Predicting Discharge from Agricultural Catchment to Support Land and Water Management in Singkarak Basin, West Sumatra

Prediksi Debit Aliran dari DAS Pertanian untuk Mendukung Pengelolaan Lahan dan Air di Danau Singkarak, Sumatera Barat

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ABSTRACT

Limited hydrological data in Paninggahan sub catchment in Singkarak basin has resulted in inappropriate land management practices for farming system development. Predicting stream flow using an appropriate hydrological model is critical for a catchment with limited data recording. The present study has been conducted from January 2006 to December 2007. The objective of this study is to characterize hydrological condition of the catchment and to predict river flow for supporting design of land and water management options. To some extend, the study is to provide inputs in negotiation of farmers community with other stakeholders in the Singkarak basin. An automatic water level recorder (AWLR) and an automatic weather station (AWS) have been installed in the catchment to record hydro-meteorological data in order to calibrate hydrological model for predicting river flow. An instantaneous discharge model based on Geomorphological Instantaneous Unit Hydrograph (H2U) and a daily discharge model of GR4J were used to predict the river flow. The instanteneous hydrological data suggested that stream discharge sharply increased during onset rain and implying that the draining water was dominated by rapid flow. After peak storm has been reached, the water was slowly released to the river the one is typical hydrological process for disturbed catchments where rainfall water may no longer be retained in the catchment. Application of both hydrological models in Paninggahan sub catchment during a period of March to April 2006 has given an appropriate result. The GR4J model has been calibrated and has given the value of similarity coefficient of 87.9%, while calibration of H2U model applied for storm event and has given the value of similarity coefficient of 96%. The succeed of predicting discharge using both models is valuable to support planning program in land and water management for farming system development in the Singkarak basin.

Keywords : Predicting discharge, Land and water management, H2U model, GR4J model, Hydrological characteristics, Singkarak basin

ABSTRAK

Keterbatasan data hidrologi di Sub-DAS Paninggahan merupakan salah satu penyebab kurang optimalnya praktek pengelolaan lahan untuk pengembangan sistem usahatani. Prediksi debit aliran sungai menggunakan model hidrologi yang tepat sangat diperlukan. Penelitian ini dilaksanakan pada Januari 2006 hingga Desember 2007 untuk mengkarakterisasi kondisi hidrologi sub DAS tersebut, memprediksi debit aliran sungai untuk mendukung perencanaan pengelolaan lahan dan air, dan memberikan masukan bagi petani dalam negosiasi dengan pemangku kepentingan di wilayah Singkarak. Alat pengukur tinggi muka air otomatis (AWLR) dan stasion iklim otomatis (AWS) dipasang di DAS tersebut untuk memonitor hidro-meteorologi data dan mengkalibrasi model prediksi debit aliran sungai. Model debit aliran sesaat dengan Geomorphological Instantaneous Unit Hydrograph (H2U) dan model debit aliran harian dengan GR4J digunakan untuk prediksi debit aliran sungai. Hasil prediksi debit aliran sesaat menunjukkan bahwa hidrograf aliran sungai meningkat secara cepat pada saat hujan yang menunjukkan bahwa aliran sungai didominasi oleh aliran cepat. Setelah puncak aliran terjadi, aliran air dari daerah tangkapan mengalir secara perlahan ke sungai, proses aliran ini sangat spesifik untuk DAS yang dibuka untuk pertanian intensif dimana hujan tidak dapat ditahan di wilayah DAS. Aplikasi kedua model prediksi hidrologi tersebut di sub DAS paninggahan selama periode Maret sampai dengan April 2006 menunjukkan hasil yang baik. Model GR4J telah dikalibrasi dan menunjukkan nilai koefisien kemiripan sebesar 87.9%, sedangkan hasil kalibrasi model H2U yang diaplikasikan menunjukkan nilai koefisien kemiripan sebesar 96%. Keberhasilan dalam prediksi debit aliran sungai menggunakan kedua model tersebut sangat penting dalam mendukung program perencanaan pengelolaan lahan dan air untuk pengembangan system usahatani di wilayah danau Singkarak.

