1.0}$, maximum river flow was found to scale with $(area)^{0.7}$ on average (Rodríguez-Iturbe and Rinaldo, 2001; van Noordwijk ~~et al~~et al., 1998). The determinants of peak flow~~s~~ are thus scale-dependent, with space-time correlations in rainfall interacting with subcatchment-level flow buffering ~~in peakflows~~ at any point along the river. Whether and where ~~peakflow~~peak flows lead to flooding depends on the capacity of the rivers to pass on ~~peakflow~~peak flows towards downstream lakes or the sea, assisted by riparian buffer areas with sufficient storage capacity (Baldasarre ~~et al~~et al., 2013); reducing local flooding risk by increased drainage increases flooding risk downstream, challenging the nested-scales management of watersheds to find an optimal spatial distribution, rather then minimization, of flooding probabilities. Well-studied effects of forest conversion on peak flows in small upper stream catchments (Alila ~~et al~~et al., 2009) do not necessarily translate to flooding downstream. As summarized by Beck ~~et al~~et al. (2013) meso- to macroscale catchment studies (>1 and >10 000 km^2, respectively) in the tropics, subtropics, and warm temperate regions have mostly failed to demonstrate a clear relationship between river flow and change in forest area. Lack of evidence cannot be firmly interpreted as evidence for lack of effect, however. Detectability of effects depends on their relative size, the accuracy of the measurement devices, background variability of the signal and length of observation period. A recent econometric study for Peninsular Malaysia by Tan-Soo ~~et al~~et al. (2014) concluded that, after appropriate corrections for space-time correlates in the data-set for 31 meso- and macroscale basins (554-28,643 km^2), conversion of inland rain forest to monocultural plantations of oil palm or rubber increased the number of flooding days reported, but not the number of flood events, while conversion of wetland forests to urban areas reduced downstream flood duration. This Malaysian study may be the first credible empirical evidence at this scale. The difference between results for flood duration and flood frequency and the result for draining wetland forests warrant further scrutiny. Consistency of these findings with river flow models based on a water balance and likely pathways of water under the influence of change in land cover and land use has yet to be shown. Two recent studies for Southern China confirm the conventional perspective that deforestation increases high flows, but are contrasting in effects of reforestation. Zhou ~~et al~~et al. (2010) ~~analyzed~~analysed a 50-year data set for Guangdong Province in China and concluded that forest recovery had not changed the annual water yield (or its underpinning water balance terms precipitation and ~~evapotransipiration~~evapotranspiration), but had a statistically significant positive effect on dry season (low) flows. Liu ~~et al~~et al~~.~~, (2015), however, found for the Meijiang watershed (6983 km2) in subtropical China that while historical deforestation had decreased the magnitudes of low flows (daily flows ≦ Q95%) by 30.1%, low flows were not significantly improved by reforestation. They concluded that recovery of low flows by reforestation may take much longer time than expected probably because of severe soil erosion and resultant loss of soil infiltration capacity after deforestation. Changes in ~~riverflow~~river flow patterns over a limited period of time can be the combined and interactive effects of variations in the local rainfall regime, land cover effects on soil structure and engineering modifications of water flow, that can be teased apart with modelling tools (Ma ~~et al~~et al~~.~~, 2014).

Lacombe ~~et al~~et al~~.~~, (2015) documented that the hydrological effects of natural regeneration differ from those of plantation forestry, while forest statistics do~~n't~~ not normally differentiate between these different land covers. In a regression study of the high and low flow regimes in the Volta and Mekong river basins Lacombe and McCartney (2016) found that in the variation among tributaries various aspects of land cover and land cover change had explanatory power. Between the two basins, however, these aspects differed. In the Mekong basin variation in forest cover had no direct effect on flows, but extending paddy areas resulted in a decrease in downstream low flows, probably by increasing evapotranspiration in the dry season. In the Volta River Basin, the conversion of forests to crops (or a reduction of tree cover in the existing parkland system) induced greater downstream flood flows. This observation is aligned with the experimental identification of an optimal, intermediate tree cover from the perspective of groundwater recharge in parklands in Burkina Faso (Ilstedt ~~et al~~et al~~.~~, 2016).

The statistical challenges of attribution of cause and effect in such data-sets are considerable with land use/land cover interacting with spatially and temporally variable rainfall, geological configuration and the fact that land use is not changing in random fashion or following any pre-randomized design (Alila ~~et al~~et al~~.~~, 2009; Rudel ~~et al~~et al~~.~~, 2005). Hydrolog~~ic~~ical analysis across 12 catchments in Puerto Rico by Beck ~~et al~~et al~~.~~, (2013) did not find significant relationships between the change in forest cover or urban area, and change in various flow characteristics, despite indications that regrowing forests increased evapotranspiration. Yet, the concept of a 'regulating function' on river flow regime for forests and other semi-natural ecosystems is widespread. The considerable human and economic costs of flooding at locations

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and times beyond where this is expected make the presumed ‘regulating function’ on flood reduction of high value (Brauman ~~et al~~et al., 2007) – if only we could be sure that the effect is real, beyond the local scales (< 10 km^2) of paired catchments where ample direct empirical proof exists (Bruijnzeel, 1990, 2004). These observations imply that percent tree cover (or other forest related indicators) is probably not a good metric for judging the ecosystem services provided by a watershed (of different levels of ‘health’), and that a metric more directly reflecting changes in river flow may be needed. Here we will explore a simple recursive model of river flow (van Noordwijk ~~et al~~et al., 2011) that (i) is focused on (loss of) predictability, (ii) can account for the types of results obtained by the cited recent Malaysian study (Tan-Soo ~~et al~~et al., 2014), and (iii) may constitute a suitable performance indicator to monitor watershed ‘health‘ through time.

⇨ ~~Fig.~~Figure 1

Figure 1 is compatible with a common dissection of risk as the product of hazard, exposure and vulnerability. Extreme discharge events plus river-level engineering co-determine hazard, while exposure depends on topographic position interacting with human presence, and vulnerability can be modified by engineering at a finer scale and be further reduced by advice to leave an area in high-risk periods. A recent study (Jongman ~~et al~~et al., 2015) found that human fatalities and material losses between 1980 and 2010 expressed as a share of the exposed population and gross domestic product were decreasing with rising income. The planning needed to avoid extensive damage requires quantification of the risk of higher than usual discharges, especially at the upper tail end of the flow frequency distribution.

The statistical scarcity, per definition, of ‘extreme events’ and the challenge of data collection where they do occur, make it hard to rely on empirical data as such. Existing data on flood frequency and duration, as well as human and economic damage are influenced by topography, human population density and economic activity, interacting with engineered infrastructure (step 4 and 5 in ~~Fig.~~Figure 1), as well as the extreme rainfall events that are their proximate cause. Subsidence due to groundwater extraction in urban areas of high population density is a specific problem for a number of cities built on floodplains (such as Jakarta and Bangkok), but subsidence of drained peat areas has also been found to increase flooding risks elsewhere (Sumarga ~~et al~~et al., 2016). Common hydrological analysis of flood frequency (called 1 in 10-, 1 in 100-, 1 in 1000-year flood events, for example) does~~s~~ not separately attribute flood magnitude to rainfall and land use properties, and analysis of likely change in flood frequencies in the context of climate change adaptation has been challenging (Milly ~~et al~~et al., 2002; Ma ~~et~~

~~al~~et al~~.~~, 2014). There is a lack of simple performance indicators for watershed health at its point of relating precipitation P and river flow Q (step 2 in ~~Fig.~~Figure 1) that align with local observations of river ~~behavior~~behaviour and concerns about its change and that can reconcile local, public/policy and scientific knowledge, thereby helping negotiated change in watershed management (Leimona ~~et al~~et al~~.~~, 2015). The ~~behavior~~behaviour of rivers depends on many climatic (step 1 in Figure 1) and terrain factors (step 7-9 in Figure 1) that make it a challenge to differentiate between anthropogenically induced ecosystem structural change and soil degradation (step 7a) on one hand and intrinsic variability on the other. Arrow 10 in Figure 1 represents the direct influence of climate on vegetation, but also a possible reverse influence (van Noordwijk ~~et al~~et al~~.~~, 2015b). Hydrological models tend to focus on predicting hydrographs at one or more temporal scales, and are usually tested on data-sets from limited locations. Despite many decades (if not centuries) of hydrological ~~modeling~~modelling, current hydrologic theory, models and empirical methods have been found to be largely inadequate for sound predictions in ungauged basins (Hrachowitz ~~et al~~et al~~.~~, 2013). Efforts to resolve this through harmonization of modelling strategies have so far failed. Existing models differ in the number of explanatory variables and parameters they use, but are generally dependent on empirical data of rainfall that are available for specific measurement points but not at the spatial resolution that is required for a close match between measured and ~~modeled~~modelled river flow. Spatially explicit models have conceptual appeal (Ma ~~et al~~et al~~.~~, 2010) but have too many degrees of freedom and too many opportunities for getting right answers for wrong reasons if used for empirical calibration (Beven, 2011). Parsimonious, parameter-sparse models are appropriate for the level of evidence available to constrain them, but these parameters are themselves implicitly influenced by many aspects of existing and changing features of the watershed, making it hard to use such models for scenario studies of interacting land use and climate change. Here we present a more direct approach deriving a metric of flow predictability that can bridge local concerns and concepts to quantified hydrologic function: the ‘flow persistence’ parameter (step 2 in Figure 1).

In this contribution to the debate we will first define the metric ‘flow persistence’ in the context of temporal autocorrelation of river flow and then derive a way to estimate its numerical value. In part II we will apply the algorithm to river flow data for a number of contrasting meso-scale watersheds. In the discussion of this paper we will consider the new flow persistence metric in terms of three groups of criteria for usable knowledge (Clark ~~et al~~et al~~.~~, 2011; Lusiana ~~et al~~et al., 2011; Leimona ~~et al~~et al., 2015) based on salience (1,2), credibility (3,4) and legitimacy (5-7):

1. Does flow persistence relate to important aspects of watershed ~~behavior~~behaviour?
2. Does it~~'~~s quantification help to select management actions?
3. Is there consistency of numerical results?
4. How sensitive is it to bias and random error in data sources?
5. Does it match local knowledge?
6. Can it be used to empower local stakeholders of watershed management?
7. Can it inform local risk management?

Questions 3 and 4 will get specific attention in part II.

2 Recursive river flow model and flow persistence

2.1 Basic equations

One of the easiest-to-observe aspects of a river is its day-to-day fluctuation in ~~waterlevel~~water level, related to the volumetric flow (discharge) via rating curves (Maidment, 1992). Without knowing details of upstream rainfall and the pathways the rain takes to reach the river, observation of the daily fluctuations in ~~waterlevel~~water level allows important inferences to be made. It is also of direct utility: sudden rises can lead to floods without sufficient warning, while rapid decline makes water utilization difficult. Indeed, a common local description of watershed degradation is that rivers become more 'flashy' and less predictable, having lost a buffer or 'sponge' effect (Joshi ~~et al~~et al., 2004; Ranieri ~~et al~~et al., 2004; Rahayu ~~et al~~et al., 2013). ~~The probably~~A simple~~st~~ model of river flow at time t, Q_t, is that it is similar to that of the day before (Q_{t-1}), to the degree F_p, a dimensionless parameter called 'flow persistence' (van Noordwijk ~~et al~~et al., 2011) plus an additional stochastic term $Q_{a,t}$:

$$Q_t = F_p Q_{t-1} + Q_{a,t} \quad [1].$$

Q_t is for this analysis expressed in mm d^{-1}, which means that measurements in $m^3 s^{-1}$ need to be divided by the relevant catchment area, with appropriate unit conversion. If river flow were constant, it would be perfectly predictable, i.e. F_p would be 1.0 and $Q_{a,t}$ zero; in contrast, an F_p-

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value equal to zero and $Q_{a,t}$ directly reflecting erratic rainfall represents the lowest possible level of predictability.

The F_p parameter is conceptually identical to the 'recession constant' commonly used in hydrological models, typically assessed during an extended dry period when the $Q_{a,t}$ term is negligible and streamflow consists of ~~baseflow~~base flow only (Tallaksen, 1995); empirical deviations from a straight line in a plot of the logarithm of Q against time are common and point to multiple rather than a single groundwater pool that contributes to base flow. The larger catchment area has a possibility to get additional flow from multiple independent groundwater contribution.

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~~With increasing size of a catchment area it is increasingly likely that there indeed are multiple, partly independent groundwater contributions.~~

As we will demonstrate in a next section, it is possible to derive F_p even when $Q_{a,t}$ is not negligible. In climates without distinct dry season this is essential; elsewhere it allows a comparison of apparent F_p between wet and dry parts of the hydrologic year. A possible interpretation, to be further explored, is that decrease over the years of F_p indicates 'watershed degradation' (i.e. greater contrast between high and low flows), and an increase 'improvement' or 'rehabilitation' (i.e. more stable flows).

