Hydrological Consequences Of Converting Forestland To Coffee Plantations And Other Agriculture Crops On Sumber Jaya Watershed, West Lampung, Indonesia

Introduction

Land use changes have been continuous since the beginning of civilization, especially for agricultural activities (e.g., Bellot, *et al*., 2001). Changes in land use and resulting land cover throughout the world have caused important effects on natural resources through deterioration of soil and water quality, loss of biodiversity, and in the long-term, through changes in climate systems. Land-use and land-cover changes also have great socio-economic sustainability of communities. When one type of use replaces another, the effects tend to be superimposed and cumulative. For example, during the process of urbanization, when rural areas are converted to urban land uses, hydrological circle and rates of soil erosion will change accordingly (de Koning *et al*., 1998).

Even though land use change is occurring in many places, the greatest concerns are when it happens in forests because these areas have many important functions. At the local and regional scales, forests are crucial for maintaining the stability of rivers and watersheds. National and regional concerns for forest conversion and reforestation often focus on the loss of the watershed functions of natural forests. The loss of watershed functions can be a combination of on-site concerns such as loss of land productivity because of erosion, off-site concerns related to water quantity (annual water yield, peak/storm flow, dry season base flow and ground water discharge) and concern about water quality including siltation of reservoirs (Krairapanod and Atkinson, 1998; Susswein *et al*., 2000).

Sumber Jaya is a district in West Lampung, Sumatra. Sumber Jaya (54,194 hectares) is located at the upper part of Tulang Bawang watershed, known as Way Besai watershed. Tulang Bawang River drains an area of 998,300 ha which consists of four districts (Pasya *et al*, 2004). Therefore, the local government considers Sumber Jaya a major water resource for Lampung Province and an electric power generation plant was built in this area. Sumber Jaya has become a focal point of discussion in local and national governments; these discussions center on the widespread conversion of forestland to coffee plantations and human settlements and the associated environmental and hydrological problems.

Coffee plantations continue to support local economies with short-term economic returns even in the current monetary crisis; in fact, the profitability of coffee plantations brought many people to Sumber Jaya (Budidarsono *et al*, 2000). Coffee is also one of the main products of Lampung Province; 15% of Indonesian coffee production in 2001 came from Lampung (Verbist *et al*, 2002). However, the long-term sustainability of such forest conversion practices is indeed questionable. Even though forests are important for many reasons, preventing the people from securing a livelihood from forests in this region will not solve the problems; it even will complicate the social problems. Therefore, a compromise needs to be reached based on intensive research and observations in areas that have actually undergone such widespread land use changes.

Since the research projects in Sumber Jaya are mainly aimed at better management of the rapidly changing land cover within the watershed, determining the method to predict runoff from rainfall inputs at larger scales than erosion plot is the main method in this research. Calculating runoff from rainfall has been the subject of many studies in various places using different methods or models (Corradini and Singh, 1985; Wang and Chen, 1996;Yu *et al.*, 2001; Schumann *et al.*, 2000; Dye and Croke, 2003; Janicek, 2007).

Hydrograph analysis will be used in this research to assess catchment characteristics, especially related to different land covers. Hydrograph analysis can be used in the assessment of land cover together with physical conditions in the catchments because the shape of the hydrograph reflects the way that a catchment transforms precipitation into runoff and embodies the integrated influence of the catchment characteristics, including vegetation (McNamara *et al.*, 1998). Unit hydrograph will be investigated with IHACRES (Identification of unit Hydrographs and Components from Rainfall, Evaporation and Streamflow data" (Jakeman *et al*., 1990). The IHACRES model is able to calculate time lags between rainfall and runoff time series as well as the relative portion of the quick flow and slow flow in the total water discharge. Comparison of quick flow and slow flow from different catchments could be used as a means to evaluate the land cover condition in respective catchments. This research aims to evaluate the Sumber Jaya watershed condition that is affected by rapidly changing land cover using hydrological methods.

Materials And Methods

Research Site

This research was conducted in Sumber Jaya (4º55' - 5º10' S and 104º19' - 104º34' E , 54,200 ha, 700 to 1878 m asl). Sumber Jaya is a district in West Lampung, Sumatra, located at the end of the long mountain range in Sumatra, Bukit Barisan. Sumber Jaya is located at the upper part of Tulang Bawang watershed, known as Way Besai Watershed. Tulang Bawang River drains an area of 998,300 ha.

