Spatial variability of rainfall governs river flow and reduces effects of land use change at landscape scale: GenRiver and SpatRain simulations

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Abstract Empirical data show an abundance of evidence for effects of land use change on streamflow (total quantity, sediment load, amplitude of fluctuations) for spatial scales up to 100 km^2 but little hard evidence beyond that scale. Is that simply based on lack of research, or are other factors, such as low spatial correlation of rainfall events plus differentiation in routing times starting to dominate beyond this scale? Are changes in local buffering that are linked to land use change swamped by these other effects? The GenRiver model is a distributed model based on basic water balance at subcatchment level, linked to a rainfall generator SpatRain that can generate a wide range of space/time patterns of rainfall. The impacts of routing time differentiation and a simple length scale of the rainfall pattern can now be compared to impacts of differences in interception, infiltration capacity and storage linked to land use change. Model parameterization for the Sumber Jaya area in Lampung (Indonesia) can generate patterns of daily river flow that are similar to the observed frequency distributions, if a strongly disaggregated rainfall pattern is used for the input, and not for more homogeneous rainfall patterns. Although a more 'patchy' rainfall may induce more surface quickflow at field scale, it tends to a more regular pattern of riverflow at landscape scale. We conclude that the factors dominating river flow patterns at landscape scale (approximately 5th order rivers) are thus essentially different from those dominant at field scale, and that effects of land use change are likely to become less important with increasing scale of consideration.

Keywords: *Forest conversion, GenRiver, Hydrological impacts, Land use change, Rainfall variability, SpatRain, Scale, WaNuLCAS, water-balance*

1. INTRODUCTION

Concerns over negative environmental effects of forest conversion are often expressed in relation to hydrological impacts. Patterns of river flow are widely perceived to change upon change in land cover from closed forest cover to an agriculturally used landscape. Different aspects of river flow such as annual water yield, the partitioning over storm flow and baseflow, and changes in water quality may, however, occur at different rates, change to different degrees, and may even move in different direction (Calder, 2002), calling for precision in the 'functions' considered rather than referring to generic 'watershed functions'.

An overview of land use change effects on various watershed functions by Kiersch and Tognetti (2002) has demonstrated an abundance of well-documented impacts for study areas of up to 100 km^2, but only found conclusive evidence for changes in water quality (especially regarding concentrations of pesticides, heavy metals or salt) for studies that considered larger areas (up to 10^{5}km^2). The 'lack of evidence of effects' of land use change may either indicate that studies so far have been inadequate ('lack of evidence') or that broadly held perceptions that land use change effects on hydrological functions are valid across scales need to be reconsidered ('lack of effect'). The latter would have considerable consequences for policies aimed at land use regulation and for ways to reduce the conflicts that often exist between downstream stakeholders and land users in the uplands.

Two alternative hypotheses thus are 1) land use effects on river flow **persist** across scales, but are **masked** by increasing variability and research so far has been inadequate to separate real effects from 'background noise'; 2) factors other than those responding to land use change become **increasingly** important with increasing size of catchment areas in influencing the volume, seasonality and regularity of river flow.

We will here explore the logical consistency of the second hypothesis, making use of ongoing studies in the uplands of Lampung (Indonesia) and modeling tools at field and landscape scale. Data on daily and monthly correlations between various measurement locations in the study area are discussed by Manik and Sidle (this symposium), while a model that considers changes in land use pattern in a dynamic sense is presented by Suyamto et al. (this symposium).

2. MODEL DESCRIPTIONS

2.1 WaNuLCAS: plot-level soil infiltration

The WaNuLCAS model of water, nutrient and light capture in agroforestry systems (Van Noordwijk and Lusiana, 1999; model available from www.icraf.org/sea) describes the partitioning of rainfall over canopy interception, surface lateral flows, soil recharge, groundwater recharge and subsurface lateral flows, on the basis of soil physical properties, slope, plant (annual crops, weeds and/or trees) water use and root distribution and the duration of rainfall events. Current versions of the model include dynamics of macroporosity of the soil impacting on the infiltration process, with a gradual decline of existing macropores and a new formation of macropores by biological activity linked to the supply of surface litter and soil organic matter feeding soil biota.

