# The Hydrology of Kaligarang Watershed: Characterization and Modelling

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## INTRODUCTION

Kali Garang Watershed is situated in the province of Central Java. It covers a total area of 195 km² spreading from Mt. Ungaran (2,050 m asl) in the south to the coast of the Java sea. It is composed of three main tributaries, Kali Kreo in the west, Kali Kripik in the centre, and upper Kali Garang in the east (Figure 1). The three merge at the city of Semarang (around 10 km from the outlet).

This provincial capital of about two million people has been subject to catastrophic floods. In the 1990 and 1993 floods, there were 75 casualties and serious damage to infrastructures like roads, buildings, and other facilities.

The high population density of about 795 people km⁻² and rapid industrialization result in changing land use in the watershed. Human settlement and industries have increased and impervious areas have also expanded. Heavy rains induced by La Niña have resulted in catastrophic floods. The situation is similar in other peri-urban areas in Indonesia.

Research conducted by the Kali Garang Project from 1996 to 1998 developed and evaluated hydrological and hydraulic approaches and models to better understand the behaviour of the catchment and make recommendations for land use policy formulation and flood risk forecasting. These models and approaches could now be adopted at other Indonesian sites. This paper presents an analysis of the hydrological characteristics of Kali Garang Watershed and the evaluation of a model to understand its hydrological behaviour.

## FEATURES OF KALI GARANG WATERSHED

### Geomorphology

Kali Garang Watershed is normally divided into three distinct geomorphological areas (Perez *et al.*, 1997): (i) highland (400–2,050m), which covers around 50% of the total watershed area. It includes the steep slopes (15 to more than 40%) of Mt. Ungaran, a volcano; (ii) the transition area (intermediate plateau) which covers about 42% of the total watershed area and is situated at 50 to 400 m asl. Its volcanic geological substratum is produced from tuff ash, sandstone, and other volcanic rock (breccia) (Damar and Kalibiuk formation). Soils are mostly Latosols and often deeper than 2 m; and (iii) the coastal area at less than 50 m asl covers about 8% of the total watershed area. It is made up of sedimentary alluvial plain, which is subject to subsidence. Swamps and lagoons cover 30% of the area.

### Drainage pattern

Kali Garang Watershed includes three main subwatersheds, Upper Kali Garang (82.86 km²), Kali Kripik (16.59 km²), and Kali Kreo (75.7 km²) (Perez *et al.*, 1999). On the highland area, the hydrological network is composed of numerous narrow concentric valleys that become fast-flowing rivers after

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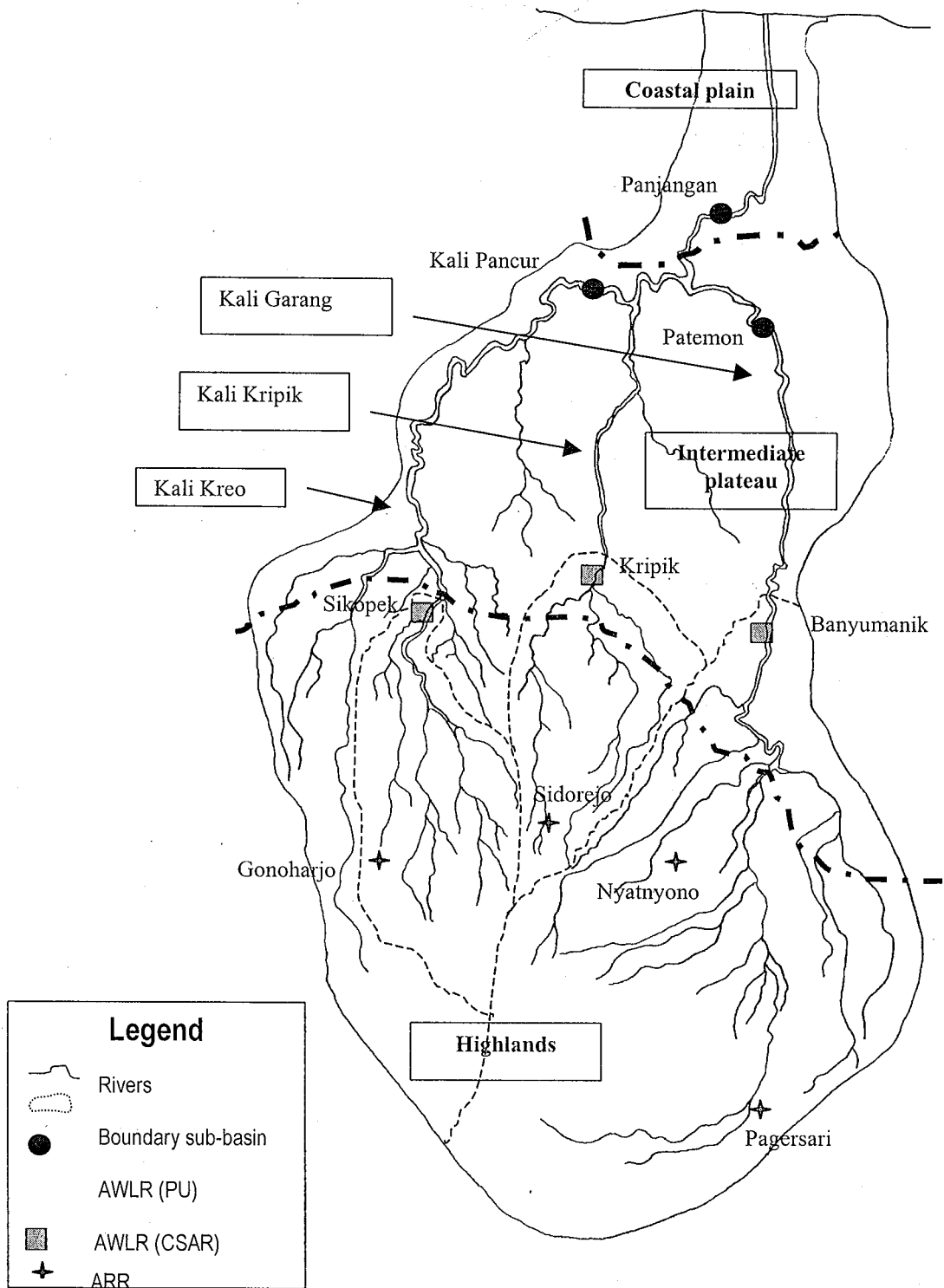
**Figure 1** River network, meteorological and hydrological station for Kali Garang Watershed.

rainfall, carrying much rock material. Downstream, through the transition area, the three rivers flow through narrow and winding valleys.