A nested catchment structure was employed in this study to assess scaling issues related to rainfall-runoff as well as land use in the area. Eight sub-catchments were included ranging in area from 2.82 ha to 67.7 ha. The elevation of these catchments ranges from 120 m to 600 m. Catchments 1 to 5 and WB reflected the current Sumber Jaya land cover;

catchment FR reflected the remain nature forest in Sumber Jaya and catchment AF reflected agro-forest area which proposed as alternative land use for protecting the watershed while maintaining local people live (Table 1).

Rainfall and Runoff Monitoring

Six tipping bucket rain gages were installed atop 1.2 m poles on the hillslopes of each sub-catchment. Parshall flumes of standard dimensions were installed at the outlets of each sub -catchment to monitor stream flow. The size of the flumes was determined based on catchments area, the size of the stream, and the likely height of the water during major storm events. Water level loggers were installed on each flume to continuously record stage. Stage readings were then converted to discharge using standard flume equations.

Data Analysis

Unit Hydrograph analysis

A. IHACRES Model

Data from water level instruments (daily rainfall, streamflow and temperature) were transferred into an Excel spreadsheet and then inserted to the IHACRES software. The observed and the predicted discharge series were plot together in series as stated previously. Two series that had consistent high correlation coefficients for all catchments between the observed and predicted series were chosen for further event analysis.

B. Determination from observations

The unit hydrograph for a catchment can also be constructed from observations of inputs and response for several significant storms of approximately equal duration.

Results And Discussion

Hydrograph Analysis

There were seven rain events that yielded significant storm runoff; 2 August, 25 September, 23 October, 25 October, 26 October, 2 November, 19 November, and 7 December 2005. Combined with the rain depth analysis, the hydrographs show that runoff only occurred if rainfall reached a minimum intensity of 20 mm/day.

The first rain event actually occurred on 11 July followed by a storm on 19 July; however, these events did not result in significant measurable storm runoff, water discharge mostly came from base flow. The first significant storm runoff was measured on 2 August, even though rain fell at a low intensity (0.076 – 0.27 mm/min). Since rain occured during the dry season (11 July, 19 July and then 2 August), the time needed for rainfall to produce the initial discharge response in all catchments including the agroforestry and forest area was long (> 1 h). The storm hydrograph of 2 August indicated that duration of the direct runoff (1 hr, 30 min) was shorter compared to the duration of rain (2 hr, 30 min) because water might infiltrate into the soil and evaporation was high on this dry day. Storm runoff peaks appeared quickly (40 to 50 min and even as short as 15 min in larger catchments 4,5 and forest catchments), indicating that runoff occurred as saturated overland flow from nearby riparian areas. See Table 2 and Figure 1.

Response factors or runoff coefficients, calculated as direct runoff divided by total rainfall, indirectly indicate how catchments respond to the water inputs (McNamara *et. al.*, 1988). The response factors for this dry season in catchments 1 and 2 were quite high (0.74 and 0.58) compared to other catchments (0.3), indicating that more water was rapidly routed as runoff in these smaller catchments compared to larger catchments where more water could be stored. Catchment 4 had the lowest response factor (0.32), indicating that most water was retained on the catchment surface, possibly due to the more dense vegetation cover in this catchment compared to other catchments. The effect of land cover was obvious from response factors from agroforestry and forest catchments that were much lower from other catchments (0.07 and 0.09). At the peak, agroforest and forest catchments also discharged water lower compared to other catchments (0.16 and 0.14 m3/s compared to 0.21-0.57 m3/s).

The next rain event (25 September) occurred with moderate intensity (0.167 – 0.610 mm/min), Five low intensity events (0.03 – 0.8 mm/min) preceded the 25 September storm (21 and 22 August, 11, 16 and 19 September); however, those events did not generate significant storm runoff. After a period of no rain, all catchments needed more than 1 hour (70 – 122 min) before discharge the water. Lag time between rain peak and discharge peak and response factors were also similar between other catchments and agroforest – forest catchments (62 – 88 min and 0.01 – 0.05 respectively). Difference was only occurred on WB catchments (214 min and 1.24) due to larger area of the catchment.