If we consider the sum of river flow over a period of time (from 1 to T) we obtain

$$\Sigma_1^T Q_t = F_p \Sigma_1^T Q_{t-1} + \Sigma_1^T Q_{a,t} \quad [2].$$

If the period is sufficiently long period for Q_T minus Q_0 (the values of Q_t for t=T and t=0, respectively) to be negligibly small relative to the sum over all t's, we may equate $\Sigma_1^T Q_t$ with $\Sigma_1^T Q_{t-1}$ and obtain a first way of estimating the F_p value:

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$$F_p = 1 - \Sigma_1^T Q_{a,t} / \Sigma_1^T Q_t \quad [3].$$

Rearranging Eq.(3) we obtain

$$\Sigma_1^T Q_{a,t} = (1 - F_p) \Sigma_1^T Q_t \quad [4].$$

~~The F_p term is equivalent with one of several ways to separate baseflow from peakflows.~~ The $\Sigma Q_{a,t}$ term reflects the sum of peak flows in mm, while F_p ΣQ_t reflects the sum of base flow, also in mm. Clarifying the Q_a contribution is ~~The F_p term is~~ equivalent with one of several ways to separate ~~baseflow~~base flow from ~~peakflow~~peak flows. For F_p = 1 (the theoretical maximum) we conclude that all $Q_{a,t}$ must be zero, and all flow is 'base flow'.

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The stochastic $Q_{a,t}$ can be interpreted in terms of what hydrologists call 'effective rainfall' (i.e. rainfall minus on-site evapotranspiration, assessed over a preceding time period tx since previous rain event):

$$Q_t = F_p Q_{t-1} + (1-F_p)(P_{tx} - E_{tx}) \quad [5].$$

Where P_{tx} is the (spatially weighted) precipitation (assuming no snow or ice, which would shift the focus to snowmelt) in mm d^{-1}; E_{tx} , also in mm d^{-1}, is the preceding evapotranspiration that allowed for infiltration during this rainfall event (*i.e.* evapotranspiration since the previous soil-replenishing rainfall that induced empty pore space in the soil for infiltration and retention), or replenishment of a waterfilm on aboveground biomass that will subsequently evaporate. More complex attributions are possible, aligning with the groundwater replenishing ~~bypassflow~~bypass flow, and the water isotopic fractionation involved in evaporation (Evaristo ~~et al~~et al., 2015).

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The consistency of multiplying effective rainfall with $(1-F_p)$ can be checked by considering the geometric series $(1-F_p)$, $(1-F_p) F_p$, $(1-F_p) F_p^2$, …, $(1-F_p) F_p^n$ which adds up to $(1-F_p)(1 - F_p^n)/(1-F_p)$ or $1 - F_p^n$. This approaches 1 for large n, suggesting that all of the water attributed to time t, *i.e.* $P_t - E_{tx}$, will eventually emerge as river flow. For $F_p = 0$ all of $(P_t - E_{tx})$ emerges on the first day, and ~~riverflow~~river flow is as unpredictable as precipitation itself. For $F_p = 1$ all of $(P_t - E_{tx})$ contributes to the stable daily flow rate, and it takes an infinitely long period of time for the last drop of water to get to the river. For declining F_p, $(1 > F_p > 0)$, river flow gradually becomes less predictable, because a greater part of the stochastic precipitation term contributes to variable rather than evened-out river flow.

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Taking long term summations of the right- and left- hand sides of Eq.(5) we obtain:

$$\Sigma Q_t = \Sigma(F_p Q_{t-1} + (1-F_p)(P_t - E_{tx})) = F_p \Sigma Q_{t-1} + (1-F_p)(\Sigma P_t - \Sigma E_{tx}) \quad [6].$$

Which is consistent with the basic water budget, $\Sigma Q = \Sigma P - \Sigma E$, at time scales long enough for changes in soil water buffer stocks to be ignored. As such the total annual, and hence the mean daily river flow are independent of F_p. This does not preclude that processes of watershed degradation or restoration that affect the partitioning of P over Q and E also affect F_p.

2.2 Low flows

The lowest flow expected in an annual cycle is $Q_x F_p^{Nmax}$ where Q_x is flow on the first day without rain and N_{max} the longest series of dry days. Taken at face value, a decrease in F_p has a strong effect on low-flows, with a flow of 10% of Q_x reached after 45, 22, 14, 10, 8 and 6 days for F_p = 0.95, 0.9, 0.85, 0.8, 0.75 and 0.7, respectively. However, the groundwater reservoir that is drained, equalling the cumulative dry season flow if the dry period is sufficiently long, is $Q_x/(1-F_p)$. If F_p decreases to F_{px} but the groundwater reservoir ($Res = Q_x/(1-F_p)$) is not affected, initial flows in the dry period will be higher ($Q_x F_{px}^i (1-F_{px})\, Res > Q_x F_p^i (1-F_p)\, Res$ for $i < \log((1-F_{px})/(1-F_p))/\log(F_p/F_{px})$). It thus matters how low flows are evaluated: from the perspective of the lowest level reached, or as cumulative flow. The combination of climate, geology and land form are the primary determinants of cumulative low flows, but if land cover reduces the recharge of groundwater there may be impacts on dry season flow, that are not directly reflected in F_p.

If a single F_p value would account for both dry and wet season, the effects of changing F_p on low flows may well be more pronounced than those on flood risk. Empirical tests are needed of the dependence of F_p on Q (see below). Analysis of the way an aggregate F_p depends on the dominant flow pathways provides a basis for differentiating F_p within a hydrologic year.

2.3 Flow-pathway dependence of flow persistence

The patch-level partitioning of water between infiltration and ~~overlandflow~~overland flow is further modified at hillslope level, with a common ~~distinciton~~distinction between three pathways that reach streams: overland flow, interflow and groundwater flow (Band ~~et al~~et al., 1993; Weiler and McDonnell, 2004). An additional interpretation of Eq.(1), potentially adding to our understanding of results but not needed for analysis of empirical data, can be that three pathways of water through a landscape contribute to river flow (Barnes, 1939): groundwater release with $F_{p,g}$ values close to 1.0, overland flow with $F_{p,o}$ values close to 0, and interflow with intermediate $F_{p,i}$ values.

$$Q_t = F_{p,g}\, Q_{t-1,g} + F_{p,i}\, Q_{t-1,i} + F_{p,o}\, Q_{t-1,o} + Q_{a,t} \qquad [7],$$

$$F_p = (F_{p,g}\, Q_{t-1,g} + F_{p,i}\, Q_{t-1,i} + F_{p,o}\, Q_{t-1,o})/Q_{t-1} \qquad [8].$$

On this basis a decline or increase in overall weighted average F_p can be interpreted as indicator of a shift of dominant runoff pathways through time within the watershed. Dry season flows are dominated by $F_{p,g}$. The effective F_p in the rainy season can be ~~intyerpreted~~interpreted as indicating the relative importance of the other two flow pathways. F_p reflects the fractions of total river flow that are based on groundwater, overland flow and interflow pathways:

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$$F_p = F_{p,g}\,(\Sigma Q_{t,g} / \Sigma Q_t) + F_{p,o}\,(\Sigma Q_{t,o} / \Sigma Q_t) + F_{p,i}\,(\Sigma Q_{t,i} / \Sigma Q_t) \qquad [9].$$

Beyond the type of degradation of the watershed that, mostly through soil compaction, leads to enhanced infiltration-excess (or Hortonian) overland flow (Delfs ~~et al~~et al~~.~~., 2009), saturated conditions throughout the soil profile may also induce overland flow, especially near valley bottoms (Bonell, 1993; Bruijnzeel, 2004). Thus, the value of $F_{p,o}$ can be substantially above zero if the rainfall has a significant temporal autocorrelation, with heavy rainfall on subsequent days being more likely than would be expected from general rainfall frequencies. If rainfall following a wet day is more likely to occur than following a dry day, as is commonly observed in Markov chain analysis of rainfall patterns (Jones and Thornton, 1997; Bardossy and Plate, 1991), the overland flow component of total flow will also have a partial temporal autocorrelation, adding to the overall predictability of river flow. In a hypothetical climate with evenly distributed rainfall, we can expect F_p to be 1.0 even if there is no infiltration and the only pathway available is overland flow. Even with rainfall that is variable at any point of observation but has low spatial correlation it is possible to obtain F_p values of (close to) 1.0 in a situation with (mostly) overland flow (Ranieri at al., 2004).

3. Methods

3.1 Numerical example

Figure 2 provides an example of the way a change in F_p values (based on Eq. 1) influences the ~~visual~~ pattern of river flow for a unimodal rainfall regime with a well-developed dry season. The figure was constructed in a Monte Carlo realization of rainfall based on a (truncated) sinus-based probability of rainfall and rectangular rainfall depth to derive the ($P_{tx} - E_{tx}$) term, with the $Q_{a,t}$ values derived as $(1 - F_p)\,(P_{tx} - E_{tx})$. The increasing '~~spikedness~~spikiness' of the graph as F_p is lowered indicates reduced predictability of flow on any given day during the wet season on the basis of the flow on the preceding day. A bi-plot of river flow on subsequent days for the same simulations (~~Fig.~~Figure~~.~~ 3) shows two main effects of reducing the F_p value: the scatter increases, and the slope of the lower envelope containing the swarm of points is lowered (as it equals F_p). Both of these changes can provide entry points for an algorithm to estimate F_p from empirical time series, provided the basic assumptions of the simple model apply and the data are of acceptable quality (see Section 3 below). For the numerical example shown in ~~Fig.~~Figure~~.~~ 2, the maximum daily flow doubled from 50 to 100 mm when the F_p value decreased from a value close to 1 (0.98) to nearly 0.

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⇨ ~~Fig.~~Figure 2

⇨ ~~Fig.~~Figure 3

3.2 Flow persistence as a simple flood risk indicator

For numerical examples (implemented in a spreadsheet model) flow on each day can be derived as:

$$Q_t = \Sigma_j^t F_p^{t-j} (1-F_p)\, p_j P_j \qquad [10].$$

Where p_j reflects the occurrence of rain on day j (reflecting a truncated sine distribution for seasonal trends) and P_j is the rain depth (drawn from a uniform distribution). From this model the effects of F_p (and hence of changes in F_p) on maximum daily flow rates, plus maximum flow totals assessed over a 2-5 d period, was obtained in a Monte Carlo process (without Markov autocorrelation of rainfall in the default case – see below). Relative flood protection was calculated as the difference between peak flows (assessed for 1-5 d duration after a 1 year 'warm-up' period) for a given F_p versus those for $F_p = 0$, relative to those at $F_p = 0$.

3.3 An algorithm for deriving F_p from a time series of stream flow data

Equation (3) provides a first method to derive F_p from empirical data if these cover a full hydrologic year. In situations where there is no complete hydrograph and/or in situations where we want to quantify F_p for shorter time periods (e.g. to characterise intraseasonal flow patterns) and the change in the storage term of the water budget equation cannot be ignored, we need an algorithm for estimating F_p from a series of daily Q_t observations.

Where rainfall has clear seasonality, it is attractive and indeed common practice to derive a groundwater recession rate from a semi-logarithmic plot of Q against time (Tallaksen, 1995). As we can assume for such periods that $Q_{a,t} = 0$, we obtain $F_p = Q_t / Q_{t-1}$, under these circumstances. We cannot be sure, however, that this $F_{p,g}$ estimate also applies in the rainy season, because overall wet-season F_p will include contributions by $F_{p,o}$ and $F_{p,i}$ as well (compare Eq. 9). In locations without a distinct dry season, we need an alternative method.

A biplot of Q_t against Q_{t-1} (as in ~~Fig.~~Figure~~.~~ 3) will lead to a scatter of points above a line with slope F_p, with points above the line reflecting the contributions of $Q_{a,t} > 0$, while the points that plot on the F_p line itself represent $Q_{a,t} = 0$ mm d^{-1}. There is no independent source of information on the frequency at which $Q_{a,t} = 0$, nor what the statistical distribution of $Q_{a,t}$ values is if it is non-zero. Calculating back from the Q_t series we can obtain an estimate ($Q_{a,Fptry}$) of $Q_{a,t}$ for any given estimate ($F_{p,try}$) of F_p, and select the most plausible F_p value. For high $F_{p,try}$ estimates there will be many negative $Q_{a,Fptry}$ values, for low $F_{p,try}$ estimates all $Q_{a,Fptry}$ values will be larger. An algorithm to derive a plausible F_p estimate can thus make use of the corresponding distribution of 'apparent Q_a' values as estimates of $F_{p,try}$, calculated as $Q_{a,try} = Q_t - F_{p,try} Q_{t-1}$. While $Q_{a,t}$ cannot be negative in theory, small negative Q_a estimates are likely when using real-world data with their inherent errors. The FlowPer F_p algorithm (van Noordwijk ~~et al~~et al.~~.~~, 2011) derives the distribution of $Q_{a\cancel{dd},\cancel{Fp}try}$ estimates for a range of $F_{p,try}$ values (~~Fig.~~Figure~~.~~ 4B) and selects the value $F_{p,try}$ that minimizes the variance $Var(Q_{a,Fptry})$ (or its standard deviation) (~~Fig.~~Figure 4C). It is implemented in a spreadsheet workbook that can be downloaded from the ICRAF website (http://www.worldagroforestry.org/output/flowper-flow-persistence-model)

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➔~~Fig.~~Figure 4

A consistency test is needed that the high-end Q_t values relate to Q_{t+1} in the same was as do low or medium Q_t values. Visual inspection of Q_{t+1} versus Q_t, with the derived F_p value, provides a qualitative view of the validity of this assumption. The F_p algorithm can be applied to any population of ($Q_{t-1,}$ Q_t) pairs, e.g. selected from a multiyear data set on the basis of 3-month periods within the hydrological year.