A model application was developed for the Sumber Jaya landscape in Lampung (Indonesia) dominated by coffee gardens of different age (time since forest conversion) and type (monocultures, coffee + shade trees, multistrata coffee gardens).

2.2 SpatRain: space/time patterns in rainfall

As most studies of r5ainfall pattern focus either on the timeseries (degree of autocorrelation) for rainfall at a single point of observation, or on the spatial patterns of cumulative rainfall over a monthly or yearly period, we identified a need for a tool that considers variation across both space and time at daily or event scale. The SpatRain model starts from the spatial characteristics of a single rainstorm pathway (with a trajectory for the core area of the highest intensity and a decrease of rainfall intensity with increasing distance from this core), and can derive daily amounts of rainfall for a grid of observation points by considering the possibility of multiple storm events per day. Options exist for including elevational effects on rainfall amount. SpatRain is implemented as an Excel workbook, with macro's that analyze semivariance as a function of increasing distance between observation points, as a way to characterize the resulting rainfall patterns accumulated over specified lengths of time (day, week, month, year). Initial results indicate that the analysis of maps accumulating over 30 events will give more consistent results than those for single or few events, while at 100 events the pattern becomes blurred by overlaps.

For use in combination with the GenRiver model, SpatRain allows for the identification of subcatchments in a watershed area and averaging the point grid pattern to derive the daily average rainfall per subcatchment.

2.2 GenRiver: a simple water balance model for (sub)catchment scale

A ***river*** is treated as a summation of ***stream***s, each originating in a ***subcatchment*** with its own daily rainfall, yearly land cover fractions and constant total area and distance to the river outflow (or measurement) point. Interactions between streams in their contribution to the river are considered to be negligible (i.e. there is no 'backflow' where rivers join). Spatial patterns in daily rainfall events in each subcatchment can be derived from a linked spreadsheet model (SpatRain). The ***subcatchment*** model represents interception, infiltration into soil, rapid percolation into subsoil, surface flow of water and rapid lateral subsurface flow into streams with parameters that can vary between land cover classes. The description of the infiltration process is similar to that in WaNuLCAS and the parametrization can be derived for a wide range of land cover types (and histories) from tests with that, more detailed model. Figure 1 represents the core module as diagram. Table 1 gives the main parameters and their default values.