The geometric and morphometric characteristics of Kali Garang Watershed are shown in Table 1. They give prominence to the features of steep slopes and high drainage network density as shown by the value of the fractal dimension. These characteristics are also supported by the data for the upstream areas of the three sub-watersheds that are equipped by the Kali Garang Project (Table 2).

Table 1.   Geometric and morphometric characteristics of Kali Garang Watershed.

| Parameters | Value |
|---|---|
| Surface area (km²) | 195.05 |
| Perimeter (km) | 65 |
| Compaction index | 1.24 |
| Length of the equivalent rectangle (km) | 23.4 |
| Slope index (%) | 8.5 |
| Maximum length of the drainage network (km) | 35.49 |
| Average length of the drainage network (km) | 19.22 |
| Confluence ratio | 4.08 |
| Stream length parameter | 2.68 |
| Fractal dimension | 1.43 |
| Strahler's basin order | 7 |

Source: Gatot (1999).

Table 2. Geometric and morphometric characteristics of the upstream areas of the three sub-watersheds.

| Parameters | Sub-basin | | |
|---|---|---|---|
| | Upper Garang | Kali Kali Kripik | Kali Kreo |
| Surface (km²) | 82.86 | 36.49 | 75.7 |
| Upstream surface studied by Kali Garang Project (km²) | 79.4 | 16.59 | 15.36 |
| Location of (automatic water level recorder (AWLR) station | Banyumanik | Gunung Pati | Sikopek |
| Maximum length of the drainage network (km) | 23.10 | 9.58 | 10 |
| Average length of the drainage network (km) | 11.75 | 4.78 | 5.32 |
| Confluence ratio | 4.65 | 4.69 | 3.56 |
| Stream length parameter | 2.51 | 2.52 | 2.18 |
| Fractal dimension | 1.67 | 1.67 | 1.63 |
| Strahler's basin order | 6 | 5 | 5 |

Source: Gatot (1999).

## Land use

There are four major land use types within Kali Garang Watershed, namely, forest, agriculture (rainfed terraces, irrigated terraces, gardening, and agro-forestry), the settlement area, and rangeland. (Perez et al., 1997). About 50% of the downstream area covering the urban district of Semarang is occupied by houses and industries and 20% is used for paddy fields, fish breeding ponds, and swamps.

The three rural districts in the upstream area consist of 40% agricultural land, 30% forest, and 30% settlement zone (Figure 2). The population density in the surrounding villages is about 795 people km$^{-2}$.



Type of Land Use

□ Forest    ▩ Agriculture    □ Settlement    ■ Rangeland
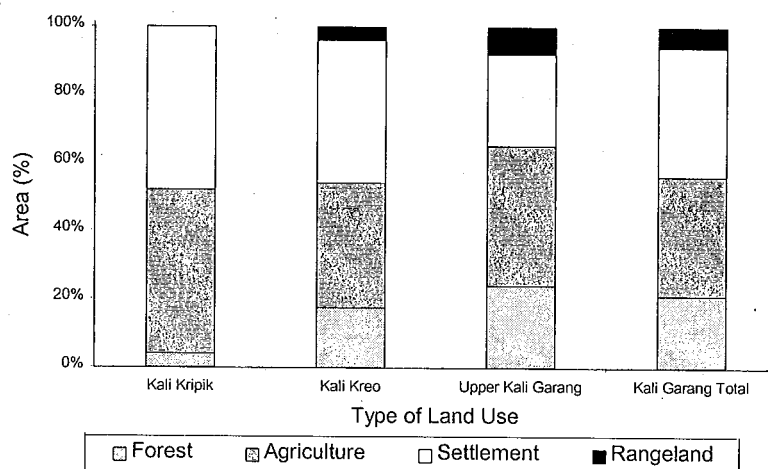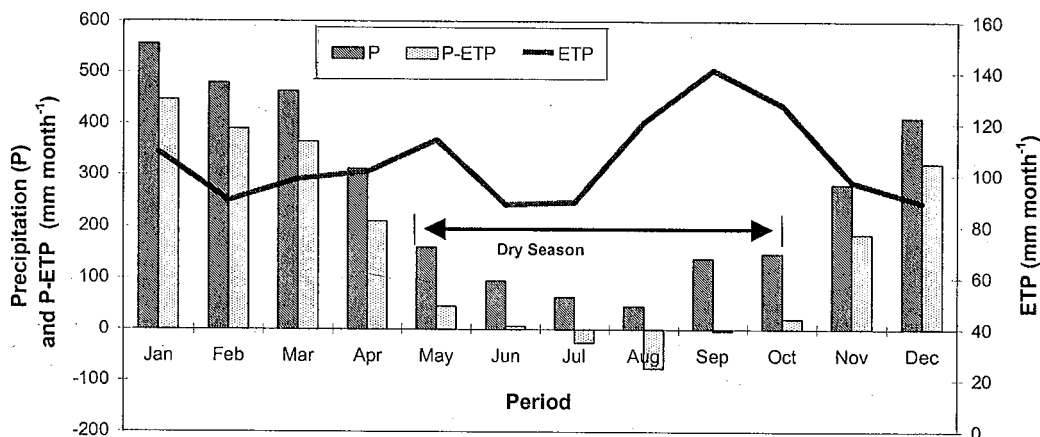
*Source:* Gatot (1999).

**Figure 2.** Different land uses within Kali Garang Watershed and its main sub-watersheds.

The settlement area covers around 38% of the watershed. In the past 20 years, the development of settlement zones has expanded rapidly from the degraded forest and agro-forestry areas. This change occurred quickly and has increased the impervious areas and the average flow velocity within the watershed.

Irrigated terraces cover about 6,000 ha or about 30% of the watershed. These structures affect the hydrology of the watershed as the terraces capture part of the runoff, significantly influencing the rainfall runoff transfer rate and the peak flow. The forest areas on the steep slopes have slightly decreased but rainfed agricultural activities have intensified on plantation zones.

## Climate

The climate in the area is characterized by two seasons, i.e. wet from November to April and dry from May to October (Figure 3). Seasonal change is controlled by the difference in atmospheric pressure between the western and eastern Pacific zones. This process is modified by El Niño, which



*Source:* Gatot (1999).

