Investigation of direct runoff in the intensive farming system of upstream Merawu watershed, Indonesia

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Abstract. Merawu watershed is located at Banjarnegara district and categorized as degraded watershed in the Serayu river basin. Upstream area in the Merawu watershed is a mountainous area of 1,500 m a.s.l., with steep slopes and high rainfall intensity. Upstream Merawu has an important function as recharge area, protect the downstream and water supply for the Merica reservoir. Forest conversion to intensive farming practices have produced large portion of erosion, surface runoff and water pollutant. Understanding the surface runoff changes in the forest conversion to intensive farming practices is important. Investigations of direct runoff in the intensive farming system in upstream area of Merawu watershed were observed using two small catchment experiments. Catchment for intensive farming system was compared to non-disturbed catchment of Pine forest. Surface disturbances associated with soil tillage, fertilization, pesticides and mulching during 2-3 months of planting reduced the soil capacity to control rainfall. During 1-year investigation, total direct runoff (DRO) in intensive farming catchment was 360.05 mm or 34.4% of rainfall or 1.63 times higher than that in the Pine forest catchment. Unit hydrograph analysis found the direct runoff coefficient was 9.4% or 1.7 times higher than that in the Pine forest catchment. This study found the important function of canopy interception, forest floor interception, soil management and infiltration to control the direct runoff in the catchment.

1. Introduction
Forest degradation is a serious environmental, social, and economic problem. Forest degradation involves changes that negatively affect the characteristics of a forest such that the value, function and production of its goods and services decline. Such change is caused by disturbances, which may vary in extent, severity, quality, origin, and frequency. Disturbances may be natural (e.g., that caused by fire, storm, or drought), human-induced (e.g., through harvesting, road construction, shifting cultivation, hunting, or grazing), or a combination of the two.

Many tropical forests around the world are being managed unsustainably, generally because of the intensity of timber harvesting and the lack of adequate techniques to preserve sustainability. One of the common forms of land-use change in humid tropical regions is the clearance of ground vegetation in association with timber harvesting, agricultural cultivation, mining, residential, and recreational development [5,9]. Reductions in vegetation cover from forest generally change the hydrologic response by increasing the average surface runoff volume and sediment yield for a given area of land. Land-surface modification that involves the removal of vegetation cover severely alters near-surface hydrologic processes and accelerates surface runoff and erosion [13], in turn, potentially resulting in a variety of on- and off-site consequences such as reduced site productivity, the degradation of downstream water/habitat quality, and changes in channel morphology [15,7,12].
There is also an increasing recognition that headwater ecosystems are ecologically unique within riverine landscapes and play important roles as sources of water, solutes, organic matter, and sediment, with potentially far-reaching influences on ecosystem processes downstream [10,14]. Thus, appropriate land management practices must be developed to conserve the unique and crucial processes of headwater ecosystems. However, there still exists a large gap in our understanding of which catchment processes maintain ecosystem integrity and are integral for land-use planning in tropical regions [4, 10].

In the high-density population like in the Java island, Indonesia, the threats to forest existence are higher due to the need for land for development and production. Natural forest is remaining in the mountainous areas and production forest is managed by a semi private company. Increasing population has implication for the increasing of agricultural land to fulfill the need of food. These needs have an impact on the conversion of forest to agricultural land. Forest conversion in the mountainous area will decreased the function of upstream area in the watershed. Increasing of open surface will accelerate the surface runoff and soil erosion. It will reduce water quality, pollutes watersheds with nutrients and sediments, and is an indicator and cause of reduced soil fertility (potentially, therefore, reducing forest productivity).

Serayu river basin in Central Java is categorized as a critical river basin. Many land uses are not in accordance with their functions in the river basin. The Merawu watershed is one of the upstream watersheds in the Serayu river basin, and mainly located in Banjarnegara Regency, Central Java Province. This watershed has a dominant function as Serayu’s catchment area. Land use changes in the Merawu’s upstream area for agriculture activities have changed the hydrological process in the watershed and caused several disasters such as massive erosion and landslide. The topographic condition is hilly to mountains areas (65%) and located between 100 to 1500 meters above sea level. This condition resulted Banjarnegara often experiencing landslides. The causes of landslides in Banjarnegara include steep slopes, rock weathering, forest conversion and high intensity rainfall with the highest average rainfall of 3,000 mm/year or 250 mm/month. Upstream area of Merawu watershed dominated with agroforestry and intensive agriculture. People around protected forest area convert the forest to intensive farming for planting the potatoes, cabbage, and carrot. High demand and good price of vegetable become the main reason for some farmers to convert the forest illegally.

Penanggungan village is located in the upstream area of Merawu watershed. Farmers in this area plant the vegetable crops with intensive farming system and intensive soil tillage. It will increase the soil infiltration rate and accelerate the soil water content. In the mountainous area, this condition will increase the vulnerability of mass erosion and landslides. Investigation is needed to clarify the hydrological response of intensive farming system in the upstream area of Merawu watershed.