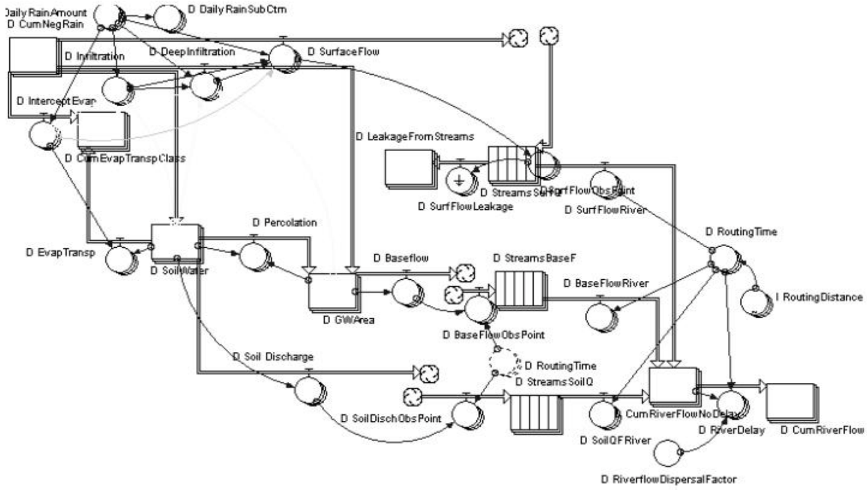


Table 1. Key parameters and default model input values for the GenRiver model

Acronym	Definition	Dimension [default value]
DailyRain (i,t)	Daily rainfall for each unit I	mm (= l per m^2)
MeanRainIntensity, CV_RainIntensity	Mean and coefficient of variation of rainfall intensity; together with slope sets time available for infiltration	mm hour^{-1}, [], (30), (0.3)
InterceptPerClass (j)	Interception storage capacity per land cover class	mm
LandCoverFreq (i,t)	Land cover class frequency per unit i	[]
MaxInfRate (i)	Maximum infiltration capacity per unit i	mm day $^{-1}$ (1000)
RelativeDrought Threshold (j)	Drought-limitation to transpiration per land cover class, as fraction of field capacity	[]
FieldCapacity (i)	Field capacity of the soil (soil water content 1 day after 'soalking' rain	mm (600)
SoilSatminusFC (i)	Difference between saturation water storage capacity and field capacity of the soil	mm (100)
MaxDynGrWatStore (i)	Dynamic groundwater storage capacity	mm (350)
RoutingDistance (i,o)	Distance from the center of the subcatchment *i* to a number of observation points on the river *o*	Km
MeanFlowVelocity	Mean flow velocity	km day^{-1}
GWReleaseFrac	Daily groundwater release fraction per subcatchment	[] (0.03)
PercFracMultiplier	Daily soil water drainage as fraction of groundwater release fraction	[] (0.5)
Epot (t)	Potential evapotranspiration (Penman type)	mm day^{-1} (5)
Area (i)	Area of each subcathment	km^2

Note: index t **refers** to time dependent input, **i** to subcatchment, **j** to land cover classes, **o** for observation points along the river

The description of the infiltration process is similar to that in WaNuLCAS and the parameterization can be derived for a wide range of land cover types (and histories) from tests with that, more detailed model. Infiltration is calculated as the minimum of :

- the daily infiltration capacity times the fraction of a day that is available for infiltration (the latter reflects rainfall intensity as well as the local storage capacity of the soil surface)
- the amount that can be held by the soil at saturation minus the amount already present ***plus*** the amount that can enter the groundwater within a day (which in itself is the minimum of the potential daily transport rate and the difference between maximum storage capacity of groundwater and the current amount)

If the first constraint is active, the model generates 'infiltration limited runoff', in the second case 'saturation overlandflow'. The sum of both is included as 'surface quickflow'. Total evapotranspiration is driven by potential evapotranspiration (Penman type) and (partially) met by :

- intercepted water
- land cover, with a drought-limitation proportional to soil water content relative to field capacity below a (vegetation dependent) threshold,
- soil surface evaporation (not explicit – to be included in the landcover/vegeation properties for transpiration)

During a rain event the soil may get saturated, but within one day it is supposed to drain till 'field capacity' (with an operational definition of the soil water content 24 hours after a heavy rainfall event). The difference between saturation and field capacity can be either:

- used for transpiration (but canopy intercepted rainfall takes priority to meet the demand)
- drain to the groundwater reserve, calculated as the minimum of the amount that can be transported downwards and the fraction of soil water that will drain on any given day,
- drain to the rivers as 'soil-quickflow': any water left above field capacity by the two preceding processes.

Surface quickflow, soilquickflow and baseflow all feed into streams. For each subcatchment a 'routing' function determines the time delay before the water passes by a defined measuring point (currently the outflow from the catchment).

3. RESULTS

3.1 WaNuLCAS parameterization of infiltration

Using a series of small constrained runoff plots (Suprayogo et al, unpublished) as reference, we found that simulations in which only the changes in aboveground vegetation are taken into account without changes in soil physical conditions were not able to account for the measured differences in runoff. A setting where soil physical conditions change with time and system linked to soil organic inputs provided a good match (Fig. 2). The key parameters of this description were transferred to the GenRiver model.