4 Results

4.1 Flood intensity and duration

Figure 5 shows the effect of F_p values in the range 0 to 1 on the maximum flows obtained with a random time series of 'effective rainfall', compared to results for $F_p = 0$. Maximum flows were considered at time scales of 1 to 5 days, in a moving average routine. This way a relative flood protection, expressed as reduction of peak flow, could be related to F_p (~~Fig.~~Figure 5A).

⇨ ~~Fig.~~Figure 5

Relative flood protection rapidly decreased from its theoretical value of 100% at $F_p = 1$ (when there was no variation in river flow), to less than 10% at F_p values of around 0.5. Relative flood protection was slightly lower when the assessment period was increased from 1 to 5 days (between 1 and 3 d it decreased by 6.2%, from 3 to 5 d by a further 1.3%). Two counteracting effects are at play here: a lower F_p means that a larger fraction (1-F_p) of the effective rainfall contributes to river flow, but the increased flow is less persistent. In the example the flood protection in situations where the rainfall during 1 or 2 d causes the peak is slightly stronger than where the cumulative rainfall over 3-5 d causes floods, as typically occurs downstream.

As we expect from equation 5 that peak flow is to (1-F_p) times peak rainfall amounts, the effect of a change in F_p not only depends on the change in F_p that we are considering, but also on its initial value. Higher initial F_p values will lead to more rapid increases in high flows for the same reduction in F_p (~~Fig.~~Figure 5B). However, flood duration rather responds to changes in F_p in a curvilinear manner, as flow persistence implies flood persistence (once flooding occurs), but the greater the flow persistence the less likely such a flooding threshold is passed (~~Fig.~~Figure 5C). The combined effect may be restricted to about 3 d of increase in flood duration for the parameter values used in the default example, but for different parametrization of the stochastic ε other results might be obtained.

4.2 Algorithm for Fp estimates from river flow time series

The algorithm has so far returned non-ambiguous F_p estimates on any modelled time series data of river flow, as well as for all empirical data set we tested (including all examples tested in part II), although there ~~proably~~probably are data sets on which it can breakdown. Visual inspection of Q_{t-1}/Q_t biplots (as in ~~Fig.~~Figure 3) can provide clues to non-homogenous data sets, ~~and~~ to potential situations where effective F_p depends on flow level Q_{t-} and where data are not ~~consisten~~consistent with a ~~straigh~~straight-line lower envelope. Where river flow estimates were derived from a model with random elements, however, variation in F_p estimates was observed, that ~~sugegsts~~suggests that specific aspects of actual rainfall, beyond the basic characteristics of a watershed and its vegetation, do have at least some effect. Such effects deserve to be further explored for a set of case studies, as their strength probably depends on context.

5 Discussion

We will discuss the flow persistence metric based on the questions raised from the perspectives of salience, credibility and legitimacy.

5.1 Salience

Key *salience* aspects are “Does flow persistence relate to important aspects of watershed ~~behavior~~behaviour?” and “Does it help to select management actions?”. A major finding in the derivation of F_p was that the flow persistence measured at daily time scale can be logically linked to the long-term water balance, and that the proportion of peak rainfall that translates to peak river flow equals the complement of flow persistence. This feature links effects on floods of changes in watershed quality to effects on low flows, although not in a linear relationship.

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The F_p parameter as such does not predict when and where flooding will occur, but it does help to assess to what extent another condition of the watershed, with either higher or lower F_p would translate the same rainfall into larger or small peak ~~waterflows~~water flows. This is salient, especially if the relative contributions of (anthropogenic) land cover and the (exogenous, probabilistic) specifics of the rainfall pattern can be further teased apart (see part II). Where F_p may describe the descending branch of hydrographs at a relevant time scale, details of the ascending branch beyond the maximum daily flow reached may be relevant for reducing flood damage, and may require more detailed study at higher ~~tempoeral~~temporal resolution.

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A key strength of our flow persistence parameter, that it can be derived from observing river flow at a single point along the river, without knowledge of rainfall events and catchment conditions, is also its major weakness. If rainfall data exist, and especially rainfall data that apply to each subcatchment, the Q_a term doesn't have to be treated as a random variable and event-specific information on the flow pathways may be inferred for a more precise account of the hydrograph. But for the vast majority of rivers in the tropics, advances in remotely sensed rainfall data are needed to achieve that situation and F_p may be all that is available to inform public debates on the relation between forests and floods.

Figures 2 and 6 show that most of the effects of a decreasing F_p value on peak discharge (which is the basis for downstream flooding) occur between F_p values of 1 and 0.7, with the relative flood protection value reduced to 10% when F_p reaches 0.5. As indicated in Figure~~.~~ 1, peak discharge is only one of the factors contributing to flood risk in terms of human casualties and physical damage. The F_p value has an inverse effect on the fraction of recent rainfall that becomes river flow, but the effect on peak flows is less, as higher F_p values imply higher base flow. The way these counteracting effects balance out depends on details of the local rainfall pattern (including its Markov chain temporal autocorrelation), as well as the downstream topography and risk of people being at the wrong time at a given place, but the F_p value is ~~c~~an efficient way of summarizing complex land use mosaics and upstream topography in its effect on river flow. The difference between wet-season and dry-season F_p deserves further analysis. In climates with a real rainless dry-season, dry season F_p is dominated by the groundwater release fraction of the watershed, regardless of land cover, while in wet season it depends on the mix (weighted average) of flow pathways. The degree to which F_p can be influenced by land cover needs to be assessed for each landscape and land cover combination, including the locally relevant forest and forest derived land classes, with their effects on interception, soil infiltration and time pattern of transpiration. The F_p value can summarize results of models that explore land use change scenarios in local context. To select the specific management actions that will maintain or increase F_p a locally calibrated land use/hydrology model is needed, such as GenRiver or SWAT (Yen ~~et al~~et al., 2015).

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Although a higher F_p value will in most cases be desirable (and a decrease in F_p undesirable), we may expect that downstream biota have adjusted to the pre-human flow conditions and its inherent F_p and variability. Decreased variability of flow achieved by engineering interventions (e.g. a reservoir with constant release of water to generate hydropower) may have negative consequences for fish and other biota (Richter ~~et al~~et al., 2003; McCluney ~~et al~~et al., 2014).

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5.2 Credibility

Key *credibility* questions are “Consistency of numerical results?” and “How sensitive are results to bias and random error in data sources?”. This is further discussed in part II, after a number of case studies has been studied. The main conclusions are that intra-annual variability of F_p values between wet and dry seasons was around 0.2 in the case studies, interannual variability in either annual or seasonal F_p was generally in the 0.1 range, while the difference between observed and simulated flow data as basis for F_p calculations was mostly less than 0.1. With current methods, it seems that effects of land cover change on flow persistence that shift the F_p value by about 0.1 are the limit of what can be asserted from empirical data (with shifts of that order in a single year a warning sign rather than a firmly established change). When derived from observed river flow data F_p is suitable for monitoring change (degradation, restoration) and can be a serious candidate for monitoring performance in outcome-based ecosystem service management contracts. In interpreting changes in F_p as caused by changes in the condition in the watershed, however, changes in specific properties of the rainfall regime must be excluded. At the scale of paired catchment studies this assumption may be reasonable, but in temporal change (or using specific events as starting point for analysis), it is not easy to disentangle interacting effects (Ma ~~et al~~et al., 2014). Recent evidence that vegetation not only responds to, but also influences rainfall (arrow 10 in Figure 1; van Noordwijk ~~et al~~et al., 2015b) further complicates the analysis across scales.

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5.3 Legitimacy

Legitimacy aspects are “Does it match local knowledge?” and “Can it be used to empower local stakeholders of watershed management?” and “Can it inform risk management?”. As the F_p parameter captures the predictability of river flow that is a key aspect of degradation according to local knowledge systems, its results are much easier to convey than full hydrographs or ~~excedance~~exceedance probabilities of flood levels. By focusing on observable effects at river level, rather than prescriptive recipes for land cover (“reforestation”), the F_p parameter can be used to more effectively compare the combined effects of land cover change, changes in the riparian wetlands and engineered water storage reservoirs, in their effect on flow buffering. It is a candidate for shifting environmental service reward contracts from input to outcome based monitoring (van Noordwijk ~~et al~~et al., 2012). As such it can be used as part of a negotiation support approach to natural resources management in which ~~leveling~~levelling off on knowledge and joint fact finding in blame attribution are key steps to negotiated solutions that are legitimate and seen to be so (van Noordwijk ~~et al~~et al., 2013; Leimona ~~et al~~et al., 2015). Quantification of F_p can help assess tactical management options (Burt ~~et al~~et al., 2014) as in a recent suggestion to minimize negative downstream impacts of forestry operations on stream flow by avoiding land clearing and planting operations in locally wet La Niña years. But the most challenging aspect of the management of flood, as any other environmental risk, is that the frequency of disasters is too low to intuitively influence human ~~behavior~~behaviour where short-term risk taking benefits are attractive. Wider social pressure is needed for investment in watershed health (as a type of insurance premium) to be mainstreamed, as individuals waiting to see evidence of necessity are too late to respond. In terms of flooding risk, actions to restore or retain watershed health can be similarly justified as insurance premium. It remains to be seen whether or not the transparency of the F_p metric and its intuitive appeal are sufficient to make the case in public debate when opportunity costs of foregoing reductions in flow buffering by profitable land use are to be compensated and shared (Burt ~~et al~~et al., 2014).

5.4 Conclusions and specific ~~questioons~~questions for a set of case studies

In conclusion, the F_p metric appears to allow an efficient way of summarizing complex landscape processes into a single parameter that reflects the effects of landscape management. Flow persistence is the result of rainfall persistence and the temporal delay provided by the pathway water takes through the soil and the river system. High flow persistence indicates a reliable water supply, while minimizing peak flow events. Wider tests of the F_p metric as

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boundary object in science-practice-policy boundary chains (~~Kirchoff~~Kirchhoff ~~et al~~et -al., 2015; Leimona ~~et al~~et al~~.~~., 2015) are needed. Further tests for specific case studies can clarify how changes in tree cover (deforestation, reforestation, agroforestation) in different contexts influence river flow dynamics and F_p values. Sensitivity to specific realizations of underlying time-space rainfall patterns needs to be quantified, before changes in F_p can be attributed to 'watershed quality', rather than chance events.

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Data availability

The algorithm used is freely available. Specific data used in the case studies are explained and accounted for in Part II.

Author contributions

Meine van Noordwijk~~vN~~ designed method and paper, Lisa Tanika~~LT~~ refined the empirical algorithm and handled the case study data and ~~modeling~~modelling for part II, and Betha Lusiana~~BL~~ contributed statistical analysis; all contributed and approved the final manuscript

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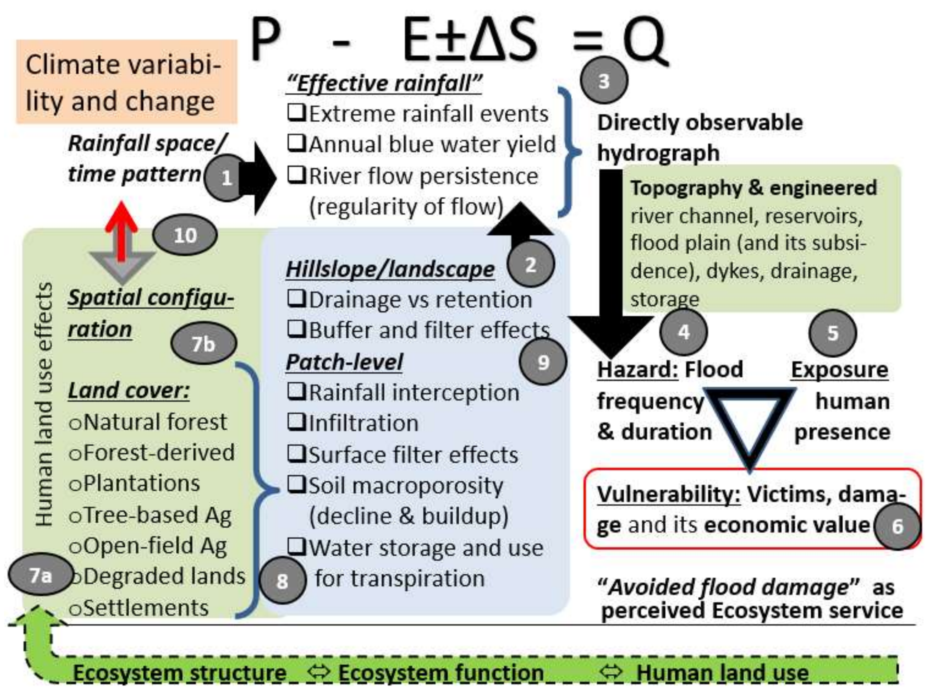