**Figure 3.** Monthly climatic water balance, Gunung Pati Station.

usually delays the onset of the wet season and disturbs the average rainfall regime (drought during the 1997/1998 period).

## Rainfall characteristics

Analysis of exceedence frequency of annual rainfall (Figure 4) underscores its quasi symmetric distribution. The average value (3,205 mm) is around the fitted median value (3,158 mm), nevertheless the high difference (1,088.9 mm) between rainfall amount relative to exceedence frequencies of 25% and 75% evidences its high inter-annual dispersion, which is certainly due to the combined effects of El Niño and La Niña. The same type of analysis applied to monthly rainfall shows the general asymmetric distribution of monthly rainfall and high dispersion increasing during the dry season (see Table 3).
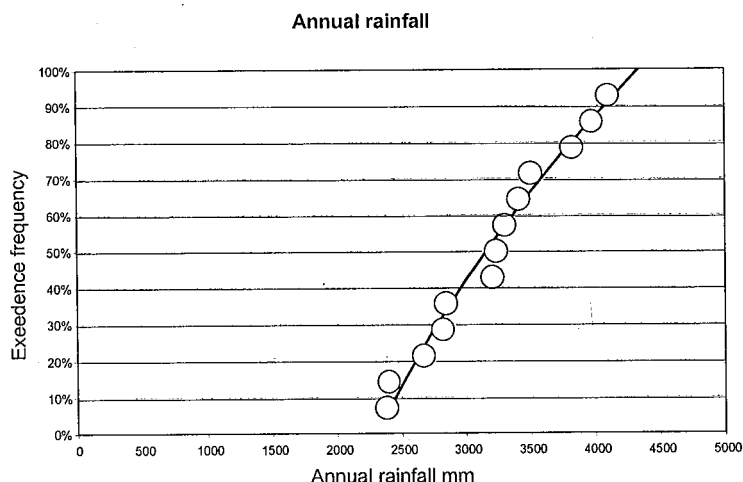
**Annual rainfall**



**Figure 4.** Exceedence frequency of annual rainfall (Gunung Pati Station 1973-1999).

**Table 3.** Value of mean monthly rainfall with fitted median value.

| Month | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average value (A) | 533.0 | 504.5 | 483.0 | 328.9 | 182.0 | 120.1 | 86.9 | 52.3 | 177.6 | 172.6 | 272.2 | 417.3 |
| Fitted median value (M) | 498.7 | 438.3 | 457.1 | 291.4 | 156.8 | 71.5 | 42.4 | 27.7 | 61.7 | 106.8 | 252.5 | 388.6 |
| Ex. Freq 75%–25% | 316.0 | 420.5 | 261.5 | 257.1 | 245.2 | 194.7 | 142.7 | 85.8 | 283.8 | 278.0 | 171.1 | 255.9 |

## Exceedence frequency of daily rainfall

The average number of rainy days varies between 12 and 18 by month during the wet season and decreases to three and eight days by month during the dry season (Figure 5). Figure 6 shows the relationship between rain amount relative to a rainy day and its exceedence frequency. This relationship has been established for Gunung Pati using rainfall data relative to a nonconsecutive period of 14 years. According to the relationship, the 10 years' rainfall is about 97 mm. On account of the duration of the considered period (14 nonconsecutive years), this value has to be regarded as a rough estimation. Nevertheless, it explains the high rate of the 10 years' flood.
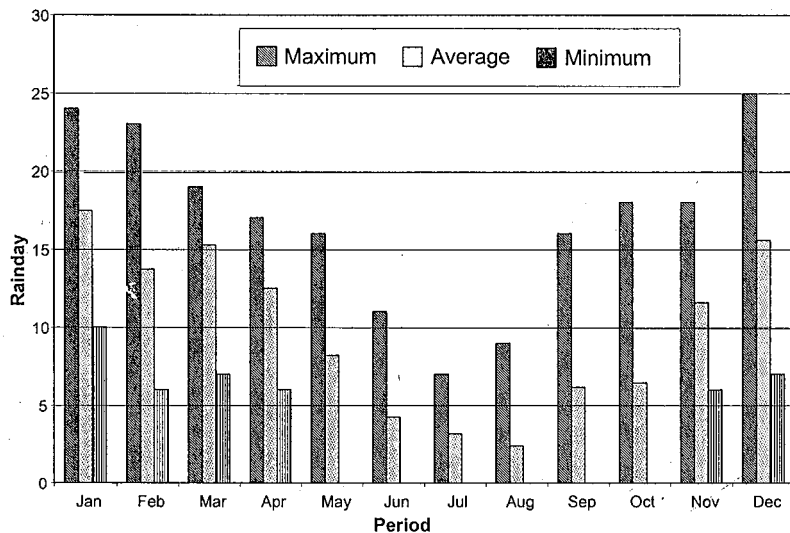
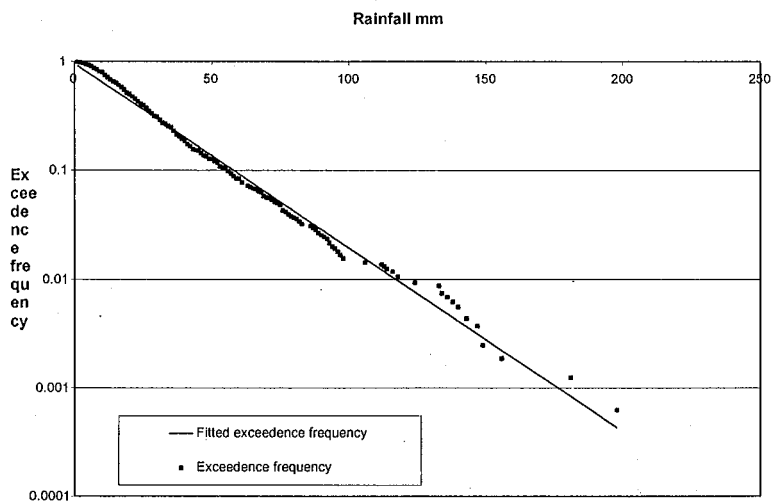**Figure 5.** Number of rainy days by month (Gunung Pati station 1973–1999).