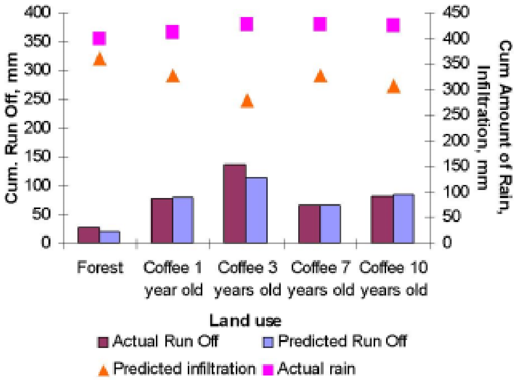
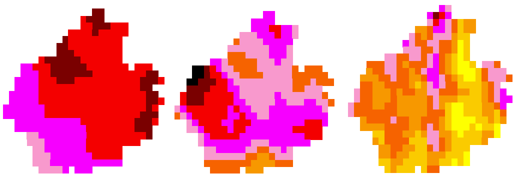


Figure 2. Comparison of WaNuLCAS simulation of infiltration rates and that measured in forest plots or coffee plots of 1,3,7 or 10 years of age, with a model parametrization for gradual decay of soil biota feeding of litter and soil organic matter pools

3.2 SpatRain simulation

A series of spatially explicit daily rainfall patterns was constructed that matches the monthly means as derived from rainfall records on the site, while differencing in pattern (Fig. 3).



Homogenous Intermediate Patchy

Figure 3. Example of the spatial distribution of rainfall on a single day for setting that are indicated as ‘ homogenous’, ‘intermediate’, and ‘patchy’ in this paper

We used fractal dimension to quantify spatial pattern of rainfalls, calculated from the semi-variance slope within the predictable range (sill) as 3-s/2 (Bian, 1997). Fractal dimension of each rainfall type was 1.44, 2.34, and 2.90, for H (‘homogeneous’), I (‘intermediate’) and P (‘patchy’), respectively.

Modifying the spatial extent of individual storm events, however, required additional changes in parameters. The number of rainfall events per day and/or the intensity of rainfall in the core area of the storm have to be adjusted to match the monthly mean point-level rainfall record.

3.3 GenRiver hydrographs

By combining the rainfall patterns of SpatRain, the infiltration process of WaNuLCAS, land cover data for a 20 year period and estimates of monthly transpiration patterns (mostly relevant for the cropped fields, as forest and coffee gardens are evergreen), we simulated river flow for the Way Besai. Results are here shown for year 3 and year 20 of this time series. We found that results for the first half of year 1 depended on initialization of a number of model parameters that became ‘self-attuned’ after year 1.

Inspection of the available rainfall and river flow data for the Way Besai catchment makes clear that no model that uses measured data as input can be expected to closely match the rise and fall pattern of the Way Besai river (Manik and Siddle, this symposium). Several peaks in the river level have no matching rainfall at any of the measurement stations and the response of the river after heavy rainfall can range from substantial to marginal. While this all points to a strongly patchy rainfall pattern, it makes a direct test of predicted versus measured river flow at daily scale meaningless as a goodness of fit test for any model. What we can do, however, is consider the frequency distribution of daily river flow values during a year and compare the mean, range (minimum, maximum), skewness, shape during rise and fall episodes, as well as the run length of rise and fall periods. We will here focus on the frequency distribution as a whole (Fig. 4), in year 3 and year 20 of the time series, reflecting land cover fractions of 58 and 14% for forest, respectively, 22 and 11% for cropland and pioneer stages of fallow vegetation, and 12 and 70% for coffee gardens, respectively.

For the same parameter settings that influence the shape of the rising stage parts (mean flow velocity-y) and decline phase (groundwater release fraction), the predicted hydrograph becomes smoother when we shift from homogeneous, via intermediate to patchy rainfall (Fig. 4). While mean and range in the simulations are close to the measured ones, there is a tendency to over predict the lower flow rates, so our estimate of storage capacity may be too high yet.