Kata kunci : Prediksi debit aliran, Pengelolaan lahan dan air, Model H2U, Model GR4J, Karakteristik hidrologi, Danau Singkarak

INTRODUCTION

The Singkarak basin in West Sumatra is an important rice production area, the basis of a large hydro-electric plant (power supply to W. Sumatra and Riau), home to the cultural heritage of the Minang Kabau, the second largest inland lake of Sumatra with endemic fish and an area of landscape beauty and potential ecotourism interest. Given these multiple stakeholders, intensification of agriculture, both in the irrigated rice fields and in the

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uplands for vegetables and agro-forestry (coffee and other tree crops) requires careful management of land and water resources, to avoid negative effects on the quality of the stream that passes these areas on the way to the lake. However, existing data are insufficient to parameterize existing models at the scale of refinement required.

The community of Paninggahan (and neighbouring Nagari's that control streams flowing into lake Singkarak) has expressed a keen interest in obtaining relevant data on hydro-meteorology. The community leaders are convinced of the relevance of data collection, therefore they have direct access in monitoring tools to judge their own impacts on the local hydrology and have a stronger position in negotiations with other stakeholders in Lake Singkarak. The Wali Nagari and key staff are keen to have a measuring point operational within their village and will provide supervision of the facilities. The community leaders are convinced that with direct access in monitoring tools to judge their own impacts on the local hydrology, they will have a stronger position in negotiations with other stakeholders in the Singkarak basin, in order to secure a healthy condition of the lake and to have transparent fund allocation mechanisms.

A lack of continues monitoring on hydro-meteorological data in this basin is also a major problem in designing land and water management options. Most of the river and other large streams are limited with installation of hydrological station which may record flow in a different time and places. Monitoring of gauging river flows, in many cases, is often discontinues due to various technical and budgeting reasons. This results in very limited data for planning and implementing program of land and water management.

Long term data monitoring and predicting river flows are becoming critical in this area for either farmers or water management planners. Farmers have often hard to find an access to hydrological data so that they may not able to guarantee their need to fulfill irrigation for farming. Despite it is not hard for the water management planners to access data, but the data available is often limited. Effort to have a tool to predict river flow is by using a model.

The use of model to predict runoff has been a concern of many researchers (Freeze, 1978; Robson, *et al.*, 1992; Robinson and Sivapalan, 1996; Scanlon *et al.*, 2000) and many were coming up with varies validity levels. This is true, because various models have different criteria and approaches. The high validity of model in many cases is resulted for very specific areas and uses. For normal watershed system, the model may not be valid for that with lake system although in some extend the validity still in reasonable level. Under lake system such as the one in Singkarak Basin, West Sumatra, developing runoff model is critical as far as long term land and water management planning is concerned.

The objective of the study is to predict river flows generation in the main catchment of Singkarak basin that would be significance for designing appropriate land and water management options for farming system development.

MATERIALS AND METHODS

Study site

The study has been conducted in Paninggahan sub-catchment (Figure 1) located in the Singkarak lake basin, West Sumatra from January 2006 to December 2007. The study site lies within the upper reaches of Kuantan/Indragiri river basin. The site has been selected by considering that there was trends of loosing natural forest cover, and associated with land and water management issues in many wet tropical forested river basins. In addition, the community of Paninggahan and neighbouring Nagari's that control streams flowing into lake of Singkarak have expressed a keen interest in obtaining relevant data on hydro-