The aim of this research is to investigate the hydrological changes of direct runoff between forested catchment and intensive-farming catchment in the upstream area of Merawu watershed. This research is important to provide evidences of hydrological changes between different land uses.

2. Methodology
2.1 Experiment sites
One of the most common approaches in the study of hydrology and nutrient export, and in evaluating the response of natural systems to various human activities within headwater areas, is catchment outlet monitoring with a paired-catchment design [3,19,20,21,22,23,17,24].

In the study site of upstream area of Merawu watershed, several experimental sites were established to study the hydrologic responses to land use type. Two paired catchments experiments were conducted for long-term monitoring of catchment hydrology based on outlet measurements to evaluate catchment hydrological responses in different land use types. The field catchment experiment was conducted in an undisturbed Pine forest as a control catchment and intensive farming catchment as disturbed catchment. Hereafter, these catchments are referred to as the “PF” and the “IF”, respectively (see figure 1 and table 1).
Figure 1. Two catchment experiments (red line borders) of catchment Pine Forest and catchment Intensive Farming in the upstream Merawu Watershed.

Table 1. Physical catchment characteristics of the two paired catchments.

| Physical characteristics       | catchment PF | catchment IF |
|-------------------------------|--------------|--------------|
| Drainage area (km$^2$)        | 0.003        | 0.036        |
| Catchment circularity (Rc)    | 0.181        | 0.528        |
| Catchment slope (%)           | 36.148       | 3.488        |
| Drainage density (km/km$^2$)  | 17.490       | 9.052        |
| Main river length (km)        | 0.060        | 0.324        |

Catchment PF had much steeper slope than catchment IF. Catchment IF had much higher level of catchment circularity, meaning that this catchment had the most circular shape. Catchment shape contributes to the rate at which surface runoff reaches the river channel. For instance, a long thin catchment will take longer to drain than a circular catchment. Catchment shape also influences peak flow during storm rainfall. Greater drainage density appears to be associated with more extreme runoff behavior, greater total surface runoff and less ground water storage; whereas the length of the main river appears to affect the lag time and time concentration. The longer the river, the longer the time concentration and the lower the peak flow compared with a shorter main river.

To determine the hydrologic responses of the two catchments, automatic tipping-bucket rain gauge was installed near the two catchments. A 90° V-notch weir and a water-level logger were also installed at each catchment outlet (figure 2).
Precipitation was monitored using an automatic tipping-bucket rain gauge (logging time, 5 min.). The discharge rates were measured using 90° V-notch weirs and water-level loggers (HOBO U-20) with 5 minute time interval at each catchment outlet (figure 2). The observed runoff hydrograph was divided into direct runoff and base flow using a straight-line method [1].

3. Result and Discussion
3.1 Runoff hydrograph
Runoff hydrograph were investigated in the catchments PF and IF during the investigation period in March 2017 – February 2018. A paired of single storm rainfall with single peak rainfall which cause a single runoff hydrograph shape was collected for each catchment. The minimum time interval between storm rainfall events used was 24 hours. During 1-year investigation period, the number of storm events used for paired hydrological analysis in the catchments PF and IF was 77. The hydrograph analysis was undertaken by dividing the runoff into direct runoff and base flow using a straight-line method and then calculating the peak discharge and direct runoff volume for each hydrograph of each catchment. Direct runoff is the sum of surface runoff, subsurface flow, and channel interception. This is the part of the hydrograph of interest when floods and flood-producing characteristics of catchments are analyzed.

Physical catchment parameters such as slope, shape, main-stream slope and drainage density affect stream flow and influence the shape of the hydrograph through catchment storage, runoff speed, infiltration and soil water content. The hydrologic behavior of small catchments tends to be different from that of large catchments. A small catchment is very sensitive to high-intensity rainfall of short duration and to land cover characteristics [8]. The response of the runoff hydrograph to rainfall in the two catchments during a 1-year monitoring period is shown in figure 3.
The runoff hydrograph in the IF produced the largest response to rainfall events. Intensive farming system lead to the formation of no canopy covers. Compared to PF, IF will eliminate the function of interception and transpiration, increasing net rainfall reaching the land surface, directly. Consequently, these conditions creating a quick runoff response that was dominated by surface flow and increased the percentage of rainfall to runoff in the catchment (figure 3).

During a 1-year monitoring, total direct runoff in the PF was 219.84 mm or 21% of rainfall. The function of canopy interception, forest floor interception, and infiltration during rainfall event were effective to control the direct runoff. In the IF, total direct runoff was 360.05 mm or 34.4% of rainfall. The function of forest hydrological system did not work in the IF, so that the total amount of rain water reaches the ground surface was much higher than that in the PF. This will accelerate the emergence of direct runoff in the IF.