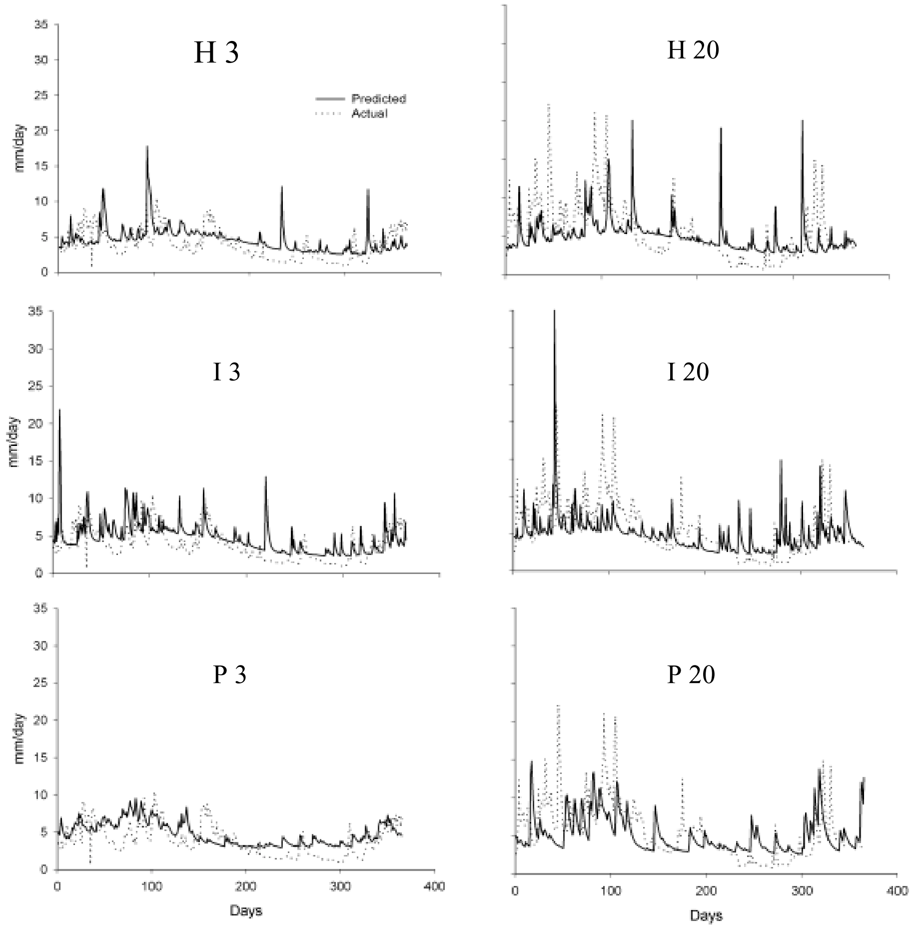


Figure 4. Predicted (lines) and measured (dots) river debit of the Way Besai (expressed in mm day^{-1}) in year 3 and year 20 for the homogeneous, intermediate and patchy rainfall pattern

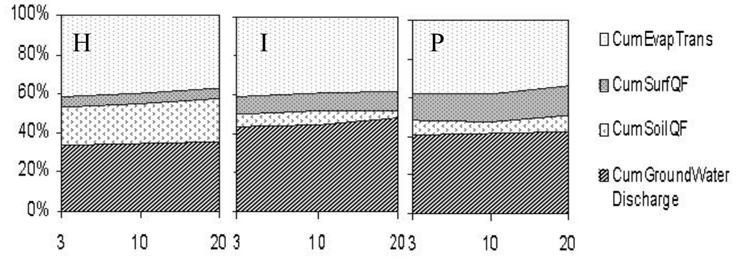


Figure 5. Water balance for homogenous (H), intermediate (I) and patchy (P) rainfall type

Over the 20 year simulation the way annual rainfall is partitioned over evapotranspiration, groundwater discharge, surface and soil quick flows shows some change in response to land use change (Fig. 5): the evapotranspiration term is expected to become smaller by some 200 mm year^{-1}. The difference between the three rainfall pattern, however, is larger than this land use change signal, with an increasing surface quick flow fraction for more patchy rainfall events. The latter is due to higher local rainfall events in parts of the landscape, exceeding infiltration capacity during the time available. The combination of a more steady river flow and a decreased importance of the groundwater discharge pathway may, however, come as a surprise to all hydrologist who link 'base flow' to a groundwater discharge pathway.

