The link between land and water
Prediction of sediment sources in a previously forested watershed in Lampung, Sumatra, Indonesia

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Abstract: Deforestation is often blamed for the loss of watershed functions. Little importance is given to what land use comes next. Resulting landscape mosaics with various degrees of tree cover are often perceived as not functional in guaranteeing these services. This was the root to often violent conflicts between guardians of forest and farmers opening the land. ICRAF and partner institutions study land use, its change and the hydrological impacts in and around Sumberjaya watershed, West-Lampung, Sumatra an area of about 730 km^2. The area was transformed in the past three decades from a large forest cover to a mosaic of coffee farms with rice paddies in the valleys and has seen quite some conflict over the past 10 years. The (weak) knowledge base used for evaluating these issues for landscape mosaics covering the wide range between pure forests and purely cropped lands is now challenged by the development of different erosion equations and models over the past ten years. In an earlier erosion modelling exercise various scenarios for the USLE, WEPP and GUEST (Rose) equations were compared at different scales. Results between models were strikingly different, especially in the spatial location of point sources of sediment delivery. Turbidity measurements in the river in a subwatershed indicate the importance of phenomena in and close by the river itself. For example criteria based on slope require definition of map resolution, as steep slopes, but short slopes close to the river are ignored in coarse resolution maps and DEM's. A good characterisation of 'filter' phenomena is more important than a qualification of land use per se. Simulation of the impact of government regulations made clear that a blind application of 'simple' regulations issued at the country level bypasses the local variety of conditions.

Keywords: *Erosion hot spots; Watershed functions; Land use change; Resolution; Scale; Turbidity*

1. INTRODUCTION

The general problem can be defined as the perceived unsustainable use of natural resources (forest conversion) and the negative impacts this has on external stakeholders. The perception may or may not be based on causal relationships and facts. Existing institutions and policies are largely based on a forest - agricultural land use dichotomy and are 'blind' for so-called agroforestry landscape mosaics. This leads often to an unnecessary sense of conflict. The issue is of particular relevance where supposed 'watershed protection functions' have been the basis for regulations of access to land. To help solving these conflicts a framework for negotiation support was developed [van Noordwijk, Tomich et al. 2001] [Verbist, van Noordwijk et al. 2002].

The underlying principles for current Indonesian legislation (e.g. decree n^0 683 of 1980 of the Ministry of Agriculture with criteria on rainfall, slope and soil type) to classify forests to protect watersheds were used by the Department of Forestry to justify the delineation of large areas in watersheds as protection forest.

Key hypothesis in our current research is that some farmer-developed agroforestry mosaics are as effective in watershed protection functions as the original forest cover. Hence conflicts between state forest managers and local population can be resolved to mutual benefit. The problems are clearly represented in the Sumberjaya watershed, an area of about 38.000 ha at the forest fringe with the Bukit Barisan National Park in Lampung, Sumatra, Indonesia. Until now the outcome was often sub-optimal - a euphemism for violent eviction of thousands of farmers in the early nineties [Kusworo, 2000]! The Forest department wants to conserve the protection forest, next to the National Park and has evicted farmers in the past. Farmers need a living and come back, often under silent approval of local government that needs income and in fact favours economic development … This scenario might be representative of possible future trajectories for many other watersheds all over Sumatra. The underlying causes of conflict are probably even more generic and are related to the lack of insight to what extent does a landscape - and its various elements - function properly in providing certain services to and meet expectations from various users and stakeholders. Recent research learnt that farmers, had a much better understanding of the ongoing processes than other stakeholders (government officials, ...) who generally spend more time in the office than in the field [Schalenbourg 2002].

2. PAST LAND USE CHANGE

Forest cover in Sumberjaya decreased over the past 30 years from 60 % in 1970 to 12 % in 2001. This analysis was done on an area of 730 km^2, which encompassed the 380 km^2 Way Besai watershed [Syam et al., 1997] and [Dinata, 2002].