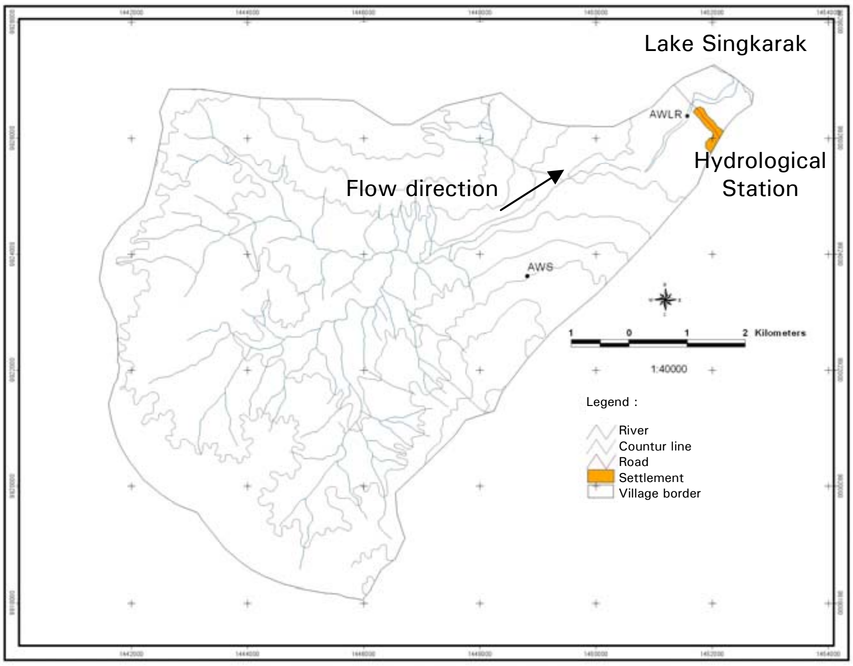

Figure 1. Study site of Paninggahan sub-catchment

Gambar 1. Lokasi penelitian di sub DAS Paninggahan

meteorology. The community leaders are convinced of the relevance of data collection so that they have direct access to monitoring tools to judge their own impacts on the local hydrology and have a stronger position in negotiations with other stakeholders in Lake Singkarak.

Table 1. Physiographical characteristics of Paninggahan sub catchment

Tabel 1. Karakteristik fisiografik sub DAS Paninggahan

Parameter	Unit	Paninggahan sub-catchment
Area (A)	km^2	58.14
Perimeter (P)	km	34.31
Compactness index (K_c)	-	1.27
Equivalent rectangular		
- Length (L)	km	12.70
- Width (l)	km	4.58
Strahler's order maximum (n)	-	5
Drainage density (D_d)	m/ha	15.08

(Subagyono *et al*., 2006)

The upper forested Paninggahan sub-catchment, in particular, contain a 'jungle coffee' enclave of several hundred hectares extent. This site currently in process of being 'opened up' and 'reclaimed' by the local community via the development of an improved motorcycle track. The catchment is representing the currently most hydrologically stable and least degraded catchments within the area of 1,130 km^2 surrounding Singkarak Lake basin and broader Singkarak-Ombilin river basin. Table 1 shows physiographical characteristic of Paninggahan sub-catchment.

METHODS

Instruments set up

The hydro-meteorological condition was monitored within Paninggahan sub-catchment to create minimum data sets for sustainable land and water management. The catchment has been instrumented with set of automatic weather station (AWS) at upstream (Aro AWS Station) and automatic water level recorder (AWLR) at downstream (Sabarang AWLR station) on March 2006.

One automatic rainfall recorder was installed in the upper catchment and one manual recorder was installed in the lower catchment. Daily rainfall data has been collecting from both automatic and manual rainfall recorders and was compared with existing rainfall data from adjacent stations situated within approximately 10 km.

The AWLR of sensor ultrasonic type has been installed in Paninggahan River by considering the result of a further survey by IAHRI staff and leaders of Paninggahan community. The rating curve to derive stream flow from the water level records was developed to standardize the AWLR. Since no weir or flume has been constructed, the wet perimeter of the stream was measured manually at high, medium and low flow rates. A minimum data set was formulated for sustainable land and water management options.

Hydrological data measurement

The AWLR provides water level and rainfall data that are stored in EPROM memory block on a 6-minute period time step. To convert water level data into discharge, rating curve (Figure 2) had been conducted and had given satisfactory result (R^2 = 0.98). The various climate data have been collected from AWS including solar radiation, rainfall, temperature, RH, wind velocity, and wind direction on an hourly period time step. The memory block of AWLR and AWS were released every 30-days period and the data were immediately transferred into a computer file. The ARR provided the data of rainfall on a daily period time step, which can be stored in the memory disk having capacity of three months period data collection before transferring to a computer.