**Figure 6.** Exceedence frequency of daily rainfall (Gunung Pati Station 14 years from 1974).

## Effect of elevation and orientation on rainfall

Analysis of rainfall data relative to the seven automatic rainfall stations settled around Kali Garang Watershed indicates variability in relation to elevation (see Table 4) (Perez *et al.*, 1999). In areas of relatively high elevation (400–800m asl), total rainfall is greater (> 1,500 mm from October to December 1998) compared to areas of relatively low elevation (200–400 m asl, namely around 900–1,300 mm).

**Table 4.** Monthly rainfall data at Kali Garang Watershed (1998) (Perez *et al.*, 1999).

| Station | Garang | Sikopek | Kripik | Nyatnyono | Pagersari | Sidorejo | Gonoharjo |
|---------|--------|---------|--------|-----------|-----------|----------|-----------|
| Altitude (m) | 212 | 310 | 290 | 650 | 560 | 420 | 702 |
| Month  J | 203.8 | 221.0 | 162.2 | 319.4 | 178.4 | 282.6 | 376.2 |
| F | 303.0 | 324.6 | 308.8 | 526.2 | 591.4 | 437.4 | 643.0 |
| M | 412.2 | 537.2 | 411.0 | 415.2 | 373.0 | 447.4 | 582.0 |
| A | 187.2 | 264.6 | 141.4 | 206.6 | 306.8 | 221.0 | 303.6 |
| M | 113.2 | 144.4 | 97.6 | 245.6 | 218.0 | 202.8 | 239.6 |
| J | 293.6 | 342.4 | 171.4 | 271.2 | 237.8 | 250.2 | 416.2 |
| J | 155.0 | 258.2 | 183.8 | 218.2 | 183.0 | 263.8 | 413.2 |
| A | 103.0 | 95.2 | 90.2 | 44.2 | 45.4 | 53.0 | 101.8 |
| S | 42.0 | 183.4 | 181.8 | 163.8 | 189.6 | 198.0 | 279.6 |
| O | 386.0 | 311.6 | 339.0 | 355.6 | 240.0 | 378.8 | 426.6 |
| N | 257.8 | 405.8 | 223.2 | 602.0 | 296.0 | 399.0 | 690.8 |
| D | 445.2 | 571.4 | 434.6 | 958.0 | 359.4 | 745.2 | 761.0 |

Apart from variability due to elevation, the analysis also underscores variability of rainfall in relation to orientation. Areas oriented to the sea (north) such as Gonoharjo, Sidorejo, and Nyatnyono tend to have higher rainfall compared to those areas oriented to the east. The variability results from the fact that in areas of greater elevation (mountains) orographic rain forms more frequently, where masses of warm air from the lowlands or from the sea bringing sufficient vapour meet masses of cold air from the highlands, the warm air mass is lifted upwards forming clouds and if air humidity is high enough the clouds will produce raindrops. The accuracy of the average rainfall over the whole watershed estimated by a classical approach (Thiessen polygon) is therefore restricted as soon as the rainfall spatial variability is high.

## Runoff on Kali Garang Watershed

### *Monthly runoff and monthly percentage runoff*

Table 5 illustrates the mean annual and monthly runoff at Panjangan during 1998 as well as the annual and monthly percentage runoff relative to the total rainfall). Of the total recorded annual rainfall of 3.712 mm; 48% was calculated as runoff. It should be kept in mind that 1998 was a relatively dry period.

**Table 5.** Runoff and percentage runoff downstream of Kali Garang Watershed (1998). Perez *et al.*, (1999).

| Month | J | F | M | A | M | J | J | A | S | O | N | D | Year |
|-------|---|---|---|---|---|---|---|---|---|---|---|---|------|
| Runoff (million m³) | 22.6 | 30.6 | 37.9 | 30.2 | 20.7 | 29.3 | 21.0 | 12.9 | 14.3 | 25.1 | 36.2 | 56.5 | 337.1 |
| Runoff (mm) | 119.0 | 161.0 | 200.0 | 159.0 | 109.0 | 154.0 | 110.0 | 68.0 | 75.0 | 132.0 | 191.0 | 297.0 | 1,774.0 |
| Rainfall (mm) | 249.0 | 446.0 | 454.0 | 233.0 | 180.0 | 283.0 | 239.0 | 76.0 | 177.0 | 348.0 | 411.0 | 615.0 | 3,712.0 |
| Percentage runoff % | 47.8 | 36.1 | 44.0 | 68.1 | 60.4 | 54.4 | 46.1 | 88.9 | 42.5 | 38.0 | 46.4 | 48.3 | 48.0 |
| Period | Wet season | | | | Dry season | | | | | | Wet season | | |

The high value of the percentage runoff during the dry season obviously illustrates a significant contribution of the groundwater runoff to the global surface flow during that period.

Looking at the data for the rainy season, the average percentage runoff was also about 48%, similar to the annual figure. This high value should also be related to the contribution of the groundwater runoff. Assuming a daily evaporation of 4 mm, an estimated 1,460 mm of water is lost through evaporation in 1998. With 1,774 mm of water lost through river flow; only about 478 mm was retained by the watershed.

## *Monthly surface runoff coefficient*

Analysis of hydrograms relative to each runoff event was done during 1998 for the three stations set up by the Kali Garang Project; the surface runoff was separated from the global runoff. Table 6 shows the mean monthly values of the surface runoff coefficient (the amount of surface runoff expressed as a percentage of the total rainfall in the watershed). The range of variation of the surface runoff coefficient was less than 10% during months with low rainfall and around or higher than 20% during high rainfall months. Comparison between percentage runoff values and the surface runoff coefficient confirms the significance of groundwater flow contribution during dry and wet seasons.