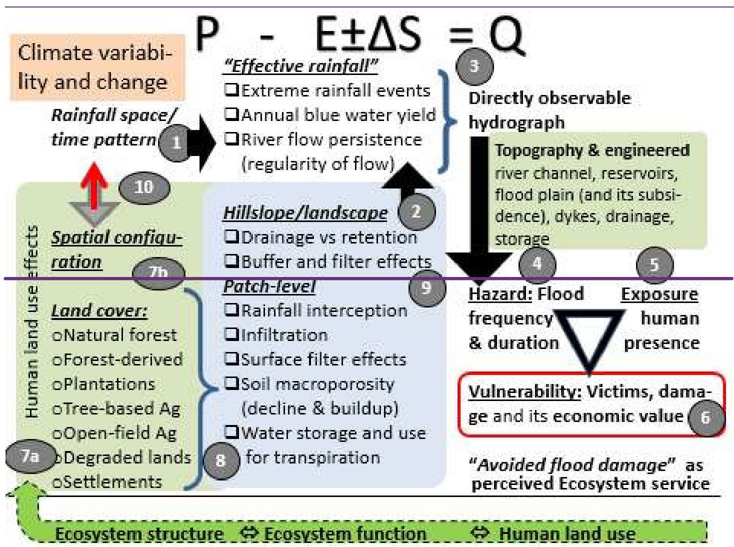

Figure 1. Steps in a causal pathway that relates rainfall (1) via watershed conditions (2) to the pattern of river flow described in a hydrograph (3), which can get modified by the conditions

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along the river channel into a hazard of flood frequency and duration (4); jointly with exposure (being in the wrong place at critical times,~~;~~ 5) and vulnerability (6) this determines flood damage; in avoiding flood damage, the condition in the watershed with its landcover and spatial configuration (7) influences the ~~patchlevel~~patch level water partitioning over ~~overlandflow~~overland flow and ~~infitration~~infiltration (8), ~~and~~ while hillslope level configuration further influences ~~on~~ flow pathwa~~t~~ys (9) and land cover potentially influences rainfall (10)

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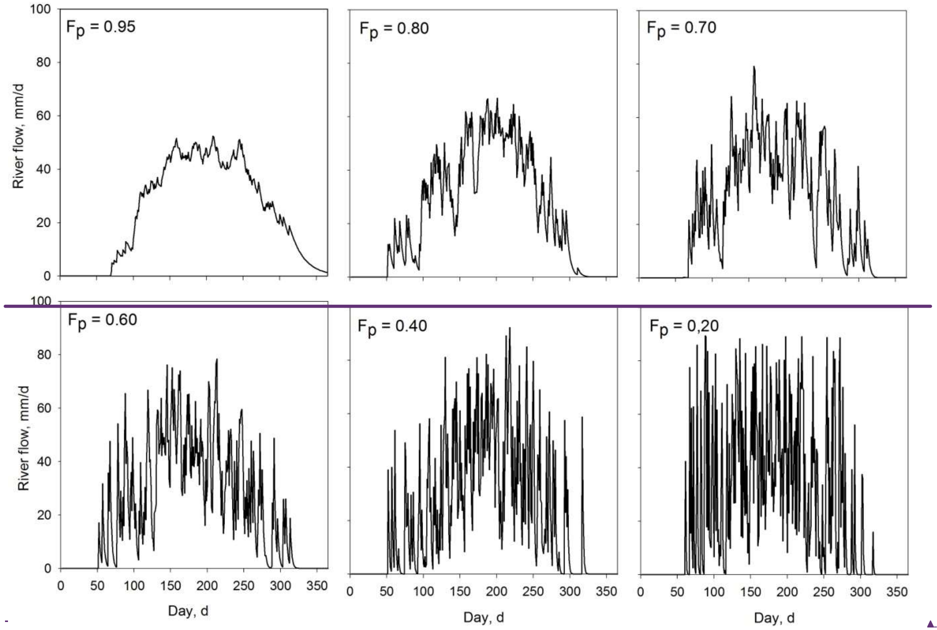

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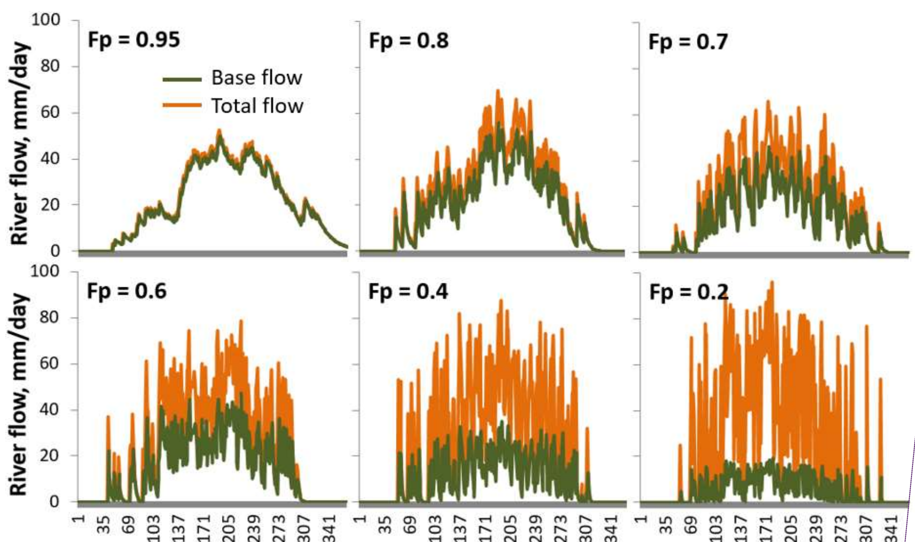

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Figure 2. Example of daily river flow, split into a base flow and additional flow component, for a unimodal sinus-based rainfall probability multiplied with a rainfall depth drawn from [0-

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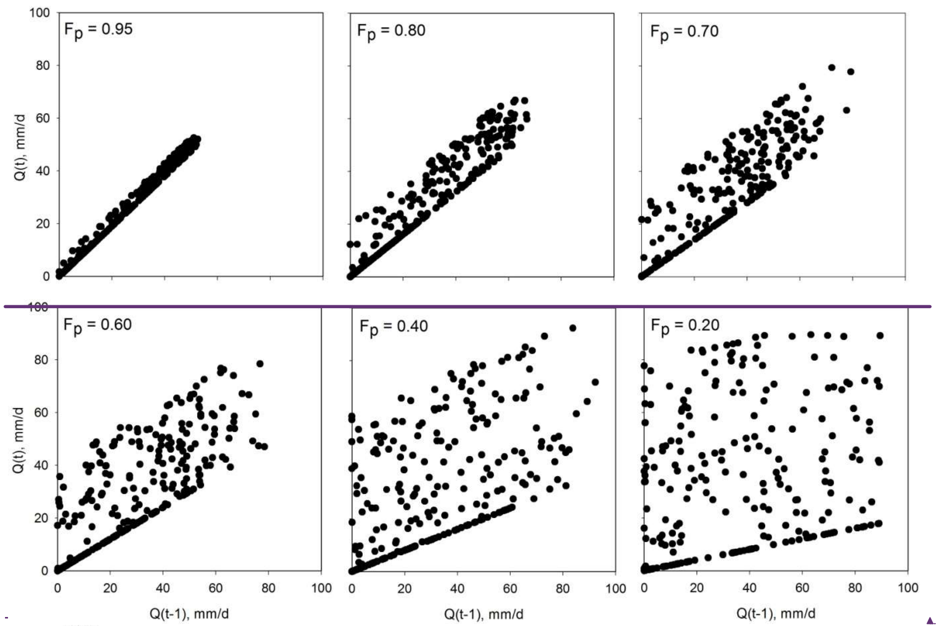
100] mm/day~~regime with clear dry season~~ in watersheds characterized by F_p values ranging from 0.95 to 0.2~~, in response to change in the flow persistence parameter F_p~~



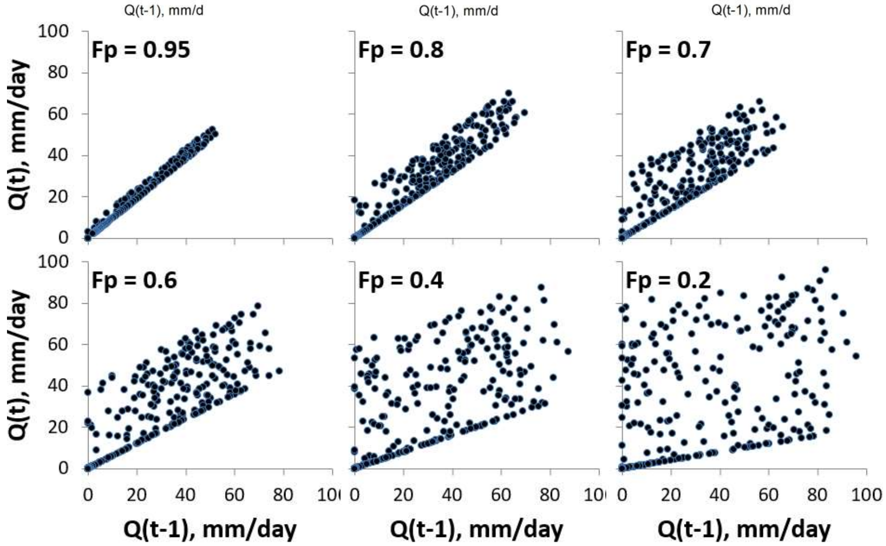


Figure 3. Biplots of Q(t) versus Q(t-1) for the same simulations as ~~f~~Figure 2

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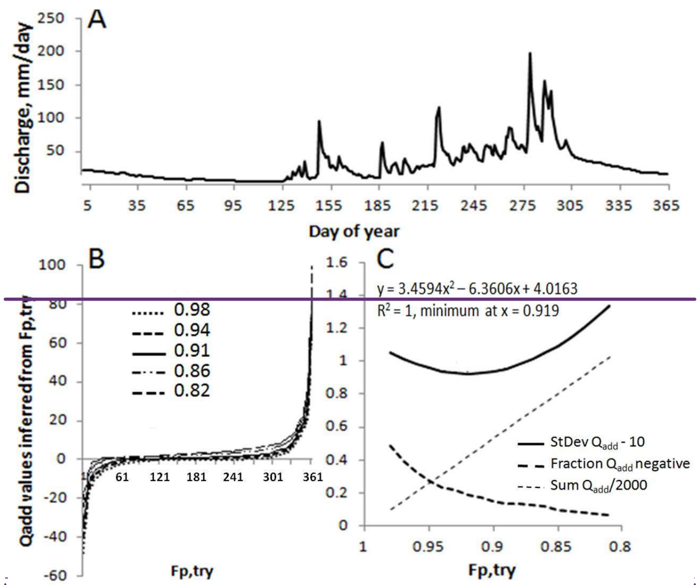

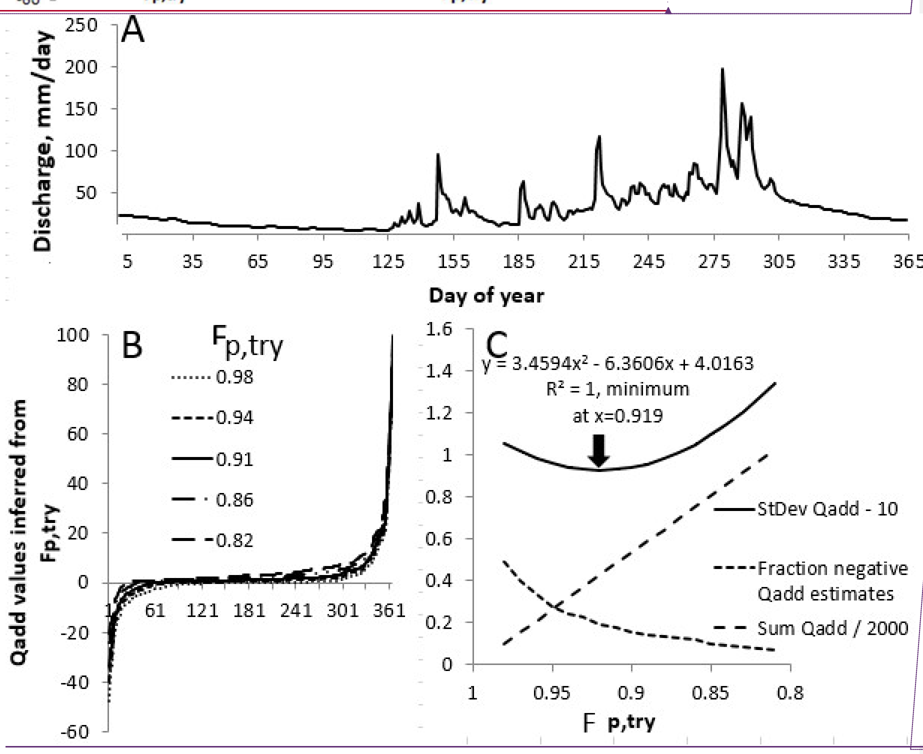

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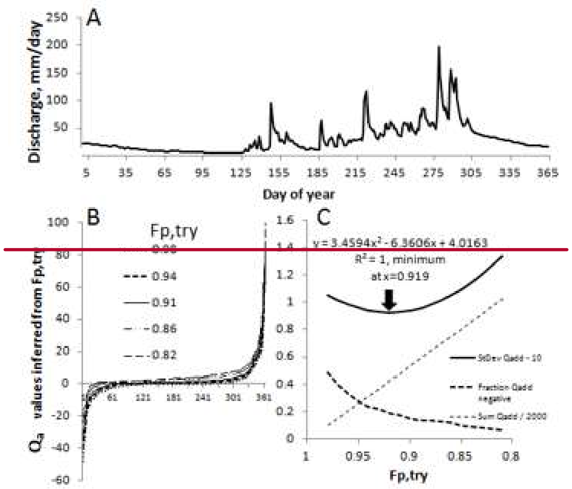