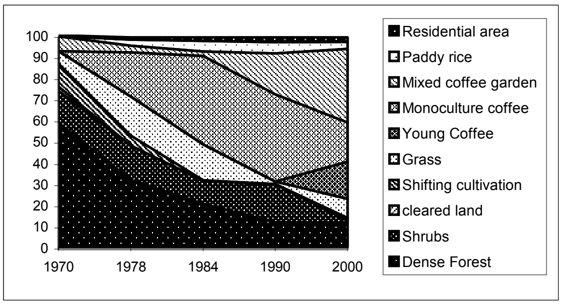

Figure 1. Past land use change in Sumberjaya area

This landscape knew a gradual deforestation and intensification of land use. The various coffee systems increased from a percentage of only 7 % in 1970 to more than 70% in 2000. A land use map of the Way Petai subcatchment was derived from ETM imagery of 2000 [Dinata, 2002] and used as an input in the erosion modeling at catchment level (Table 1).

Table 1. Land use in the Way Petai watershed

Land cover class	%
1 Forest	17.1
2 Shade coffee	33.9
3 Sun coffee	4.8
4 Young coffee	21.2
5 Shrub	15.2
6 Herb and grass	1.2
7 Rice	0.3
8 Cleared land	0.5
9 Road and residential	2.8
10 River	3.0

The Way Petai catchment itself has relatively a bit more forest and less paddy rice than the Sumberjaya area as a whole. Due to the low spatial resolution of the ETM sensor (30 m), the area of paddy rice is underestimated, especially when it appears as narrow strips along the rivers.

3. ASSESSMENT OF SLOPES

A first digital elevation model was derived from a digitised topographic map with scale 1/50.000.
Comparison of the digitised rivers and the local drain direction (ldd) map showed clear anomalies in the mapped rivers. The digitised rivers were then lowered with 1 m, to improve the *ldd* in the flat areas in the northern part. Deriving the rivers from the local drain direction map afterwards using the stream order of Strahler [Karssenberg] gave a better result in the more hilly part, where quite some rivers were missing on the topographic map. The Way Petai area (1.589 ha) consisted of a grid of 347 x 263 cells of 20 m x 20 m each.
For the same area another digital elevation model was made, but then derived from aerial photographs, scale 1/25.000 using PCI 's Ortho-engine software (http://www.pcigeomatics.com/).
This resulted in a catchment area of 1.260 ha. The aerial photographs did not cover a small part of the Way Petai catchment in the north (28 ha), but more importantly it did show that two rivers were actually not flowing into the Way Petai, so the watershed is actually 20% smaller than was first derived from the topographic map! (It is interesting to note that some years ago in a neighbouring watershed (Way Rarem) a similar overestimation based on the topographic map affected an irrigation project. The shortfall in water supply was consecutively blamed on deforestation activities by farmers (sic!).)

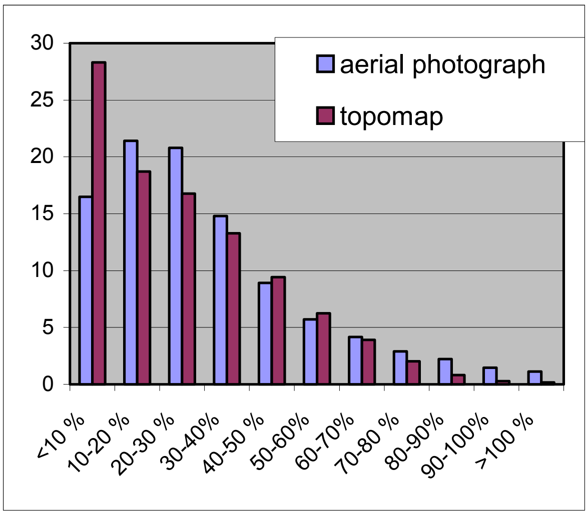

Figure 3. Comparison of slopes derived from the topographic map and the aerial photographs

The Sumberjaya watershed area is characterised by rivers, which are often cut into the landscape. The coarse scale of the topo map smoothens the slope map, especially close to the rivers as is illustrated in Figure 4, where one finds relatively short but steep slopes. The river shown in Figure 4 was in both cases derived from the topographic map.