**Table 6**. Rainfall and percentage runoff (Ke) and surface runoff coefficient (Kr) (1998).

| Month | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Monthly rainfall (mm)* | | | | | | | | | | | | |
| Banyumanik | | | | | | | | | | | | |
| Station | * | 508.3 | 401 | 236.1 | 215.3 | 263.9 | 196.6 | 64.0 | 152.6 | 322.8 | 447.0 | 680.5 |
| Jedung Station | * | 406.3 | 438.6 | 201.7 | 177.3 | 231.1 | 244.4 | 620.0 | 194.1 | 369.2 | 356.4 | 670.0 |
| Sikopek Station | * | 559.1 | 570.2 | 293.3 | 214.5 | 396.7 | 372.3 | 100.1 | * | * | * | 711.0 |
| *Percentage runoff (%)* | | | | | | | | | | | | |
| Banyumanik | | | | | | | | | | | | |
| Station | * | 31.6 | 57.6 | 62.3 | 74.0 | 64.2 | 72.4 | 101.5 | 56.8 | 48.5 | 47.6 | 43.9 |
| Jedung Station | * | 22.5 | 39.3 | 48.0 | 44.0 | 42.3 | 36.7 | 109.5 | 66.6 | 27.4 | 35.3 | 39.6 |
| Sikopek Station | * | 35.4 | 45.6 | 52.1 | 65.4 | 42.1 | 23.0 | 78.1 | * | * | * | 52.4 |
| *Surface runoff coefficient (%)* | | | | | | | | | | | | |
| Banyumanik | | | | | | | | | | | | |
| Station | * | 12.0 | 24.9 | 12.5 | 19.3 | 19.5 | 13.8 | 0.1 | 15.9 | 12.1 | 22.2 | 25.6 |
| Jedung Station | * | 9.8 | 21.4 | 14.5 | 10.6 | 19.7 | 12.6 | 6.8 | 9.3 | 10.4 | 13.8 | 20.9 |
| Sikopek Station | * | 16.7 | 21.9 | 12.8 | 13.5 | 11.9 | 1.6 | 0.9 | * | * | * | 22.5 |

* Data are missing .

## *Daily runoff downstream of the Kali Garang Watershed (Panjangan Station)*

Figures 7 and 8 illustrate the range of variability of the daily runoff flow registered at Panjangan Station during 1998. Each rainfall event of high intensity increases the runoff flow significantly. Comparing the maximum value registered (133.08 $m^3s^{-1}$) with the daily related one (21.08 $ms^{-1}$) indicates the shortness of the rising period. This assumption is confirmed by time lag durations measured on the three experimental subwatsheds (see Table 7) (1 hour 18 minutes for Upper Kali Garang Watershed, 50 minutes for Kripik, and 49 minutes for Kreo).
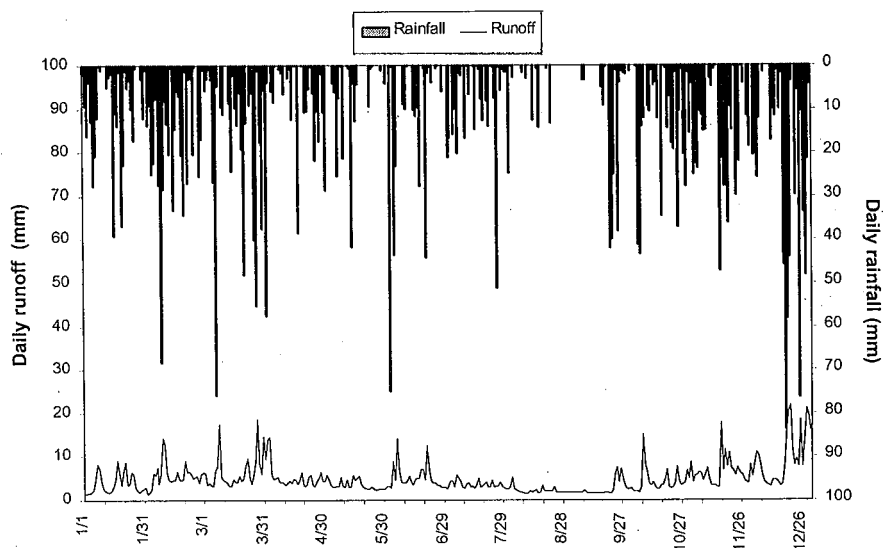
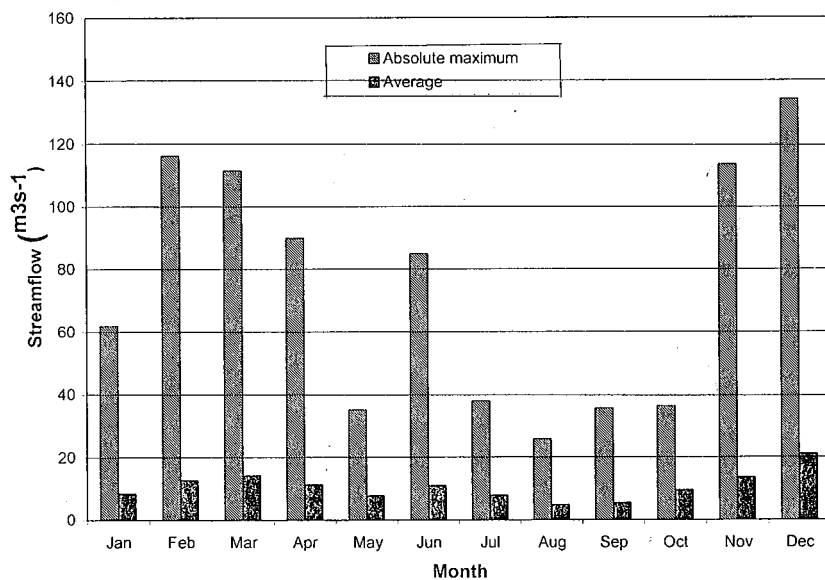**Figure 7.** Variability of the runoff flow downstream of Kali Garang Watershed (Panjangan Station 1998).



**Figure 8.** Maximum daily and mean monthly values of runoff flow relative to a 30 minute time step (Panjangan Station, 1998).

**Table 7.** Time lags registered on the Upper Kali Garang, Kripik and Kreo subwatersheds. (Lechat, 1999).

| Subwatershed | Upper Kali Garang | Kripik | Kreo |
|---|---|---|---|
| Average time lag (minutes) | 88 | 50 | 49 |
| Number of samples | 12 | 13 | 12 |
| Minimum value registered (minutes) | 66 | 36 | 30 |
| Maximum value registered (minutes) | 108 | 84 | 66 |

## DISCUSSION

Geomorphological, drainage pattern, and land use characteristics as well as climatic conditions contribute to explaining the high variability of the runoff and the high occurrence of risky floods:

- Upstream steep slopes and the high density of the drainage network explain the rapid response time of the catchments as illustrated by the time lag values.
- The high percentage of the impervious settlement areas combined with the density and steep slopes of the drainage network as well as the rainfall characteristics (height and intensity) contribute to explaining the high surface runoff coefficient and the size of peak floods.

In such conditions, developing models that describe the relationship between environmental conditions and the hydrological function was essential to help in understanding the overall behaviour of the catchments and in making recommendations to orient the land use policy and forecast flood risk.