During the next two storms (18 and 22 October; 0.12 – 1.14 mm/min), no significant storm flow was recorded; however, storm flow occurred during the 23 October event. The intensity of the 23 October event was quite high (0.6 to 0.9 mm/min) and had two peaks except over catchment 5 (0.3 mm/min) and WB catchment (0.123 mm/min). This situation explains why the time lags from the onset of rainfall to initial storm discharge in this 23 October event was shorter for the first peak (20 – 30 min); much shorter for catchment 1 (2 min). Catchments were moist from the previous rain and only needed a small amount of additional moisture (2 – 13 mm) prior to the initial hydrograph response compared to the 2 August event. Catchment response was similar to the previous event (2 August); high response factors occurred in catchments 1 and 2 (0.25 and 0.69) and a low response factor (0.17) was measured in catchment 4. In catchment 3, which usually had a low response factor (but higher than catchment 4), the response factor was quite high (0.47) during the 23 October event. Catchment 1 might be nearly saturated at this time with most of the runoff produced as saturated overland flow. Based on field surveys, catchment 3 was well covered with thick brush, monoculture coffee and mixed coffee plantations, but the slopes were relatively steep (33%). Probably with high rainfall and the wet antecedent moisture conditions, the steep slopes promoted rapid flow to streams via overland flow. Interesting to observe that at this rain event no significant water discharge occurred from agroforest and forest catchments; this happen due to lower rain intensity over the agroforest catchment (0.153 mm/min) and no rain over the forest catchments.

Unit Hydrograph

IHACRES model

To evaluate the catchments condition, which resembles the situation with Sumberjaya watershed, in general, IHACRES model was used to analyze whether water discharge in catchment 1-5 mostly came from quick flow or slow flow.

Comparisons of observed stream discharge with simulated discharge for runoff data in the dry season (July – August) and in the beginning of rainy season (November – December) are presented in Table 3. The IHACRES model predicted discharge quite well for the dry season (July - August 2005) with correlation coefficients > 0.9 for catchments 1 to 3 and r >0.7 for catchments 4 and 5; only catchment WB had a low correlation for this period (r = 0.4). During the early part of the rainy season (November - December 2005) correlation coefficients for IHACRES simulations during the seven storms were ~ 0.7 for all catchments except catchments 1 and 3 (Table 3).

From the stream flow data series for the dry season and the beginning of rainy season, two storm events were chosen to evaluate hydrograph parameters: the storm on 2 August and the storm on 7 December. The hydrograph parameters derived from the IHACRES model are presented in Table 4 and Figure 2 for the 2 August event.

Lag times between rainfall and runoff predicted by the IHACRES model typically ranged between 4 to 20 min in catchments 1 through 5 and were about 1 h for WB. In smaller catchments, time lags were not related to catchment area. Water discharge from nearby riparian areas in small catchments reached the stream channel more quickly than water routed from the upper catchment, while in larger catchments water discharge was significant only when water routed from upper catchments reached the main stream. Peak responses (βs and βq) are coefficients of effective rainfall (Table 4), the relative volume of effective rainfall that contributes to hydrograph peaks for slow (s) and quick (q) flow, respectively. The recession rate (αs) is a storage constant.

The results of the IHACRES analysis for the case of a single storage system (Table 4 A and B) show that when slow flow was the only discharge component (volume proportion for slow flow = 1) then > 80% of the slow flow was stored in all catchments, and only a small amount (< 1 %) contributed to the peak of the hydrograph (β).

Analyzing the catchments based on two storage components (quick and slow flow; Table 4C and D) indicate that storm discharge also contained quick flow. Relative portions of the discharge volume that occurred as quick flow were 0.2 – 0.4 for catchments 1 through 4, but this proportion was almost negligible for catchments 5 and WB (0.02 to 0.07) (see the volume proportion v^q in Table 4 C and D). Despite the domination of slow flow in storm runoff, only small amounts of slow flow contributed to the hydrograph peak; most of this slow flow was stored in the catchments or discharged as base flow. Slow flow contributed only 2-6% to the hydrograph peaks in catchments 1 through 5 and only 0.3% in WB (see the value of peak response of slow flow β^s); > 90% of the water discharge simulated during these storms was stored in the catchments (see the value of recession rate αs). In contrast, all of the quick flow contributed to the hydrograph peaks (βq and νq have the same value in Table 4. C-

D).