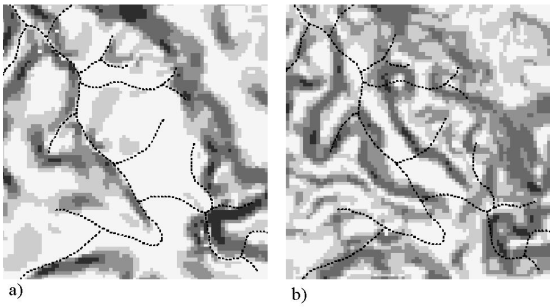

Figure 4. Comparison of slope map derived from the topographic map (a) and from the aerial photograph (b).

4. SEDIMENT TRANSPORT

4.1 Introduction

Sediment transport is an important process in catchment soil erosion. By far the most important transporting agent in the Sumberjaya watershed is flowing water. Quite some research efforts at plot-level were oriented towards a characterisation of erosion processes in various coffee based systems, as the coffee gardens are seen by the Department of Forestry as a major source of erosion. This was confirmed by some plot-level experiments in the neighbouring Bodong subwatershed [Noveras, 2002] and is illustrated in Figure 5.

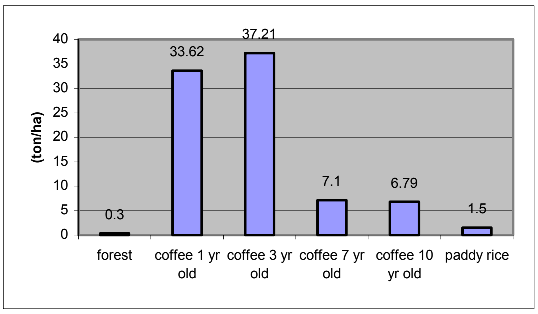

Figure 5. Erosion at plot level in forest and coffee gardens in Bodong subwatershed, Sumberjaya [Noveras, 2002], paddy rice erosion [Agus, 2002].

There is quite some young coffee (less than 3 years) in the Way Petai watershed. From Figure 5 it is clear that especially the first three years coffee gardens are quite prone to erosion. The basis for low soil loss from paddy rice was derived from experiments in other catchments in Indonesia [Agus et al., 2002].

Quantifying erosion and especially the scaling up is tricky. In this exercise erosion transport over the landscape was modelled using the GUEST-equation [Coughlan and Rose, 1997], whereby sediment travels along slopes into so-called 'pit cells' next to the river. At those points the sediment was considered a sediment point source, ready to flow into the river.

4.2 Equations

The GUEST – equation is described in Coughlan and Rose [1997]:

$$C_t = k^{\beta} * Q^{0.4\beta} * Q_t * \exp^{(-Ks*Cs)} \qquad (1)$$

Where C_t is the estimated soil loss, β is the erodibility, Q the total run-off amount per event (m^3), Q_t is the runoff rate per unit area ($m^3\ s^{-1}$), Ks is a non-dimensional crop factor, Cs is the fraction of surface contact cover and where

$$k = \frac{F\sigma S L^{2/5}}{(\sigma/\rho - 1)\varphi} * \left(\frac{\sqrt{S}}{n}\right)^{3/5} \qquad (2)$$

The parameter k depends on the slope S, Manning's roughness coefficient n, slope length L, depositability φ, wet sediment density σ (= 2600 kg m^{-3}), water density ρ (= 1000 kg m^{-3}) and the fraction of the stream power F. As the GUEST-equation gave superior results compared to the USLE in an earlier modelling exercise [Verbist, van Noordwijk et al. 2002] we limit ourselves to the GUEST-equation in the current paper.