The frequency distribution of river flow clearly corresponds with the simulations for 'patchy' rainfall, much more closely that it does with those for homogeneous or intermediate rainfall types (Fig. 6).

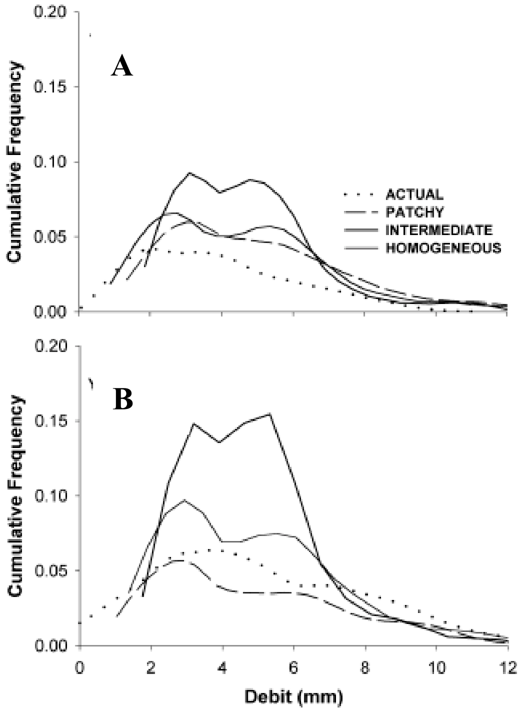


Figure 6. Probability/frequency distribution of the river debit, actual and as simulated by GenRiver simulations driven by homogenous, intermediate or patchy rainfall pattern for year 3 (A) and year 20 (B).

In general, patchy rainfall produces a better match of actual probability distribution of river flow, compare to more homogeneous rainfall pattern. Although overall the model is still unable to produces low value of riverflow.

4. DISCUSSION AND CONCLUSION

The GenRiver model is 'parsimonious' in as far as it allows generic parameter values (for the 6 soil storage related ones: MaxInfRate (i), SoilSatminusFC (i), FieldCapacity (i), MaxDynGrWatStore (i), GWReleaseFrac(i) and PercFracMultiplier) to be used for all subcatchments *i*, while allowing the exploration of stepwise adding more spatial precision. Being explicit in spatial distribution of rainfall appears to be essential in predicting important properties of the hydrograph.

We propose the following conclusions:

1. As actual rainfall patterns are not adequately captured at usual densities of rainfall gauges, tests of riverflow models have to focus on properties of the frequency distribution of river debit, rather than on a close match between daily measured and predicted riverflow,
2. Rainfall patterns with a higher degree of spatial variability, need to be more frequent and/or more intense to reach the same total amount at landscape scale. With SPATRAIN a broad range of patterns can be generated and evaluated, but all have to be constrained by data collected at 'station' level; we need to improve on the current algorithms in this regard,
3. More 'patchy' rainfall patterns tend to create more surface runoff as their higher local intensity is likely to exceed instantaneous infiltration capacity,
4. At landscape scale, however, patchy rainfall leads to more homogeneous riverflow, that may appear to consist of a higher 'baseflow' character when dissecting a hydrograph, even if more of this riverflow derives from 'quickflow' at field scale,
5. As the relative spatial variability of rainfall increases with increasing size of area considered, the relative importance of land use change in affecting riverflow patterns declines because 'baseflow' may derive from sources other than groundwater discharge,
6. River flow of the Way Besai river in Lampung is consistent with GenRiver simulations for a highly spatially disaggregated rainfall pattern, with a relatively small impact of the drastic land use change ('deforestation') of the last two decades.

5. ACKNOWLEDGEMENTS

ACIAR and World Bank-Netherlands Partnership Program (Functional Value of Biodiversity project) grants support this research.

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