When rain is the only source of water input, using one storage component will result in all runoff occurring as slow flow and most of the slow flow will be stored. When storm discharge is dominated by slow flow, this implies that the catchments are dry and the majority of flow is derived from water that has percolated through the soil subsurface (Post, 1999). Stored water may indicate that the land surface is well covered by vegetation and water is actively transpired by vegetation roots. However, some quick flow was simulated in the dual storage analysis. Quick flow likely originates from overland flow on bare surfaces and steep slopes or from saturated land flow (e.g., riparian areas). In catchments 1 through 4, quick flow comprised 20-40% of the water discharge. Catchments 1 to 4 were covered by monoculture coffee plantations and shaded coffee with rather open soil surfaces and steep slopes (29-46%). While quick flow was almost negligible for catchments 5 and WB (2 to 7%) because catchment 5 was moderately steep (20%) with multistrata coffee and monoculture coffee and catchment WB was relatively flat with monoculture coffee, multistrata coffee, and paddy fields. The fact that slow flow was the dominant component in Sumber Jaya catchment indicating that Sumber Jaya catchment responds slowly to rainfall.

The time constant calculated in the IHACRES hydrograph analysis is the time for water discharge to decay to exp (-1) or about 37% of its peak value. These values were relatively short for all catchments except WB (Table 4 ABCD). Because slow flow dominated water discharge in these catchments, only the time constant for slow flow is presented in the IHACRES model. The longest decay time calculated for catchments 1 to 5 was 29.6 time steps (since 2 min steps were used in this analysis, this is about 1 h). Exceptions were the WB catchment for all events and all catchments during the 7 December event that had a time constant of > 100 time steps (> 200 minutes). In smaller catchments (up to catchment 5, 27.2 ha), all slow flow stopped discharged to the stream in about 1 h. For catchment WB (70 ha), slow flow persisted longer because of the large catchment area, indicating that storm water routing from the upper catchments continued to discharge to the stream.

In general, it can be concluded that most of the storm discharge from these catchments was slow flow. From the value of βq in Table 4, the maximum effective rainfall that was translated into quick flow in the smaller catchments was only 50%; in the large, relatively flat catchment, WB this value was only 2%. Of the remainder of the effective rainfall that discharged as slow flow, only 1 to 10% of this contributed to hydrograph peaks, the rest was stored.

Since slow flow contributes insignificantly to the hydrograph peak, the peak could be estimated merely from quick flow. Considering IHACRES simulations for both events (2 August and 7 December), when water inputs were only from rainfall (Table 4 C and D) the values of βq (the relative volume of effective rainfall that contributes to hydrograph peak for quick flow) were highest in catchment 1 (2.84 ha; 0.443) compared to catchments 2 (8.21 ha; 0.269), 3 (12.39 ha; 0.231), and 4 (20.45 ha; 0.358). These proportions were much smaller in the larger catchments: the peak response (βq) in catchment 5 (27.2 ha) was only 0.074 and in catchment WB (67.7 ha) βq was only 0.003. Both of these larger catchments required more water flow from the upper catchments to increase storm discharge rather than only rainfall. Therefore, better land cover management is needed in the upper catchments to retain water to reduce the amount of quick flow from upper catchments that contributes to discharge at catchment outlet or river.

Unit hydrographs estimated from several observations

The analyses of hydrographs shown in Figure 3 (summarized in Table 5). These hydrographs show the basic hydrograph shape resulting from the average of several hydrographs for individual events. Based on this composite hydrographs the peak responses and recession rates for each catchment are derived.

Results show that most catchments had similar peak discharge rates (between 0.0729 – 0.0837 ln (t)); exceptions were catchments 3 and 5, which had slightly higher rates (0.0939 and 0.1116 ln (t)). Stormflow increased slowly in the study catchments; this response supported the previous unit hydrograph analysis that indicated that most of the water was stored within the catchments rather than directly contributing to storm runoff in streams as quickflow. Peak runoff responses from the agroforestry catchment were similar to those in catchment 1 (0.0729 ln (t) and 0.0739 ln(t) respectively), while peak responses in the forest catchment (FR) were similar to catchment 2 (0.0833 ln(t) and 0.0834 ln(t), respectively); however, these results do not suggest that land cover had no effect on discharge. Discharge rate from the agroforesty catchment was much lower (0.041 m3/s) compared to other catchments (0.1 to 4.3 m^3/s) (Table 5).