**Figure 3.** Relationship between rainfall and the runoff hydrograph. (a) PF, and (b) IF.
3.2. Peak discharge
During a 1-year investigation period, peak storm discharge (Qp) in the small of 30-minute rainfall intensity (<30 mm) of IF tends to be larger than that in the PF. The same trend also found in the large of 30-minutes rainfall intensity (>30 mm) (figure 4).

Short rotation crops in the catchment IF need to intensive treatments such as sprinkling, fertilization, pesticides and soil tillage during 2-3 months of planting. Large open area and high rate of surface disturbance caused Qp response to increase dramatically in the catchment IF, both in small and large rainfall intensities. Steeper topography and shorter main river commonly will produce higher surface runoff and peak discharge. Pine forest in the catchment PF is effective to control the surface runoff and peak discharge from the function of canopy and forest floor interception. That is, forest cover in the catchment PF effectively controlled Qp compared to the intensive farming system in catchment IF.

3.3. Direct runoff
Many factors play an important role in the process of transforming rainfall into runoff, especially the characteristics of rainfall as the input of transformation and characteristics of the watershed as a medium of transformation. The rain factors include the storm movement, the rainfall intensity, rainfall duration and rainfall distribution, while the watershed factors include land cover, stream network characteristics and watershed morphometry, soil characteristics and composition, topography and watershed management by people [11, 16, 18].

Event-based runoff coefficients can provide information on watershed response. They are useful for catchment comparison to understand how different landscapes “filter” rainfall into event-based runoff and to explain the observed differences with catchment characteristics and related runoff mechanisms [2]. Direct runoff is one of the most important hydrological components that affect to the occurrence of flooding in the downstream. Many factors affecting the direct runoff such as rainfall intensity, topography, land cover, soil characteristics and land management. To clarify the direct runoff production between two catchment experiments, comparison of relationship between rainfall and direct runoff is shown in figure 5.
Figure 5. Comparison of direct runoff (DRO) response to rainfall: (a) small rainfall (<30 mm), (b) large rainfall (>30 mm).

Figure 5a shows that, during the small rainfall, DRO in catchment IF was greater than DRO in the catchment PF. In the small rainfall <5 mm, DRO between two catchment shows similar. Rainfall in this stage was captured by the canopy interception in the PF and infiltrated in the IF. While the rainfall was larger than 5 mm, forest floor interception and infiltration process in the catchment PF still continue to captured and trapped rain water, while in the catchment IF, soil moisture content increased rapidly to the maximum value which then produces the surface runoff flows to the river channel. Higher rainfall will produce higher DRO in catchment IF than that in the catchment PF (Figure 5a and b). To clarify the relationship between rainfall and DRO, all investigated data analyzed in figure 6.

Figure 6. Relationship between rainfall and direct runoff (DRO) in the catchment PF and IF

Figure 6 shows that DRO in the catchment IF increased rapidly than that DRO in the catchment PF. Large open area in catchment IF without vegetation cover eliminate the function of canopy interception and evapotranspiration, all rainfall reaching the farming floor and increasing soil moisture rapidly. These conditions created quick runoff responses that were dominated by surface flow, and also increased the ratio of rainfall to runoff in the catchment. Figure 6 shows the relationship equation between rainfall and direct runoff as follow:

\[
\text{Direct runoff in catchment PF (DRO}_{PF} = 0.0032(P)^{1.8091}
\]

\[
\text{Direct runoff in catchment IF (DRO}_{IF} = 0.0048(P)^{1.8498}
\]
Based on figure 6, direct runoff coefficient in the catchment PF was 5.4%, while in the catchment IF was 9.4%. This indicates that the intensive farming system produce higher direct runoff 1.7 times than that in the Pine forest.

4. Conclusion
Investigations of direct runoff in the intensive farming system in upstream area of Merawu watershed were observed using two small catchment experiments. Catchment for intensive farming system was compared to non-disturbed catchment of Pine forest. Surface disturbances associated with soil tillage, fertilization, pesticides and mulching during 2-3 months of planting reduced the soil capacity to control rainfall. During 1-year investigation, total direct runoff (DRO) in catchment IF was 360.05 mm or 34.4% of rainfall or 1.63 times higher than that in the catchment PF. Unit hydrograph analysis found the direct runoff coefficient was 9.4% or 1.7 times higher than that in the catchment PF. This study found the important function of canopy interception, forest floor interception, soil management and infiltration to control the direct runoff in the catchment. Agricultural management practices should consider and attempt to minimize disturbance during each management stage to control direct runoff. Underlying climatic and geographic factors that increase direct runoff risk, even without human intervention, such as steep topography, soil vulnerability, and rainfall characteristics, should also be taken into consideration. Adequate protection of the ground floor with strict control over agricultural activities, combined with soil conservation practice, may also reduce the impacts of intensive farming system on runoff and direct runoff.

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