4.3 Methodology

The GUEST equation was applied using PC-Raster, a grid based dynamic modelling package, developed at the Faculty of Geographical Sciences, University of Utrecht, the Netherlands (www.pcraster.nl). Grid size was 20 m x 20 m. Most data were derived from field data and if unavailable from literature. For this exploration a rainfall year consisted of 94 big rainfall events, measured in a nearby weather station and each event was then a time step.

For the erosion models *pit cells* were defined as the cells neighbouring the river system. Various runs were done for respective particle diameters (4 μ, 100 μ, 379 μ). Smaller particles have a lower depositability φ (Equation 2). The amount of sediment in the various pit cells did increase for smaller particle sizes, but did not affect the spatial location of so-called sediment delivery hot spots.

4.4 Modelling results

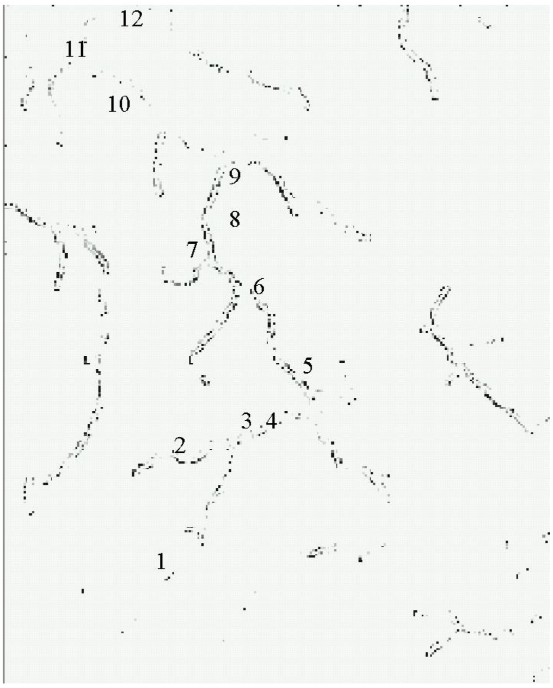

Figure 6. Cumulative sediment yield in *pit* cells around the Way Petai river system.

In Figure 6 the darker an area the more sediment it is predicted to receive. Most sediment is expected to reach the river between point 5 and 9 and around point 2. This spatial pattern is the same for simulations based on the DEM derived from the topographic map as from the aerial photograph.

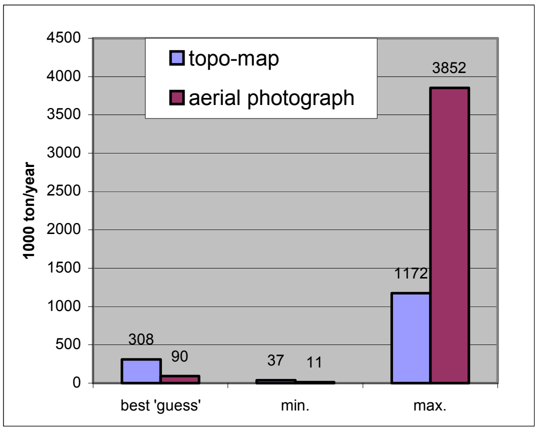

Figure 7. Simulated cumulative sediment yield prediction in ton/year for the Way Petai catchment for a particle size of 379 µ for a DEM derived from the topographic map and the aerial photograph.