Predicting discharge

Discharge model was generated to identify characteristic of various discharge during a year hydrologic cycle. An instantaneous discharge model based on Geomorphological Instantaneous Unit Hydrograph (H2U) and a daily discharge model (GR4J) were used.

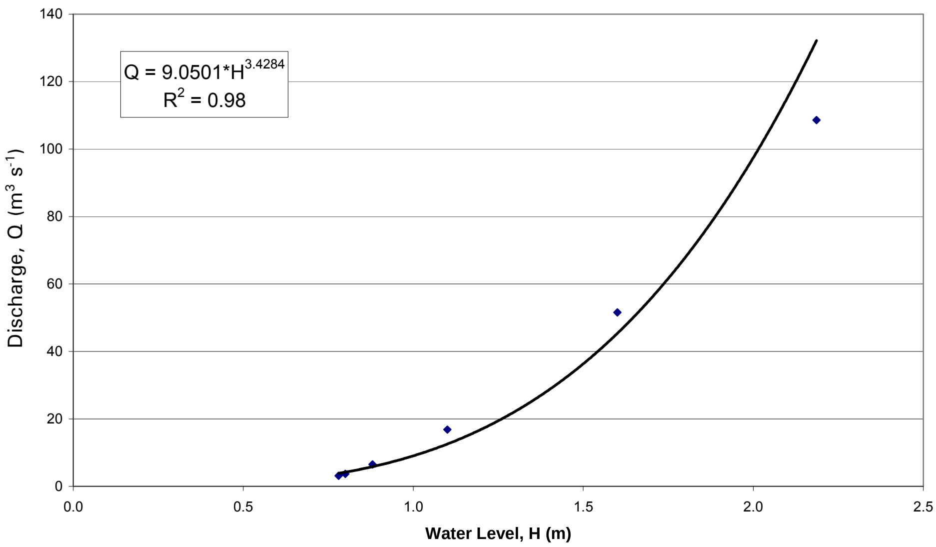

Figure 2. Rating curve of Batang Sabarang River, Paninggahan

Gambar 2. Kurva lengkung debit aliran Sungai Batang Sabarang, Paninggahan

H2U Model

H2U Model (from French *Hydrogramme Unitaire Universel*) has been developed by Professor Jean Duchesne from *Ecole Nationale Supérieure Agronomique* (ENSA) Rennes, France (Duchesne and Cudennec, 1998). This model was developed from geomorphological instantaneous unit hydrograph (GIUH) concepted by Rodriguez-Iturbe and Valdes (1979). H2U model simulates probability density function (PDF) of traveling time of droplet from catchment to the outlet. There are two types of PDF of droplet time travel, namely PDF of drainage network and PDF of hillslope (Kartiwa, 2004):

$$\rho_{RH}(t) = \left(\frac{n.\overline{V_{RH}}}{2.\overline{L}}\right)^{\frac{n}{2}} . \frac{1}{\Gamma\left(\frac{n}{2}\right)} .t^{\frac{n}{2}-1} .e^{-\frac{n.\overline{V_{RH}}.t}{2.\overline{L}}} \quad \text{..................} \quad (1)$$

where:

$\rho_{RH}(t)$: PDF of drainage network

n : maximum catchment order

$\overline{V_{RH}}$: stream velocity in drainage network

$\overline{L}$: mean of hydraulic length of drainage network

Γ : gamma function

t : time interval

$$\rho_v(t) = \frac{\overline{V_v}}{\overline{l_o}} .e^{-\frac{\overline{V_v}.t}{\overline{l_o}}} \quad \text{..} \quad (2)$$

where:

$\rho_v(t)$: PDF of hillslope

$\overline{V_v}$: stream velocity in hillslope

$\overline{l_o}$: mean of hydraulic length of hillslope

t : time interval

PDF of catchment can be calculated by:

$$\rho_{DAS}(t) = \rho_v(t).\rho_{RH}(t) \quad \text{.....................} \quad (3)$$