Figure 4. Example of the derivation of best fitting $F_{p,try}$ value for an example hydrograph (A) on the basis of the inferred Q_a distribution (cumulative frequency in B), and three properties of this distribution (C): its sum, frequency of negative values and standard deviation; the $F_{p,try}$ minimum of the latter is derived from the parameters of a fitted quadratic equation

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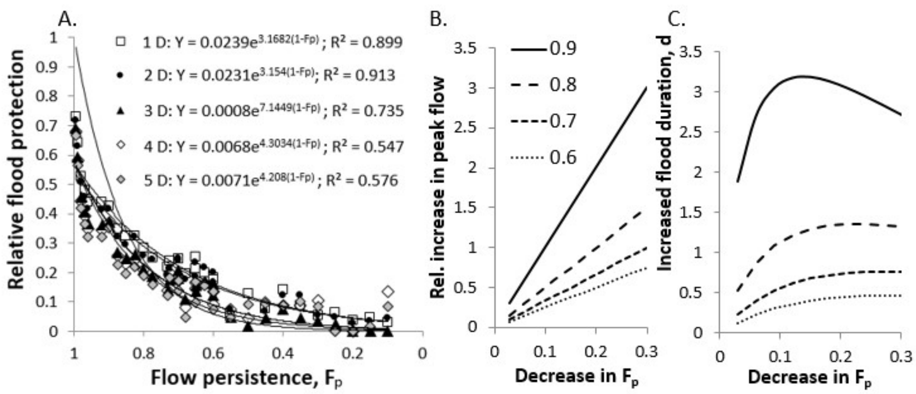

Figure 5. A. Effects of flow persistence on the relative flood protection (decrease in maximum flow measured over a 1 – 5 d period relative to a case with $F_p = 0$ (a few small negative points were replaced by small positive values to allow the exponential fit); B and C. effects of a decrease in flow persistence on the volume of water involved in peak flows (B; relative to the volume at F_p is 0.6 – 0.9) and in the duration (in d) of floods (C)

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Flood risk reduction and flow buffering as ecosystem services: II. Land use and rainfall intensity effects in Southeast Asia

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Abstract

The way watersheds ~~with their vegetation, soils, geomorphology and geological substrate as well as riparian wetlands~~ buffer the temporal pattern of ~~riverflow~~river flow relative to the temporal pattern of rainfall is an important ecosystem service. ~~that requires quantification.~~ Part of this buffering ~~it i~~is inherent to its geology and climate, but another part is ~~also~~ responding to human use and misuse of the landscape, and can be part of management feedback loops if salient, credible and legitimate indicators can be found and used. ~~The benefits to humans of reduced exposure to floods and increased riverflow in periods without rain are logically linked through the water balance.~~ Dissecting the anthropogenic change from exogenous variability (e.g. the specific time-space pattern of rainfall during an observation period) is relevant for designing and monitoring of watershed management interventions. Part I introduced the concept of flow persistence, key to a parsimonious recursive model of river flow. It also discussed the operational derivation of the F_p parameter. Here we compare F_p estimates from four meso-scale watersheds in Indonesia (Cidanau, Way Besai, and Bialo) and Thailand (Mae Chaem), with varying climate, geology and land cover history, at a decadal time scale. The likely response in each of these four to variation in rainfall properties (incl. the maximum hourly rainfall intensity) and land cover (comparing scenarios with either more or less forest and tree cover than the current situation) was explored through a basic daily ~~waterbalance~~water balance model, GenRiver. This model was calibrated for each site on existing data, before being used to explore alternative land cover and rainfall parameter settings. In both data and model runs, the wet-season (3-monthly) F_p values were consistently lower than dry-season values for all four sites. Across the four catchments F_p values decreased with increasing annual rainfall, but specific aspects of

watersheds, such as the riparian swamp (peat soils) in Cidanau reduced effects of land use change in the upper watershed. Increasing the mean rainfall intensity (at constant monthly totals for rainfall) around the values considered typical for each landscape was predicted to decrease F_p values by between 0.047 (Bialo) and 0.261 (Mae Chaem). ~~In three of the four watersheds the effects on F_p of shifts in mean rainfall intensity were 2.2 to 3.1 times larger than the land use change scenarios, but in Bialo its relative effect was only 58%. Apparently, the ~~S~~s~~ensitivity of F_p to changes in land use change plus changes in rainfall intensity depends on other characteristics of the watersheds, and generalizations made on the basis of one or two case studies may not hold, even within the same climatic zone. A wet-season F_p value above 0.7 was achievable in forest-agroforestry mosaic case studies. Interannual variability in F_p was found to be large relative to effects of land cover change and likely reflects ~~. The ~~sensitivity in the model of Hortonian overland flow to variations in rainfall intensity. ~~can account for the interannual variability.~~ Multiple (5-10) years of paired-plot data would generally be needed to reject no-change null-hypotheses on the effects of land use change (degradation and restoration). While empirical evidence of such effects at scale is understandably scarce, F_p trends over time serve as a holistic scale-dependent performance indicator of degrading/recovering watershed health and can be tested for acceptability and acceptance in a wider socio-ecological context.

Introduction

Inherent properties (geology, geomorphology) interact with climate and human modification of vegetation, soils, drainage and riparian wetlands in the degree of buffering that watersheds provide (Andréassian 2004; Bruijnzeel, 2004). Buffering of ~~riverflow~~river flow relative to the space-time dynamics of rainfall is an ecosystem service, reducing the exposure of people living on geomorphological floodplains to high-flow events, and increasing predictability and river flow in dry periods (Joshi ~~et al~~et al~~.~~., 2004; Leimona ~~et al~~et al~~.~~., 2015; Part I). In the absence of any vegetation and with a sealed surface, ~~riverflow~~river flow will directly respond to the spatial distribution of rainfall, with only the travel time to any point of specific interest influencing the ~~temporal~~temporal pattern of river flow. Any persistence or predictability of river flow in such a situation will reflect temporal autocorrelation of rainfall, beyond statistical predictability in seasonal rainfall patterns. On the other side of the spectrum, ~~riverflow~~river flow can be constant every day, beyond the theoretical condition of constant rainfall, in a watershed that provides

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perfect buffering, by passing all water through groundwater pools that have sufficient storage capacity at any time during the year. Both infiltration-limited (Hortonian) and saturation-induced use of more rapid flow pathways (inter and overland flows) will reduce the flow persistence and make it, at least in part, dependent on rainfall events. Separating the effects of land cover (land use), engineering and rainfall on the actual flow patterns of rivers remains a considerable challenge (Ma ~~et al~~et al., 2014; Verbist ~~et al~~et al., 2019). It requires data, models and concepts that can serve as effective boundary object in communication with stakeholders (Leimona ~~et al~~et al., 2015; van Noordwijk ~~et al~~et al., 2012). There is a long tradition in using forest cover as such a boundary object, but there is only a small amount of evidence supporting this (Tan-Soo ~~et al~~et al., 2014; van Dijk ~~et al~~et al., 2009; van Noordwijk ~~et al~~et al., 2015a).

In part I, we introduced a flow persistence parameter (F_p) that links the two, asymmetrical aspects of flow dynamics: translating rainfall excess into river flow, and gradually releasing water stored in the landscape. Here, in part II we will apply the F_p algorithm to river flow data for a number of contrasting meso-scale watersheds in Southeast Asia. These were selected to represent variation in rainfall and land cover, and test the internal consistency of results based on historical data: two located in the humid and one in the ~~subhumid~~subhumid tropics of Indonesia, and one in the unimodal ~~subhumid~~subhumid tropics of northern Thailand.

After exploring the patterns of variation in F_p estimates derived from river flow records, we will quantify the sensitivity of the F_p metric to variations in rainfall intensity~~,~~ and its response, on a longer timescale to land cover change. To do so, we will use a model that uses basic water balance concepts: rainfall interception, infiltration, water use by vegetation, overland flow, interflow and groundwater release, to a spatially structured watershed where travel time from ~~subwatersheds~~sub watersheds to any point of interest modifies the predicted ~~riverflow~~river flow. In the specific model used land cover effects on soil conditions, interception and seasonal water use have been included. After testing whether F_p values derived from model outputs match those based on empirical data where these exist, we rely on the basic logic of the model to make inference on the relative importance of modifying rainfall and land cover inputs. With the resulting temporal variation in calculated F_p values, we consider the time frame at which observed shifts in F_p can be attributed to factors other than chance (that means: null-hypotheses of random effects can be rejected with accepted chance of Type I errors).

2. Methods

2.1 GenRiver model for effects of land cover on river flow

The GenRiver model (van Noordwijk ~~et al~~et al., 2011) is based on a simple water balance concept with a daily ~~timestep~~time step and a flexible spatial subdivision of a watershed that influences the routing of water and employs spatially explicit rainfall. At patch level, vegetation influences interception, retention for subsequent evaporation and delayed transfer to the soil surface, as well as the seasonal demand for water. Vegetation (land cover) also influences soil porosity and infiltration, modifying the inherent soil properties. Water in the root zone is modelled separately for each land cover within a subcatchment, the groundwater stock is modelled at subcatchment level. The spatial structure of a watershed and the routing of surface flows influences the ~~timedelays~~time delays to any specified point of interest, which normally includes the outflow of the catchment. Land ~~-~~cover change scenarios are interpolated annually between time-series (measured or modelled) data. The model may use measured rainfall data, or use a rainfall generator that involves Markov chain temporal autocorrelation (rain persistence). As our data sources are mostly restricted to daily rainfall measurements and the infiltration model compares instantaneous rainfall to infiltration capacity, a stochastic rainfall intensity was applied at subcatchment level, driven by the mean as parameter and a standard deviation for a normal distribution (truncated at 3 standard deviations from the mean) proportional to it via a coefficient of variation as parameter. For the Mae Chaem site in N Thailand data by Dairaku ~~et al~~et al. (2004) suggested a mean of less than 3 mm/hr. For the three sites in Indonesia we used 30 mm/hr, based on Kusumastuti ~~et al~~et al. (2016). Appendix 1 provides further detail on the GenRiver model. The model itself, a manual and application case studies are freely available (http://www.worldagroforestry.org/output/genriver-genetic-river-model-river-flow; van Noordwijk ~~et al~~et al., 2011).

2.2 Empirical data-sets, model calibration

Table 1 and Figure 1 provide~~s~~ summary characteristics and the location of river flow data ~~are~~ used in four meso-scale watersheds for testing the F_p algorithm and application of the GenRiver model. Figure 1 includes a water tower category in the agro-ecological zones; this is defined on the basis of a ratio of precipitation and potential evapotranspiration of more than 0.65, and a product of that ratio and relative elevation exceeding 0.277.

⇨ Table 1
⇨ ~~Fig.~~Figure 1

As major parameters for the GenRiver model were not independently measured for the respective watersheds, we tuned (calibrated) the model by modifying ~~paraemeters~~parameters within a ~~predetrimined~~predetermined plausible range, and used correspondence with measured

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hydrograph as test criterion (Kobolt ~~et al~~et al~~.~~, 2008). We used the Nash-Sutcliff Efficiency (NSE) parameter (target above 0.5) and bias (less than 25%) as test criteria and targets. Meeting these performance targets (Moriasi ~~et al~~et al~~.~~, 2007), we accepted the adjusted models as basis for describing current conditions and exploring model sensitivity. The main site-specific parameter values are listed in Table 2 and (generic) land ~~-~~cover specific default parameters in Table 3.

⇨ Table 2
⇨ Table 3

Table 4 describes the six scenarios of land ~~-~~use change that were evaluated in terms of their hydrological impacts. Further description on the associated land cover distribution for each scenario in the four different watersheds is depicted in Appendix 2.

⇨ Table 4

2.3 Bootstrapping to estimate the minimum observation

The bootstrap methods (Efron and Tibshirani, 1986) is a resampling methods that is commonly used to generate ‘surrogate population‘ for the purpose of approximating the sampling distribution of a statistic. In this study, the bootstrap approach was used to estimate the minimum number of observation (or yearly data) required for a pair-wise comparison test between two time-series of stream flow or discharge data (representing two scenarios of land use distributions) to be distinguishable from a null-hypothesis of no effect. The pair-wise comparison test used was Kolmogorov-Smirnov test that is commonly used to test the distribution of discharge data (Zhang eta al, 2006). We built a simple macro in R (R Core Team, 2015) that entails the following steps:

(i) Bootstrap or resample with replacement 1000 times from both time-series discharge data with sample size *n*;

(ii) Apply the Kolmogorov-Smirnov test to each of the 1000 generated pair-wise discharge data, and record the P-value;

(iii) Perform (i) and (ii) for different size of *n*, ranging from 5 to 50.

(iv) Tabulate the p-value from the different sample size *n*, and determine the value of *n* when the p-value reached equal to or less than 0.025 (or equal to the significance level of 5%). The associated *n* represents the minimum number of observations required.

Appendix 3 provides an example of the macro in R used for this analysis.

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3. Results

3.1 Empirical data of flow persistence as basis for model parameterization

Inter-annual variability of F_p estimates derived for the four catchments (~~Fig.~~Figure 2) was of the order of 0.1 units, while the intra-annual variability between dry and rainy seasons was 0.1-0.2. For all for the years and locations, rainy season F_p values, with mixed flow pathways, were consistently below dry-season values, dominated by groundwater flows. If we can expect $F_{p,i}$ and $F_{p,o}$ (see equation 8 in part I) to be approximately 0.5 and 0, this difference between wet and dry periods implies a 40% contribution of interflow in the wet season, a 20% contribution of overland flow or any combination of the two effects.