In order to develop such recommendations, Kali Garang Project intervened on the two following issues:

- Calibration and validation of a rain surface flow transfer model (H2U deterministic model) as a flood risk early-warning support.
- Evaluation of the land use change on peak debit and response time characteristics.

## MODELLING OF THE HYDROLOGICAL SYSTEM

### The hydrological model (H2U)

#### *Model description. (Gatot et al., 1997)*

The deterministic H2U model has been developed (Duchesne and Cudennec (1998). The H2U model is based on the combination of two parameters: n (Strahler's basin order) and $\overline{L}$ (mean hydraulic length) These parameters are directly extracted from the drainage network representation. The geomorphological response (IUH) links the parameters n, $\overline{L}$ and a so-called gamma function as follows:

$$\rho(L) = \left(\frac{n}{2\overline{L}}\right)^{\frac{n}{2}} \cdot \frac{1}{\Gamma\left(\frac{n}{2}\right)} \cdot L^{\frac{n}{2}-1} \cdot \exp\left(-\frac{nL}{2\overline{L}}\right)$$

with:  
$n$      Strahler's basin order,  
$\overline{L}$      mean hydraulic length  
$\Gamma$      gamma function.

This analytical expression of the nugget of the Instantaneous Unit Hydrograph echoes the statement suggested by Rodriguez-Iturbe *et al.* (1982) that the hydrological response of a basin depends only on some of the gross features, not on the details of the network geometry. The discharge. is then calculated through the following product of convolution, assuming that $\overline{L} = \overline{t.v}$ ($\overline{t}$ :average routing time of the raindrops and n : runoff mean velocity):

$$Q(t) = S \int_0^t \overline{i_{eff}}(\tau).\rho(t - \tau).d\tau$$

with:
- $Q$      Discharge ($m^3s^{-1}$)
- $t$      Time (s)
- $S$      basin area ($m^2$)
- $\overline{i_{eff}}$      Average rainfall intensity ($ms^{-1}$)
- $p$      Probability density function

The transfer function of the hydrological model is based on the previous equation and the parameters used are shown in Tables 1 and 2.

The "production function", transforming rainfall into runoff, was calibrated using runoff and rainfall data registered on the three experimental sub-basins.

## Results

Simulation of the flood registered at Pantangan on 31 January, 1993 is highly illustrative of the simulated hydrograms. Due to a complex rainfall event of 232 mm with an intensity maximum (I 30) of 22.7 mm h$^{-1}$, the total flow registered at Panjangan reached 25,576 m$^3$ with a maximum peak discharge of 695 m$^3$ s$^{-1}$. The model calibration obtained is presented in Figure 9. Its efficiency statistic is 0.58; this low value is partly explained by the groundwater rate arising at the end of the flood (7, 310 m$^3$), which is not taken into account by the model.



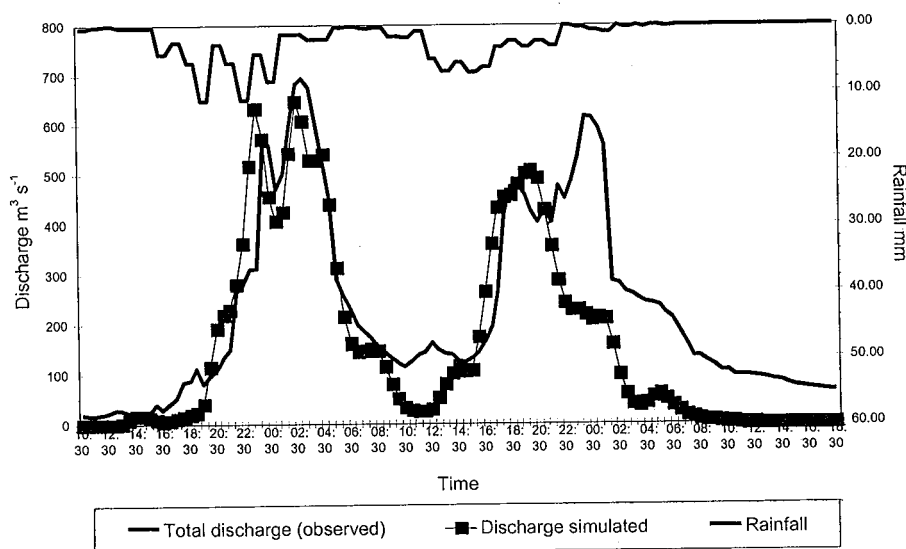**Figure 9.** Observed and simulated hydrograph of the Kali Garang Watershed on 30 January, 1990. kr = 0.410, Vm = 3.55 ms$^{-1}$, step = 30 minutes

Figure 10 shows the comparison of a direct runoff hydrograph with a simulated one. The efficiency statistic of the calibration increases to 72%, which is a reasonable value for such a complex flood event. The efficiency statistic of the calibration is in the same range when the model is applied on a subwatershed with a time step of six minutes.
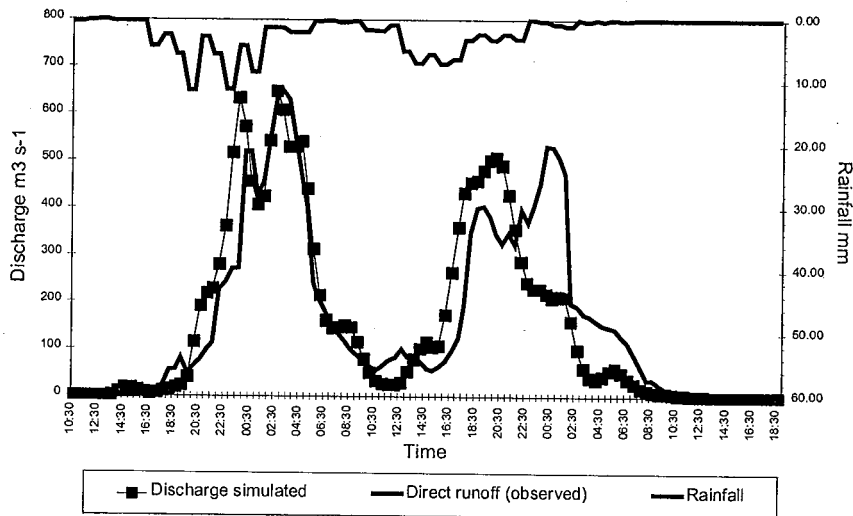


**Figure 10**. Observed and simulated hydrograph of Kali Garang Watershed on 30 January 1990, Comparison between simulated hydrograph and direct runoff. kr = 0.410, Vm = 3.55 ms⁻¹, step = 30 minutes.