$\rho_{DAS}(t)$: PDF of cathcment

$\rho_v(t)$: PDF of hillslope

$\rho_{RH}(t)$: PDF of drainage network

The infiltration index (Φ) was applied to determine the excess rainfall as an input model:

$$Ru = \sum_{m=1}^{M} (Pb_m - \Phi\Delta t) \quad \text{...........................} \quad (4)$$

where:

Ru : total observed runoff according to hydrograph separation analysis (mm)

Pb_m : gross rainfall intensity to interval m (mm)

GR4J Model

The GR4J model is a simple, reliable, continuous lumped rainfall-runoff model at daily time step, having just four parameters of maximum capacity of production storage (x1), coefficient of water exchange (x2), maximum capacity of transfer storage (x3), and initial time of unit hydrograph (x4) (Perrin, 2000]. It belongs to the family of soil moisture accounting models. The GR4J model is the last modified version of the GR3J model originally proposed by Edijatno and Michel (1989). Figure 3 shows a diagram of the model.

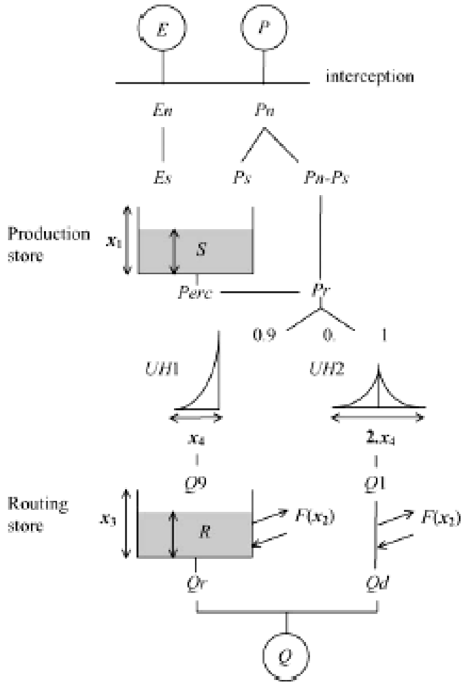

Figure 3. Diagram of the GR4J rainfall-runoff model

Gambar 3. Diagram model hujan-aliran permukaan GR4J

RESULTS AND DISCUSSION

Flow characteristics

Hydrological condition of Paninggahan sub catchment is characterized by discharge, which was recorded at Sabarang River outlet. Figure 4 shows daily discharge variation of Sabarang River during a period of March to May 2006. During this period, maximum discharge was 52.9 m^3s^{-1} on March 23, 2006 with minimum discharge of 3.6 m^3s^{-1} on May 30, 2006 and base flow was about 4-5 m^3s^{-1}.

Maximum discharge was recorded when rainfall amount at upstream (Aro AWS Station) and downstream (Sabarang AWLR station) reaches to 102 mm and 61.8 mm respectively. The antecedent rainfall of a day before was 52.6 mm and 92.6 mm respectively for Aro and Sabarang Station.

Other maximum discharge of 33.9 $m^3s^{-1}$was recorded on March 27, 2006 as a response of rainfall event. Rainfall was recorded as high as 13.2 mm and 20.6 mm respectively at downstream and upstream with 1 day antecedent rainfall of 24 mm at Sabarang and 59 mm at Aro station. Smaller storm event were monitored on April 14-16, April 21-27 and April 27-29.