Overall the estimates from ~~modeled~~modelled and observed data are related with 16% deviating more than 0.1 and 3% more than 0.15 (~~Fig.~~Figure 3). As the Moriasi ~~et al~~et al~~.~~. (2007) performance criteria for the hydrographs were met by the calibrated models for each site, we tentatively accept the model to be a basis for sensitivity study of F_p to modifications to land cover and/or rainfall

⇨ ~~Fig.~~Figure 2

⇨ ~~Fig.~~Figure 3

3.2 Comparing F_p effects of rainfall intensity and land cover change

A direct comparison of model sensitivity to changes in mean rainfall intensity and land use change scenarios is provided in Fig~~.~~ure 4. Varying the mean rainfall intensity over a factor 7 shifted the F_p value by only 0.047 and 0.059 in the case of Bialo and Cidanau, respectively, but by 0.128 in Way Besai and 0.261 in Mae Chaem (~~Fig.~~Figure 4A). The impact of the land use change scenarios on F_p was smallest in Cidanau (0.026), intermediate in Way Besai (0.048) and relatively large in Bialo and Mae Chaem, at 0.080 and 0.084, respectively (~~Fig.~~Figure 4B). The order of F_p across the land use change scenarios was mostly consistent between the watersheds, but the contrast between the ReFor and NatFor scenario was largest in Mae Chaem and smallest in Way Besai. In Cidanau, Way Besai and Mae Chaem, variations in rainfall were 2.2 to 3.1 times more effective than land use change in shifting F_p, in Bialo its relative effect was only 58%. Apparently, the sensitivity to changes in land use change plus changes in rainfall intensity depends on other characteristics of the watersheds, and generalizations made on the basis of one or two ~~dace~~case studies may not hold, even within the same climatic zone.

⇨ ~~Fig.~~Figure 4

3.3 Further analysis of F_p effects for scenarios of land cover change

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Among the four watersheds there is consistency in that the 'forest' scenario has the highest, and the 'degraded lands' the lowest F_p value (~~Fig.~~Figure 5), but there are remarkable differences as well: in Cidanau the interannual variation in F_p is clearly larger than land cover effects, while in the Way Besai the spread in land use scenarios is larger than interannual variability. In Cidanau a peat swamp between most of the catchment and the measuring point buffers most of landcover related variation in flow, but not the interannual variability. Considering the frequency distributions of F_p values over a 20 year period, we see one watershed (Way Besai) where the forest stands out from all others, and one (Bialo) where the degraded lands are separate from the others. Given the degree of overlap of the frequency distributions, it is clear that multiple years of empirical observations will be needed before a change can be affirmed.

Figure 54 shows the frequency distributions of expected effect sizes on F_p of a comparison of any land cover with either forest or degraded lands. Table 5 translates this information to the number of years that a paired plot (in the absence of measurement error) would have to be maintained to reject a null-hypothesis of no effect, at p=0.05. As the frequency distributions of F_p differences of paired catchments do not match a normal distribution, a Kolmorov-Smirnov test can be used to assess the probability that a no-difference null hypothesis can yield the difference found. By bootstrapping within the years where simulations supported by observed rainfall data exist, we found for the Way Besai catchment, for example, that 20 years of data would be needed to assert (at P = 0.05) that the ReFor scenario differs from AgFor, and 16 years that it differs from Actual and 11 years that it differs from Degrade. In practice, that means that empirical evidence that survives statistical tests will not emerge, even though effects on watershed health are real.

⇨ ~~Fig.~~Figure 5

⇨ Table 5

At process-level the increase in 'overland flow' in response to soil compaction due to land cover change has a clear and statistically significant relationship with decreasing F_p values in all catchments (~~Fig.~~Figure 6), but both year-to-year variation within a catchment and differences between catchments influence the results as well, leading to considerable spread in the biplot. Contrary to expectations, the disappearance of 'interflow' by soil compaction is not reflected in measurable change in F_p value. The temporal difference between overland and interflow (one or a few days) gets easily blurred in the river response that integrates over multiple streams with variation in delivery times; the difference between overland- or interflow and baseflow is much more pronounced. Apparently, according to our model, the high macroporosity of forest soils that allows interflow and may be the 'sponge' effect attributed to forest, delays delivery to rivers by one or a few days, with little effect on the flow volumes at locations downstream where flow of multiple days accumulates. The difference between overland- or interflow and baseflow in time-to-river of rainfall peaks is much more pronounced~~.~~.

⇨ ~~Fig.~~Figure 6

Tree cover has two contradicting effects on baseflow: it reduces the surplus of rainfall over evapotranspiration (annual water yield) by increased evapotranspiration (especially where evergreen trees are involved), but it potentially increases soil macroporosity that supports infiltration and interflow, with relatively little effect on ~~waterholding~~water holding capacity measured as 'field capacity' (after runoff and interflow have removed excess water). Figure~~.~~ 7 shows that the total volume of baseflow differs more between sites and their rainfall pattern than it varies with tree cover. Between years total evapotranspiration and baseflow totals are positively correlated, ~~(see supplementary information),~~ but for a given rainfall there is a ~~tradeoff~~trade-off. Overall these results support the conclusion that generic effects of deforestation on decreased flow persistence, and of (agro)/(re)-forestation on increased flow persistence are small relative to interannual variability due to specific rainfall patterns, and that it will be hard for any empirical data process to pick-up such effects, even if they are qualitatively aligned with valid process-based models.

⇨ ~~Fig.~~Figure 7

4. Discussion

In the discussion of Part I the credibility questions on replicability of the F_p metric and its sensitivity to details of rainfall pattern versus land cover as potential causes of variation were seen as requiring case studies in a range of contexts. Although the four case studies in Southeast Asia presented here cannot be claimed to represent the global variation in catchment behaviour (with absence of a snowpack and its dynamics as an obvious element of flow buffering not included), the diversity of responses among these four ~~allready~~already point to challenges for any generic interpretation of the degree of flow persistence that can be achieved under natural forest cover, as well as its response to land cover change.

The empirical data summarized here for (sub)humid tropical sites in Indonesia and Thailand show that values of F_p above 0.9 are scarce in the case studies provided, but values above 0.8 were found, or inferred by the model, for forested landscapes. Agroforestry landscapes generally presented F_p values above 0.7, while open-field agriculture or degraded soils led to F_p

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values of 0.5 or lower. Due to differences in local context, it may not be feasible to relate typical F_p values to the overall condition of a watershed, but temporal change in F_p can indicate degradation or restoration if a location-specific reference can be found. The difference between wet and dry season F_p can be further explored in this context. The dry season F_p value primarily reflects the underlying geology, with potential modification by engineering and operating rules of reservoirs, the wet season F_p is generally lower due to partial shifts to overland and interflow pathways. Where further uncertainty is introduced by the use of ~~modeled~~modelled rather than measured river flow, the lack of fit of models similar to the ones we used here would mean that scenario results are indicative of directions of change rather than a precision tool for fine-tuning combinations of engineering and land cover change as part of integrated watershed management.

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The differences in relative response of the watersheds to changes in mean rainfall intensity and land cover change, suggest that generalizations derived from one or a few case studies are to be interpreted cautiously. If land cover change would influence details of the rainfall generation process (arrow 10 in Figure 1 of part I; e.g. through release of ice-nucleating bacteria Morris ~~et al~~et al., 2014; van Noordwijk ~~et al~~et al., 2015b) this can easily dominate over effects via interception, transpiration and soil changes.

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Our results indicate an intra-annual variability of F_p values between wet and dry seasons of around 0.2 in the case studies, while interannual variability in either annual or seasonal F_p was generally in the 0.1 range. The difference between observed and simulated flow data as basis for F_p calculations was mostly less than 0.1. With current methods, it seems that effects of land cover change on flow persistence that shift the F_p value by about 0.1 are the limit of what can be asserted from empirical data (with shifts of that order in a single year a warning sign rather than a firmly established change). When derived from observed river flow data F_p is suitable for monitoring change (degradation, restoration) and can be a serious candidate for monitoring performance in outcome-based ecosystem service management contracts.

In view of our results the lack of robust evidence in the literature of effects of change in forest and tree cover on flood occurrence may not be a surprise; effects are subtle and most data sets contain considerable variability. Yet, such effects are consistent with current process and scaling knowledge of watersheds.

Conclusion

Overall, our analysis suggests that the level of flow buffering achieved depends on both land cover (including its spatial configuration and effects on soil properties) and space-time patterns of rainfall (including maximum rainfall intensity as determinant of overland flow). Generalizations on dominant influence of either, derived from one or a few case studies are to be interpreted cautiously. If land cover change would influence details of the rainfall generation process this can easily dominate over effects via interception, transpiration and soil changes. Multi-year data will generally be needed to attribute observed changes in flow buffering to degradation/restoration of watersheds, rather than specific rainfall events. With current methods, it seems that effects of land cover change on flow persistence that shift the F_p value by about 0.1 are the limit of what can be asserted from empirical data, with shifts of that order in a single year a warning sign rather than a firmly established change. When derived from observed river flow data F_p is suitable for monitoring change (degradation, restoration) and can be a serious candidate for monitoring performance in outcome-based ecosystem service management contracts.

Further tests on the performance of the F_p metric and its standard incorporation into the output modules of river flow and watershed management models will broaden the basis for interpreting the value ranges that can be expected for well-functioning watersheds in various conditions of climate, topography, soils, vegetation and engineering interventions. Such a broader empirical base could test the possible use of F_p as performance metric for watershed rehabilitation efforts.

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Data availability

Table 6 specifies the rainfall and river flow data we used for the four basins and specifies the links to detailed descriptions.

⇨ Table 6

Acknowledgements

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Table 1. Basic physiographic characteristics of the four study watersheds

Parameter	Bialo	Cidanau	Mae Chaem	Way Besai
Location	South Sulawesi, Indonesia	West Java, Indonesia	Northern Thailand	Lampung, Sumatera, Indonesia
Coordinates	5.43 S, 120.01 E	6.21 S, 105.97 E	18.57 N, 98.35 E	5.01 S, 104.43 E
Area (km^2)	111.7	241.6	3892	414.4
Elevation (m a.s.l.)	0 ~~0~~– 2874	~~30~~ 30 – 1778	475-2560	720-1831
Flow pattern	Parallel	Parallel (with two main river flow that meet in the downstream area)	Parallel	Radial
Land cover type	Forest (13%) Agroforest (59%) Crops (22%) Others (6%)	Forest (20%) Agroforest (32%) Crops (33%) Others (11%) Swamp(4%)	Forest (evergreen, deciduous and pine) (84%) Crops (15%) Others (1%)	Forest (18%) Coffee (monoculture and multistrata) (64%) Crop and ~~Holticulture~~Horticulture (12%) Others (6%)
Mean annual rainfall, mm	1695	2573	1027	2474
Wet season	April – June	January - March	July - September	January - March
Dry season	July - September	July - September	January - March	July - September
Mean annual runoff, mm	947	917	259	1673
Major soils	Inceptisols	Inceptisols	Ultisols, Entisols	Andisols

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~~% Natural forest~~	~~13~~	~~3.1 (forest and swamp forest)~~	~~84 (deciduous, evergreen, pine)~~	~~3.6~~

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Table 2. Parameters of the GenRiver model used for the four site specific simulations (van Noordwijk ~~et al~~et al~~.~~., 2011 for definitions of terms; sequence of parameters follows the pathway of water)

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Parameter	Definition	Unit	Bialo	Cidanau	Mae Chaem	Way Besai
RainIntensMean	Average rainfall intensity	mm hr^{-1}	30	30	3	30
RainIntensCoefVar	Coefficient of variation of rainfall intensity	mm hr^{-1}	0.8	0.3	0.5	0.3
RainInterceptDripRt	Maximum drip rate of intercepted rain	mm hr^{-1}	80	10	10	10
RainMaxIntDripDur	Maximum dripping duration of intercepted rain	h~~H~~r	0.8	0.5	0.5	0.5
InterceptEffectontrans	Rain interception effect on transpiration	-	0.35	0.8	0.3	0.8
MaxInfRate	Maximum infiltration capacity	mm d^{-1}	580	800	150	720
MaxInfSubsoil	Maximum infiltration ~~sub soil~~ capacity of the sub soil	mm d^{-1}	80	120	150	120
PerFracMultiplier	Daily soil water drainage as fraction of groundwater release fraction	-	0.35	0.13	0.1	0.1
MaxDynGrWatStore	Dynamic groundwater storage capacity	mm	100	100	300	300
GWReleaseFracVar	Groundwater release fraction, applied to all subcatchments	-	0.15	0.03	0.05	0.1
Tortuosity	Stream shape factor	-	0.4	0.4	0.6	0.45
Dispersal Factor	Drainage density	-	0.3	0.4	0.3	0.45

River Velocity	River flow velocity	m s^{-1}	0.4	0.7	0.35	0.5

Table 3. GenRiver defaults for land-use specific parameter values, used for all four watersheds (BD/BDref indicates the bulk density relative to that for an agricultural soil pedotransfer function; see van Noordwijk ~~et al~~et al., 2011)