## DISCUSSION

The above results assert the capacity of H2U to simulate hydrographs on Kali Garang Watershed for time steps of six and 30 minutes. The peak flood and response time are accurately simulated (statistic efficiency of calibration higher than 0.8). Nevertheless, the quality of the statistic efficiency of the calibration relative to the whole hydrograph seldom exceeds 70%.

Generally, the simulated hydrograph overestimates the runoff rate during the runoff-increasing period and underestimates it during the decreasing period as shown in Figure 11. Such performance has to be attributed to the buffer effect of the irrigated terraced areas.

To improve the quality of the model and adapt it to the local conditions (e.g. buffer effect due to irrigated terraces) a specific model has been developed in order to simulate the hydraulic functioning of terraced areas.

## Hydraulic model simulating the functioning of terraced area

### Model description (Gatot, 1999)

The model developed by Gatot (1999) assumes that a cascade of irrigated terraces is similar to linear reservoirs in series. According to this approach, the output discharge is calculated as a linear function of the water storage in the reservoir (Chow, 1964). Assuming a parallelepiped shape for the reservoir, the equation is:
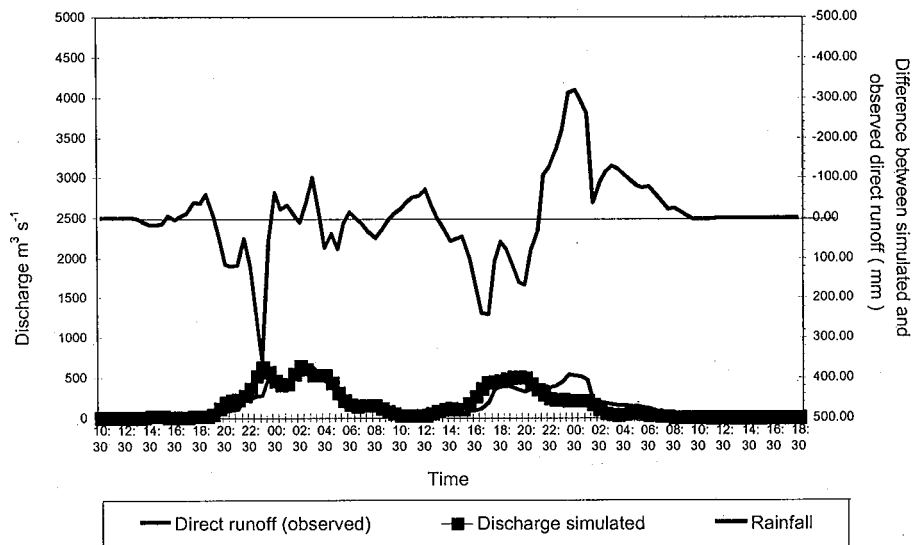
**Figure 11.** Difference between observed and simulated hydrograph of the Kali Garang watershed on 30 January, 1990, kr = 0.410, Vm = 3.55 ms$^{-1}$, step = 30 minutes.

$$Q = k.A.h$$

With :   $k$       reservoir parameter (s$^{-1}$)
         $A$       reservoir area (m$^2$)
         $h$       hydraulic elevation (m)

In order to limit the number of parameters, the system is considered to comprise identical terraces, i.e. the plot area, the outlet section, and the initial water level are the same for each terrace. In this case, it has been demonstrated that:

$$Q_n = Q_0 .e^{-kt}.[1 + k.t/(1!) + k^2.t^2/(2!) +...+ k^{(n-1)}.t^{(n-1)}/(n-1)!]$$

With :   $Q_n$        discharge from the n$^{th}$ terrace (m$^3$ s$^{-1}$)
         $Q_0$        initial discharge from the first terrace (m$^3$ s$^{-1}$)
         $t$          time (s)
         $k$          reservoir parameter (s$^{-1}$)

Nevertheless, the above equation describes the output discharge from a series of terraces continuously supplied with water, as $Q$ tends to be zero when time is infinite. Besides, the proposed expression does not take into account natural factors such as rainfall, evaporation, and infiltration, though they are essential in hydrological processes. Thus, for the first terrace, the global equation of continuity gives:

$$EAdt + IAdt + Qdt = -Adh + iAdt$$

With :   $E$       evaporation from the terrace (m s$^{-1}$)
         $I$   .   infiltration in the soil (m s$^{-1}$)
         $i$       rainfall intensity (m s$^{-1}$)

The model assumes that evaporation, infiltration, and rainfall are constant during the monitoring period, i.e. a single flooding event. In fact, evaporation as well as the infiltration as the discharge from irrigated terraces is simulated during the rainy season. The assumption concerning the rainfall intensity is more questionable, as flooding often occurs after nonuniform precipitations.

According to the equation calculating output discharge as a linear function of the water storage and neglecting evaporation and infiltration, the above equation becomes:

$$dh = -K.(h - i/K).dt$$

In order to take into account the rainfall input, considering the new variable $h' = h - i/K$, Gatot (1999) has demonstrated that the equation estimating discharge becomes:

$$Q_n = Ai + Q_0 e^{-Kt}\left[1\left(1 - \frac{i}{Kh_0}\right) + \frac{Kt}{1!}\left(1 - \frac{i}{Kh_0}\right) + \frac{K^2 t^2}{2!}\left(1 - \frac{i}{Kh_0}\right) + \dots + \frac{K^{(n-1)} t^{(n-1)}}{(n-1)!}\right]$$

## Coupling the two models

Several assumptions were necessary to run the simulations, coupling the two models:

1. The basin is divided into terraced and nonterraced areas.
2. Each terraced area is represented by a set of three identical terraces in cascade, continuously supplied with water. When the water is released it enters the drainage network and the transfer is simulated by the H2U model with $(L)$. The parameters $n_{Ter}$ and $_{Ter}$ are extracted from the digitized map of the terraced area.
3. It is assumed that the observed peak discharge (Qp) is only due to the response of the nonterraced area. Thus, the runoff coefficient (Kr) is optimized, for each flooding event, by comparing the simulated and observed values of Qp.
4. The storage capacity (h0 = 50 mm) is the same for each terrace. The outlets are closed until the observed rainfall intensity falls to 5 mm h$^{-1}$.