The differences in absolute sediment yields seem to work in two directions (Figure 7). In a so-called 'best-guess' scenario, parameters were set at their most frequent value. In the minimum, respective maximum scenario parameters were at their lowest, respective highest value as derived from the experimental plots or literature. It seems that a more accurate assessment of the slopes (using the aerial photograph) would lower the value of the 'best guess' sediment yield predictions. Apparently the 'surface roughness' of the DEM increases, reducing sediment transport over the slopes, as there would be more places where the sediment can settle on its downstream way. This factor would not play so much in the case parameters are set in a way (max.) that sediment can flow 'easily' over the landscape. If we recalculate the 'best guess' results on a hectare basis then sediment yield seems to be on the high side in either case: 194 Gg ha $yr^{-1}$for the DEM derived from the topographic map and 71 Gg ha yr^{-1} in the case of a DEM derived from aerial photographs. Although quite some uncertainty remains on the magnitude of the sediment yield, partly due to the difference in basin size, it is important to note that the spatial pattern of major *pit cells* or sediment point sources did not vary under the different scenarios.

5. TURBIDITY MEASUREMENTS

Turbidity measurements were made at various spots between source and spring of the 12 km long Way Petai river. Each time it was also recorded what was the directly neighbouring land use on each side of the river.

Between August and November 2002 the measurements were carried out on a weekly basis or when there was a storm event. If we discard the peak values there is an (expected) trend of increasing turbidity from source (1–5 NTU) to mouth (13-26 NTU) [Arweström, pers. Comm.]. When we look at the peak values the observations between 11 and 27 September are particularly interesting (Figure 8). The forest delivers always clear water as expected. However tributary 2 also remains relatively clean, whereby the model would predict a high influx of sediment as it is quite a steep area with a lot of coffee gardens. The peaks in turbidity at spot 3 and 4 are just below some rice paddies, which were predicted to give a low sediment yield. However during those particular weeks these fields were being prepared for the upcoming planting season and caused quite high turbidity values. At location 5 with neighbouring rice paddies, which were not being worked, the water got more clear again suggesting that the inflowing sediment upstream was settling in the river bed. It was striking that at a place where a landslide actually reached the river in May 2002 there was no increase in turbidity. Apparently the rains of late May 2002 washed away already the sediment that was readily available. Very high peaks of sediment were recorded at location 10 where a road was constructed 'literally' in the river for the harvest of sand for road construction elsewhere. A cloud of sediment propagated in the river down to locations 11 and 12 during more than two weeks.

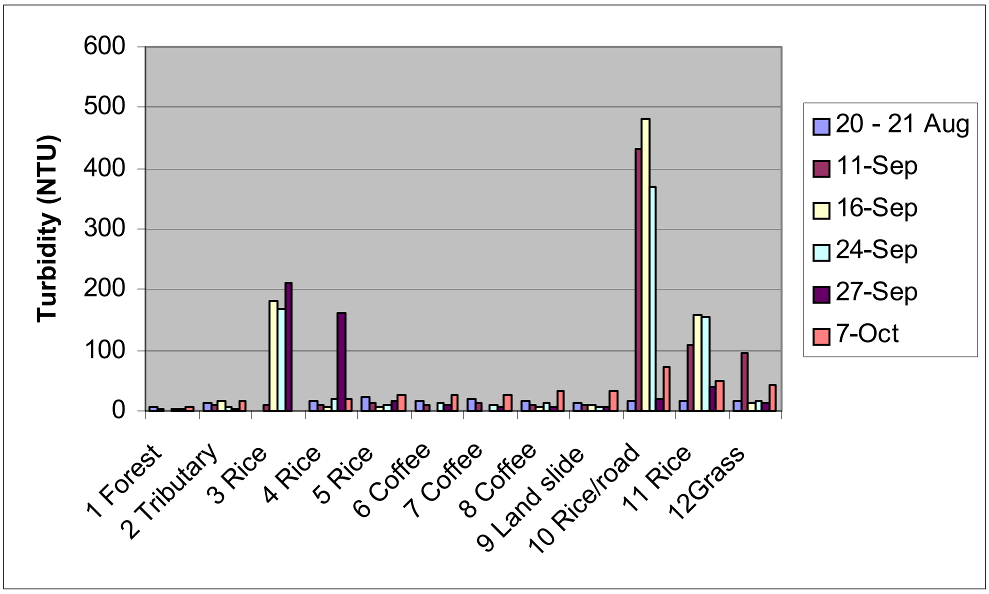

Figure 8. Variation in turbidity from source to mouth along the Way Petai in relation with the neighbouring land use. The numbers used here correspond with the ones put on the map in Figure 6.