Land cover Type	Potential interception (mm/d)	Relative drought threshold	BD/BDref
Forest[1]	3.0 - 4.0	0.4 - 0.5	0.8 - 1.1
Agroforestry[2]	2.0 - 3.0	0.5 - 0.6	0.95 - 1.05
Monoculture tree[3]	1.0	0.55	1.08
Annual crops	1.0 - 3.0	0.6 - 0.7	1.1 - 1.5
Horticulture	1.0	0.7	1.07
Rice field[4]	1.0 - 3.0	0.9	1.1 - 1.2
Settlement	0.05	0.01	1.3
Shrub and grass	2.0 - 3.0	0.6	1.0 - 1.07
Cleared land	1.0 - 1.5	0.3 - 0.4	1.1 - 1.2

Note: 1. Forest: primary forest, secondary forest, swamp forest, evergreen forest, deciduous forest

2. Agroforestry: mixed garden, coffee, cocoa, clove

3. Monoculture : coffee

4. Rice field: irrigation and rainfed

Table 4. Land use scenarios explored for four watersheds

Scenario	Description
NatFor	Full natural forest, hypothetical reference scenario
ReFor	Reforestation, replanting shrub, cleared land, grass land and some agricultural area with forest
AgFor	Agroforestry scenario, maintaining agroforestry areas and converting shrub, cleared land, grass land and some of agricultural area into agroforestry
Actual	Baseline scenario, based on the actual condition of land cover change during the ~~modeled~~modelled time period
Agric	Agriculture scenario, converting some of tree based plantations, cleared land, shrub and grass land into rice fields or dry land agriculture, while maintain existing forest
Degrading	No change in already degraded areas, while converting most of forest and agroforestry area into rice fields and dry land agriculture

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Table 5. Number of years of observations required to estimate flow persistence to reject the null-hypothesis of 'no land use effect' at p-value = 0.05 using Kolmogorov-Smirnov test. The probability of the test statistic in the first significant number is provided between brackets and where the number of observations exceeds the time series available, results are given in *italics*

A. Natural Forest as reference

Way Besai (N=32)	ReFor	AgFor	Actual	Agric
ReFor		20 (0.035)	16 (0.037)	13 (0.046)
AgFor			n.s.	n.s.
Actual				n.s.
Agric				
Degrading				

Bialo (N=18)	ReFor	AgFor	Actual	Agric
ReFor		n.s.	n.s.	*37 (0.04)*
AgFor			n.s.	n.s.
Actual				n.s.
Agric				
Degrading				

Cidanau (N=20)	ReFor	AgFor	Actual	Agric
ReFor		n.s.	n.s.	*32 (0.037)*
AgFor			n.s.	n.s.
Actual				n.s.
Agric				
Degrading				

Mae Chaem (N=15)	ReFor	Actual	Agric	Degrade
ReFor		n.s.	*23 (0.049)*	*18 (0.050)*
Actual			*45 (0.037)*	*33 (0.041)*
Agric				*33 (0.041)*
Degrading				

B. **Degrading scenario as reference**

Way Besai (N=32)	NatFor	ReFor	AgFor	Actual	Agric
NatFor		n.s.	17 (0.042)	13 (0.046)	7 (0.023)
ReFor			21 (0.037)	19 (0.026)	7 (0.023)
AgFor				n.s.	28 (0.046)
Actual					30 (0.029)
Agric					

Bialo (N=18)	NatFor	ReFor	AgFor	Actual	Agric
NatFor		n.s.	n.s.	*41 (0.047)*	*19 (0.026)*
ReFor			n.s.	n.s.	*32 (0.037)*
AgFor				n.s.	n.s.
Actual					n.s.
Agric					

Cidanau (N=20)	NatFor	ReFor	AgFor	Actual	Agric
NatFor		n.s.	n.s.	*33 (0.041)*	8 (0.034)
ReFor			n.s.	n.s.	15 (0.028)
AgFor				n.s.	n.s.
Actual					*25 (0.031)*
Agric					

Mae Chaem (N=15)	NatFor	ReFor	Actual	Agric
NatFor		n.s.	25 (0.031)	12 (0.037)
ReFor			n.s.	*18 (0.050)*
Actual				*18 (0.050)*
Agric				

Table 6. Data availability

	Bialo	Cidanau	Mae Chaem	Way Besai
Rainfall data	1989-2009, Source: BWS Sulawesi[a] and PUSAIR[b]; Average rainfall data from the stations Moti, Bulo-bulo, Seka and Onto	1998-2008, source: BMKG[c]	1998-2002, source: WRD55, MTD22, RYP48, GMT13, WRD 52	1976-2007, Source: BMKG, PU[d] and PLN[e] (interpolation of 8 rainfall stations using Thiessen polygon)
River flow data	1993-2010, source; BWS Sulawesi and PUSAIR	2000-2009, source: KTI[f]	1954-2003, source: ICHARM[g]	1976-1998, source: PU PUSAIR
Reference of detailed report	http://old.icraf.org/regions/southeast_asia/publications?do=view_pub_detail&pub_no=PP0343-14	http://worldagroforestry.org/regions/southeast_asia/publications?do=view_pub_detail&pub_no=PO0292-13	http://worldagroforestry.org/regions/southeast_asia/publications?do=view_pub_detail&pub_no=MN0048-11	http://worldagroforestry.org/regions/southeast_asia/publications?do=view_pub_detail&pub_no=MN0048-11

Note:

[a] BWS: Balai Wilayah Sungai (*Regional River Agency*)

[b]PUSAIR: Pusat Litbang Sumber Daya Air (*Centre for Research and Development on Water Resources)*

[c]BMKG: Badan Meteorologi Klimatologi dan Geofisika (*Agency on Meterology, Climatology and Geophysics*)

[d]PU: Dinas Pekerjaan Unum *(Public Work Agency)*

[e]PLN: Perusahaan Listrik Negara (*National Electric Company*)

[f]KTI: Krakatau Tirta Industri, a private steel company

[f]ICHARM: The International Centre for Water Hazard and Risk Management

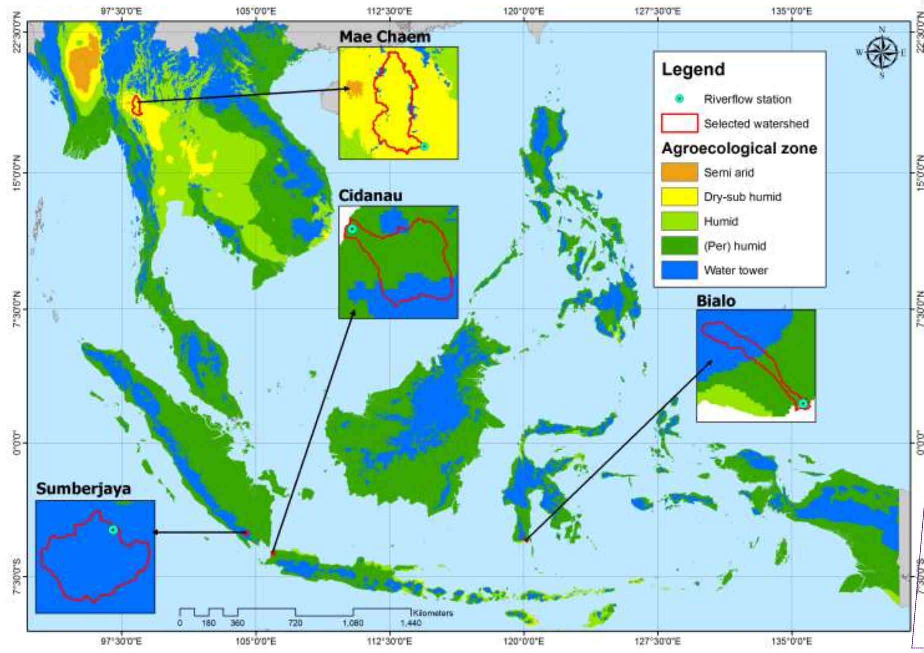

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Figure 1. Location of the four watersheds in the agroecological zones of Southeast Asia (water towers are defined on the basis of ability to generate ~~riverflow~~river flow and being in the upper part of a watershed)

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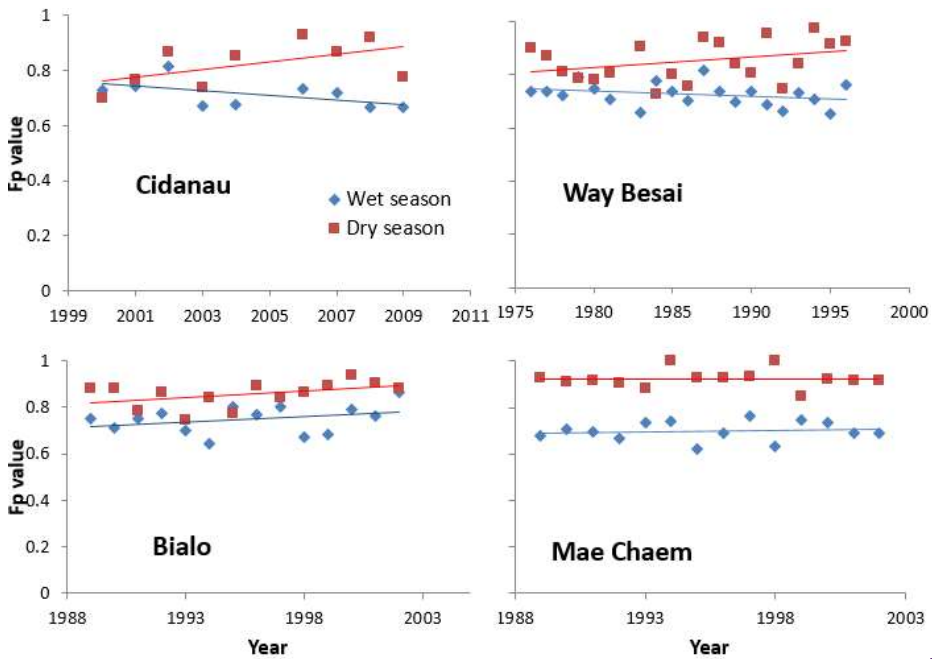

Figure 2. Flow persistence (F_p) estimates derived from measurements in four watersheds, separately for the wettest and driest 3-month periods of the year

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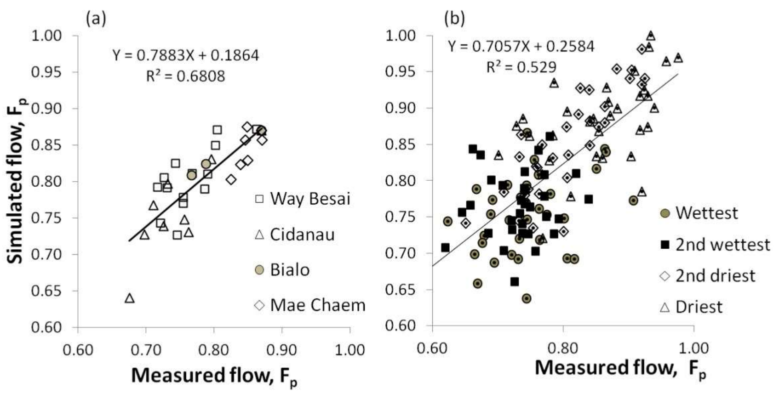

Figure 3. Inter- (A) and intra- (B) annual variation in the F_p parameter derived from empirical versus modeled flow: for the four test sites on annual basis (A) or three-monthly basis (B)

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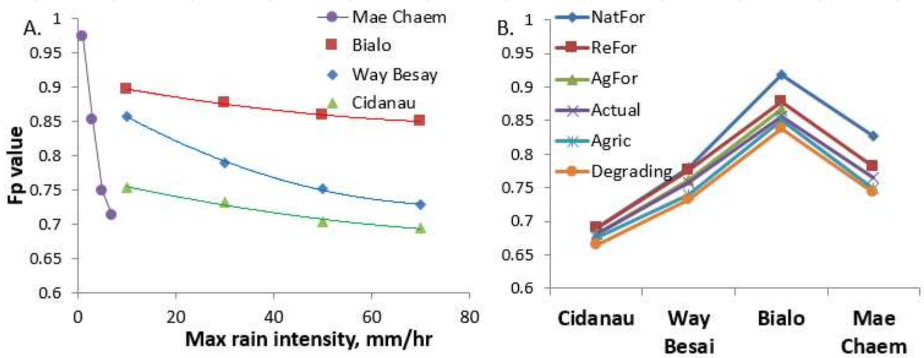

Figure 4 Effects on flow persistence of changes in A) the mean rainfall intensity and B) the land use change scenarios of Table 4 across the four watersheds