Peak discharge rate is determined by the rate and duration of the input and the catchment characteristics. Since the rainfall could be considered heterogeneous and catchment characteristics varied, peak runoff response is not totally reflected by catchment land cover (Dingman, 1993). The same situation is true for the forest catchment. The peak responses of the forest catchment were similar with other catchments and so were the discharge rates (0.114 m3/s). Even though the discharge rate from the forest catchment was similar with catchment 1 (0.129 m3/s), significant stormflow response in the forest stream only occurred during 2 storms compared to 7 events in the other catchments. Thus, for most storms the forest catchment retained much of the water.

Catchment WB had the slowest recession rate (0.0021t), followed by catchments 1, 2, and AF (-0.0054t, -0.0056t and -0.0058t, respectively), with catchments 3, 4, and 5 having the fastest recession rates (-0.0083t, -0.008t and -0.0071t, respectively). Surprisingly, the forest catchment (FR) had the fastest recession rate (- 0.0253t), but this was only documented for two 2 discharge events compared with seven events in the other catchments. The larger size of catchment WB along with the flat outlet area is the reason why the recession limbs of storm hydrographs were slowest in WB. Storm runoff continued to be routed from the upper catchments long after rainfall stopped. Although the similar recession rates in catchments 1, 2 and AF may indicate that storage constants were similar, these do not reflect the same catchment characteristics. Comparing peak responses and recession rates, storm hydrographs generally exhibited slower rising limbs and more rapid falling limbs. This response pattern indicated that soils in the catchments were able to hold and store the water. When the rain started, rainwater initially infiltrated into the soil before flowing to streams; when the rain stopped, the discharge ceased rapidly.

Time constants are a parameter to represent characteristics of catchment response. However, since different ranges in discharge typically follow different decay constants at different times, it is difficult to identify a precise catchment time constant. Time constant, which is equal to the centroid lag of the catchment, is related to the time required for water to travel to the catchment outlet and is influenced by catchment size, soil properties, geology, slope gradient, and land use (Dingman, 1993). Time constants are strongly related to drainage area even though such relationships vary from region to region. In general, the most rapid response occurred in the smallest catchments: 23 min in catchment 1 (2.84 ha) compared to 44 min in catchment 5 (27.22 ha), and 220 min in WB (67.68 ha) (Table 5).

However, the response did not always increase linearly with catchment size. Catchments 2, 3, and 4 had similar response times (34, 37 and 37 min with areas of 8.4,12.4 and 20.5 ha, respectively). Catchments 1, AF (agroforestry) and FR (forest) had similar time constants (23, 29 and 27 min, respectively) which were lower compared to the other catchments (Table 4.17). The most rapid response that was observed in catchment 1 is related to the small catchment size (2.84 ha) and land cover, which was dominated by monoculture coffee plantations. The similar time constants obtained for the agroforestry (4.4 ha) and forest (10.3 ha) catchments do not imply that the better land cover of the forest catchment did not affect the travel time for water to reach the streams. Discharge rate from the agroforesty catchment was much lower (0.041 m3/s) compared to other catchments (0.1 to 4.3 m3/s) (Table 5). Therefore, the rapid discharge from the agroforestry catchment obviously came from saturated overland flow in the riparian area while other water was stored in the catchment. The same situation is true for the forest catchment; even though the time constant for the forest catchment was similar to catchment 1, significant storm flow response in the forest stream only occurred during two storms compared to seven events in the others. Thus, forest catchment retained much of the water.

Conclusions

In general it can be concluded, that besides being affected by rainfall intensity and distribution, hydrograph shape was significantly affected by land surface condition, such as slope and vegetation cover. Most of the stormflow from these catchments consisted of slow flow, meant that most of the water was stored within catchments rather than directly routed to streams during storms. Therefore, land cover of a catchment is important in keeping water from the rain stored inside the catchment rather than flow quickly to the river.

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