6. DISCUSSION

It is clear that the match between predicted sediment point sources and measured turbidity in the river is quite weak. A few reasons could be possible for that:

1. Rice paddies were considered a relatively good buffer against erosion. Their terraces were supposed to reduce flow velocity, allowing sediment to settle [Agus et al., 2002]. This might be true for most of the year, but on the other hand every time the field is being prepared for planting, the soil is worked up and quite some sediment does flow into the river. The end of the dry season (when the turbidity measurements were taken!) seems a critical period. The 'strategic' location of most of the rice paddies next to the river will need more assessments of these paddies in the future. ETM-imagery is too 'coarse' to 'see' most of these narrow rice paddies. The use of high resolution imagery (SPOT5, aerial photographs) should be explored more to characterise the strips around the river system.
2. The soils under coffee gardens are perhaps more 'cohesive' than was fed into the model. Data used were from the neighbouring Bodong subwatershed, which tended to give also at plot level higher erosion than in the Way Petai area. The plot data in the Way Petai area were unavailable at the time of analysis.
3. Other factors (litter layer, macro-pores, ...) were not considered in this exercise, but probably play a major role.

The ultimate 'litmus' test is a continuous monitoring of the sediment content and transport in the river. Current assessments are still preliminary. The months of August until December were relatively dry and there were no measurement of rainfall intensity. It seems that turbidity measurements were taken at a time of the year when paddy rice was giving the highest sediment yields, which was clearly not the case for the coffee gardens. The period of three months of turbidity measurements needs to be expanded to at least a full year to assess effects of various activities over a full cropping season and more importantly under a higher rainfall intensity than was available when the current assessment took place.

7. CONCLUSIONS

The main point of this study is that the predicted absolute sediment yields contain quite some uncertainty, but the model consistently points to the same pit cells as main receiver of sediment transport (over the landscape) and thus main point sources of sediment delivery to the rivers. So at this point in time the results from plot level analysis, the consecutive scaling up to a watershed and the turbidity measurements in the river system do not seem to match very well.

It must be mentioned that measurements took place at a time when rice paddies were more prone to erosion than the coffee gardens, which were expected to give a higher sediment yield. Turbidity measurements need to be covered at least a full year. The temporal variation and cropping calendar seems to have quite a large impact on the erosivity of certain land use systems. Another factor is a more accurate assessment of soil qualities like cohesiveness, …

The effect of the slopes did not have a large effect on the location of those sediment point sources. However it did have a large effect on the absolute values, which had a large band of uncertainty in this exercise.

It is clear that the current criteria used to classify erosion risk areas, and to delineate ‘protection forest’ as mentioned in the introduction are quite crude. There are definitely more factors at play. Some areas probably don’t need to be protected, while on the other hand the current methodology (and legislation) is ‘blind’ for some erosion ‘hot spot’ areas, as was also illustrated in an earlier modelling exercise [Verbist, van Noordwijk et al. 2002].

A participatory water quality-monitoring scheme is now envisaged to cover those ‘blind spots’. Monitoring turbidity only at the outflow point of the Way Petai, would miss the upstream dynamics and variations of sediment yield both in a spatial and temporal domain.

This monitoring scheme could work as an entry towards discussions on how water quality can be improved and to what quality level? Better criteria, directly linked to the envisaged objectives, need to be developed, preferably in discussion with the various stakeholders. Delineation of protection areas can then be revised accordingly. Further iterations in modelling design and field observations help clarify where ‘mental models’ with their underlying hypotheses go wrong (and to what order of magnitude) and what could be possible interventions.

8. ACKNOWLEDGEMENTS

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