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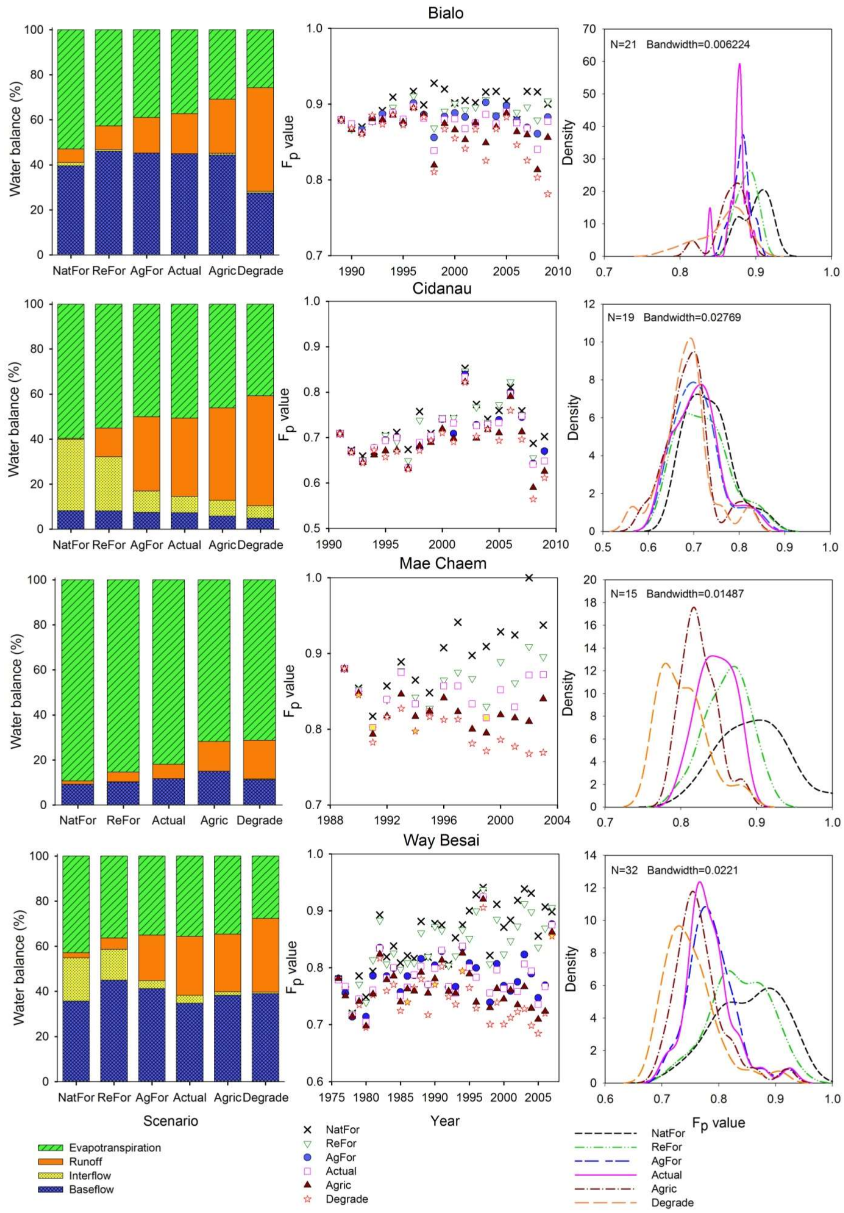

Figure 5. Effects of land cover change scenarios (Table 4) on the flow persistence value in four watersheds, modelled in GenRiver over a 20-year time-period, based on actual rainfall records; the left side panels show average water balance for each land cover scenario, the

Formatted: English (United Kingdom), Check spelling and grammar middle panels the Fp values per year and land use, the right-side panels the derived frequency distributions (best fitting Weibull distribution)

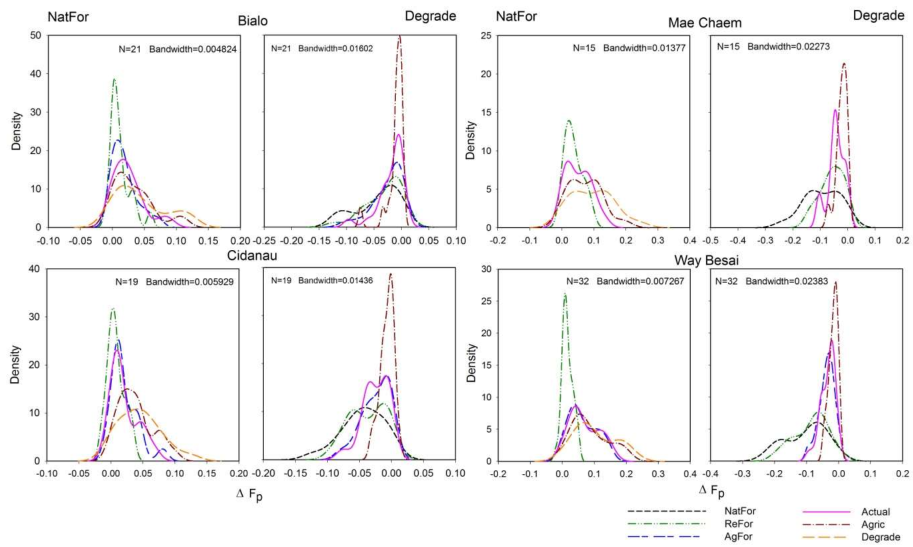

Figure 6. Frequency distribution of expected difference in F_p in ‘paired plot’ comparisons where land cover is the only variable; left panels: all scenarios compared to ‘reforestation’, right panel: all scenarios compared to degradation; graphs are based on a kernel density estimation (smoothing) approach

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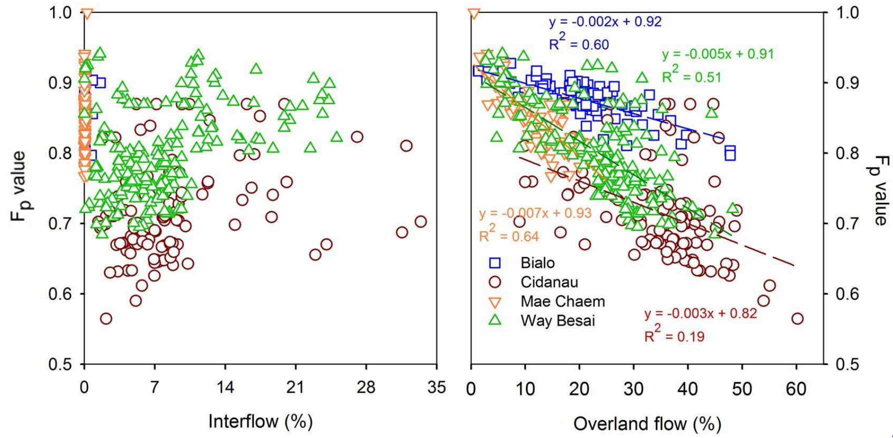

1223

1224 Figure 7. Correlations of F_p with fractions of rainfall that take overland flow and interflow

1225 pathways through the watershed, across all years and land use scenarios of Figure~~.~~ App2

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Appendix 1. GenRiver model for effects of land cover on river flow

The Generic ~~Riverflow~~River flow (GenRiver) model (van Noordwijk ~~et al~~et al.., 2011) is a simple hydrological model that simulates river flow based on water balance concept with a daily time step and a flexible spatial subdivision of a watershed that influences the routing of water. The core of the GenRiver model is a "patch" level representation of a daily water balance, driven by local rainfall and modified by the land cover and land-~~-~~ cover change and soil properties. The model starts accounting of rainfall or precipitation (P) and traces the subsequent flows and storage in the landscape that can lead to either evapotranspiration (E), river flow (Q) or change in storage (ΔS) (Figure App1):

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$$P = Q + E + \Delta S \qquad [1]$$

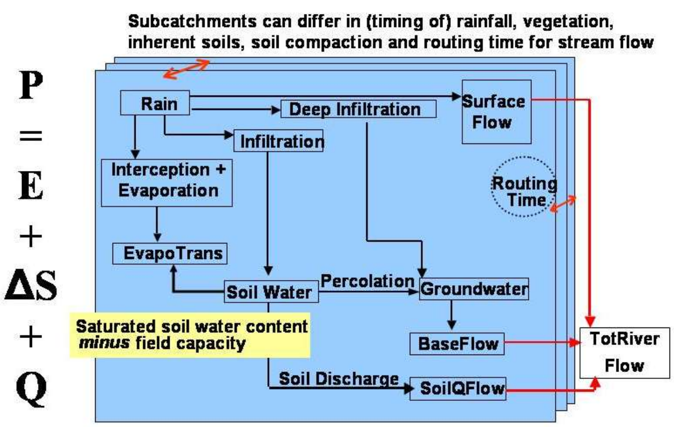

Figure App1.Overview of the GenRiver model

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The model may use measured rainfall data, or use a rainfall generator that involves Markov chain temporal autocorrelation (rain persistence). The model can represent spatially explicit rainfall, with stochastic rainfall intensity (parameters RainIntensMean, RainIntensCoefVar in Table 2) and partial spatial correlation of daily rainfall between subcatchments. Canopy interception leads to direct evaporation of an amount of water controlled by the thickness of waterfilm on the leaf area that depends on the land cover, and a delay of water reaching the soil surface (parameter RainMaxIntDripDur in Table 2). The effect of evaporation of intercepted water on other components of evapotranspiration is controlled by the InterceptEffectontrans parameter, that in practice may depend on the time of day rainfall occurs and local climatic conditions such as windspeed)

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At ~~patchlevel~~patch level, vegetation influences interception, retention for subsequent evaporation and delayed transfer to the soil surface, as well as the seasonal demand for water. Vegetation (land cover) also influences soil porosity and infiltration, modifying the inherent soil properties. Groundwater pool dynamics are represented at subcatchment rather than patch level, integrating over the landcover fractions within a subcatchment. The output of the model is river flow which is contribution from three types of stream flow: surface flow on the day of the rainfall event; interflow on the next day; and base flow as the slow flow. the multiple subcatchments that make up the catchment as a whole can differ in basic soil properties, land-cover fractions that affect interception, soil structure (infiltration rate) and seasonal pattern of water use by the vegetation. The subcatchment will also typically differ in "routing time" or in the time it takes the streams and river to reach any specified observation point (with default focus on the outflow from the catchment). The model itself (currently implemented in Stella plus Excel), a manual and application case studies are freely available (http://www.worldagroforestry.org/output/genriver-genetic-river-model-river-flow ;van Noordwijk ~~et al~~et al., 2011).

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Appendix 2. Watershed-specific consequences of the land use change scenarios

The generically defined land use change scenarios (Table 4) led to different land cover proportions, depending on the default land cover data for each watershed, as shown in Figure App2.

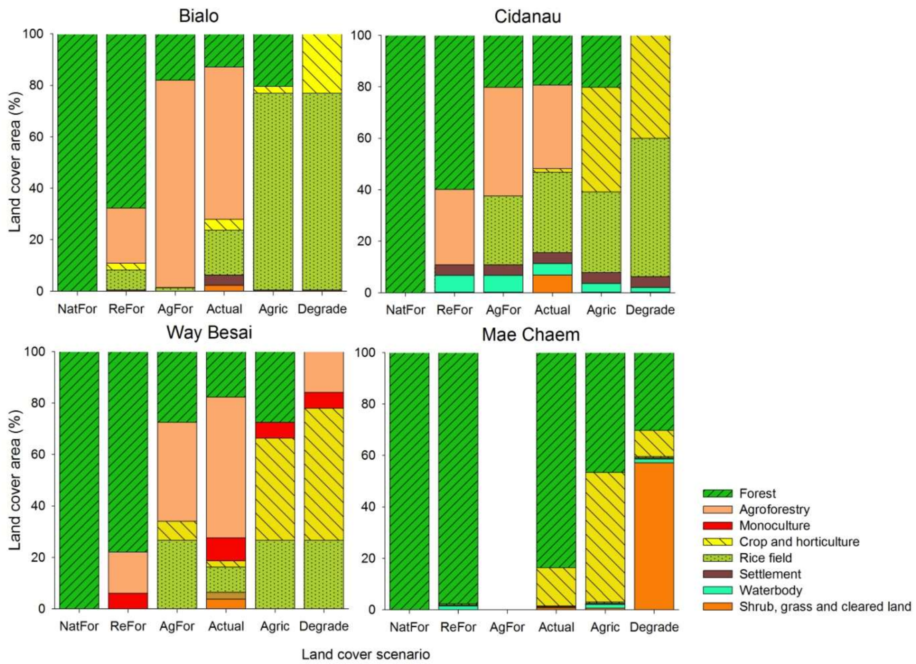

Figure App2. Land use distribution of the various land use scenarios explored for the four watersheds (see Table 4)

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Appendix 3. Example of a macro in R to estimate number of observation required using bootstrap approach.

```
#The bootstrap procedure is to calculate the minimum sample size (number of observation) required
#for a significant land use effect on Fp
#bialo1 is a dataset contains delta Fp values for two different from Bialo watershed

#read data
bialo1 <- read.table("bialo1.csv", header=TRUE, sep=",")

#name each parameter
BL1 <- bialo1$ReFor
BL5 <- bialo1$Degrade

N = 1000 #number replication

n <- c(5:50) #the various sample size

J <- 46 #the number of sample size being tested (~ number of actual year observed in the dataset)

P15= matrix(ncol=J, nrow=R) #variable for storing p-value
P15Q3 <- numeric(J) #for storing p-Value at 97.5 quantile

for (j in 1:J) #estimating for different n

#bootstrap sampling
{
for (i in 1:N)
{
#sampling data
S1=sample(BL1, n[j], replace = T)
S5=sample(BL5, n[j], replace = T)

#Kolmogorov-Smirnov test for equal distribution and get the p-Value
KS15 <- ks.test(S1, S5, alt = c("two.sided"), exact = F) P15[i,j] <- KS15$p.value
}

#Confidence interval of CI
P15Q3[j] <- quantile(P15[,j], 0.975)

}

#saving P value data and CI

write.table(P15, file = "pValue15.txt") write.table(P15Q3, file = "P15Q3.txt")v
```