Calibration of the H2U model (Figure 12) showed an efficiency statistics of 0.66. This increased to 0.89 when the H2U model was coupled with terrace model (Figure 13). This demonstrates that significant advantage appears to be gained by coupling the two models.

The "buffer" effect of irrigated terraces is taken into account by the hydraulic model while the effects of settlement and other types of land use are integrated by the calculation and calibration of the parameters used by the H2U model. The effect of the settlement area is presented in Figure 14.

The upper Kali Garang subwatershed which is dominated by settlement areas, is characterized by a short response time and by a high peak of discharge due to the high velocity of the surface runoff and the low infiltration rate on such an area. On the other hand, the Kreo subwatershed characterized by agricultural land use had a higher response time and by a smaller peak discharge.

These results are based on specific calibrations of the "production function". A preliminary analysis (Kartiwa, 1999) of the spatial and temporal variability of the "production function" (see Table 8) underscores the complexity of the rainfall-runoff relationship

Finding an approach describing the "production function adapted to Indonesian conditions" remains the key point for a regionalized model. The complexity of the problem favours developing a programmatically-based genetic programming system to discover the rainfall-runoff relationship (Wingham and Crapper, 1998).

Table 8. Statistical relationship to estimatr the daily volume of direct runoff (in mm) (Lr) from the peak daily rainfall (P) and the cumulative rainfall from the beginning of the rainy season (Pc).

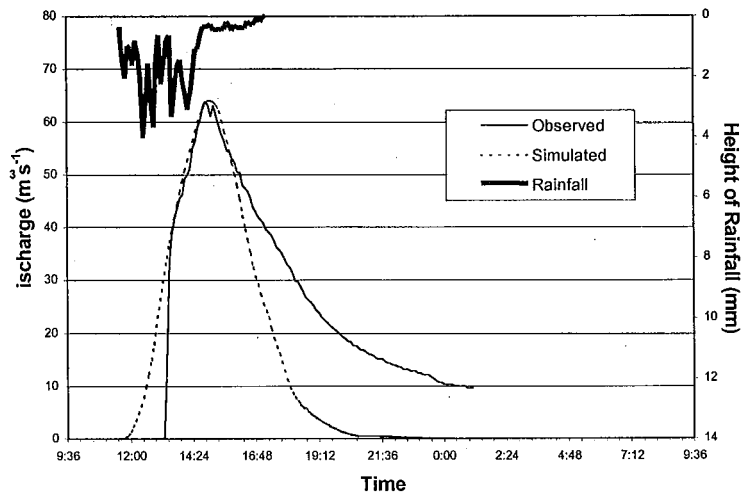| Subwatershed | Equation estimating the daily amount of direct runoff | $r^2$ |
|---|---|---|
| Upper Kali Garang | Lr = 0,07149.P - 0,00049.Pc + 0,00006.P.Pc + 1,83098 | 0.64 |
| Kali Kripik | Lr = -0,07979.P - 0,00197.Pc - 0,00019.P.Pc + 1.51940 | 0.76 |
| Kali Kreo | Lr = 0,11868.P + 0,00092.Pc - 0,00005.P.Pc - 0,83817 | 0.62 |

Figure 12. Observed and simulated hydrograph without coupling H2U and terrace model. At Upper Kali Garang sub-basin, 19 December 1998 (P=65,3 mm; Kr=0.22)
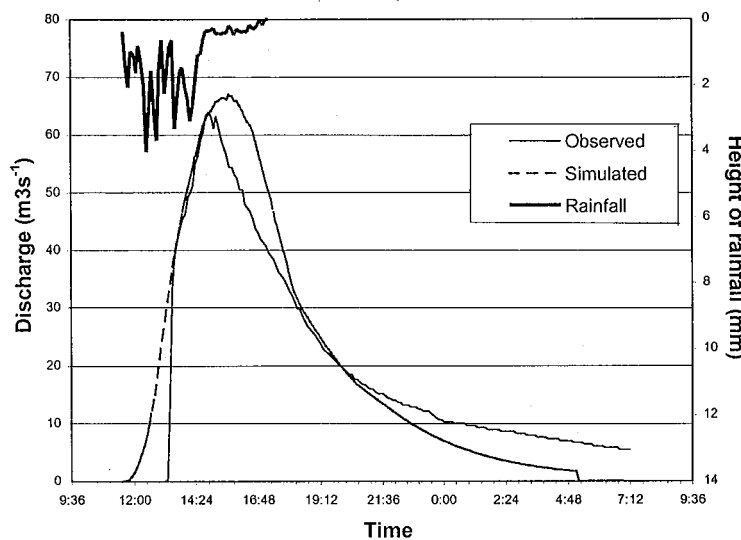


Figure 13. Observed and simulated hydrograph coupling H2U and the terrace model. Upper Kali Garang sub-basin, 19 December 1998 (P=65.3 mm; Kr=0.22).

## SUMMARY AND CONCLUSION

The research conducted in the Kali Garang Watershed from 1996 to 1998 developed and evaluated hydrological and hydraulic approaches and models to better understand the behaviour of the catchments and make recommendations for land use policy and flood risk forecasting. This paper shows that the H2U model can provide a concrete basis for flood forecasting, especially the peak discharge time. It also provides an understanding of the effect of land use on the hydrological behaviour of the drainage basin. When coupled with a hydraulic model describing the functioning of the terraced areas, the runoff flow can be better simulated.
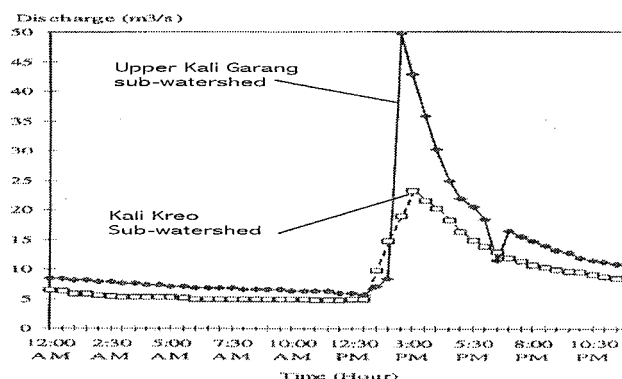
**Figure 14.** Comparison of hydrographs relative to Upper Kali Garang and Kali Kreo
         subwatersheds. Flood events from 7 December 1996. Gatot *et al.,* 1997)

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