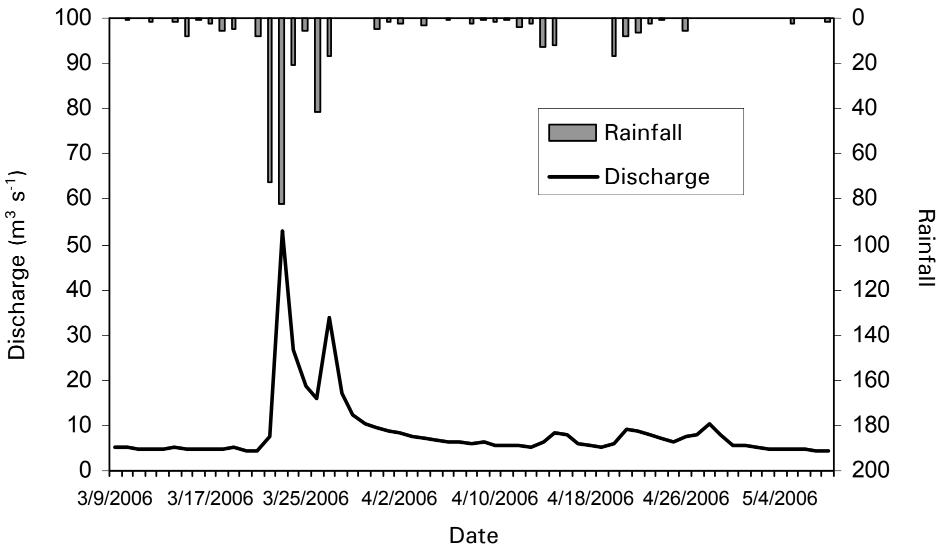

Figure 4. Daily discharge variation of Sabarang River, Paninggahan sub-catchment during a period of March to May 2006

Gambar 4. Variasi debit harian sungai Sabarang, sub DAS Paninggahan selama Maret-Mei 2006

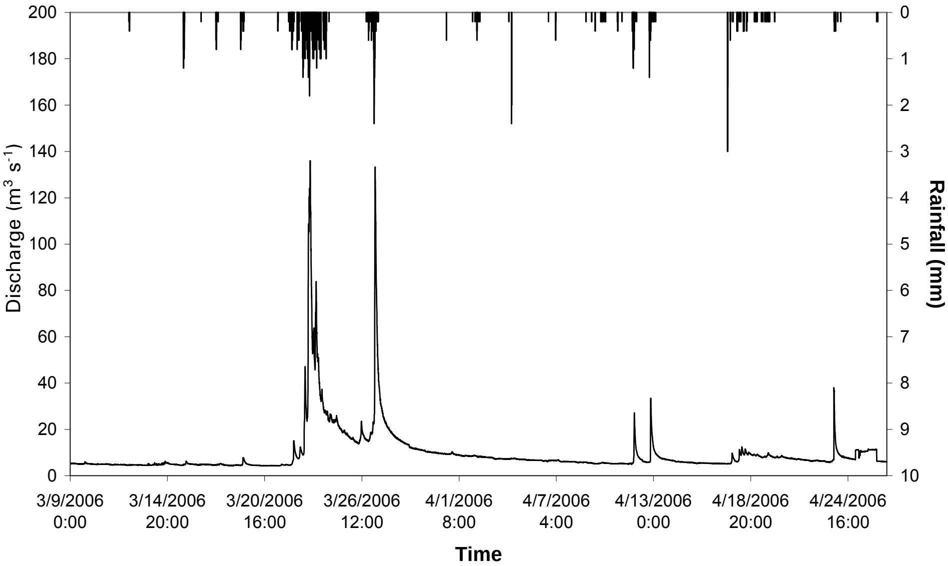

Figure 5. Instantaneous discharge of Sabarang River, Paninggahan sub-catchment during a period of March to April 2006

Gambar 5. Aliran sesaat sungai Sabarang, sub DAS Paninggahan selama Maret-April 2006

Figure 5 shows instantaneous discharge of Sabarang River during a periode of March to April 2006 in 6 minutes time interval. Peak flow has been observed as high as 136.02 m^3s^{-1} at 09.48 am on March 23, with minimum flow of 4.18 m^3s^{-1} at 12.42 am on March 20. Another storm event was recorded at 7.06 am on March 27 with peak discharge of 132 m^3s^{-1}, and smaller discharge of about 25 m^3s^{-1}on April 11, 12 and 23.

The hydrograph shape showed that stream discharge sharply increased during onset rain showing that the runoff was conducted by rapid flow. After peak storm has been reached, the water was slowly released to the river. This process is typical for disturbed catchments as it is found in the study area where rainfall water may not be retained in the catchment. There were more than one peaks of discharge during the entire storm event, which due to the temporal variation of rainfall as it was clearly observed during March 23 event.

Predicting discharge of Paninggahan sub catchment

Application of GR4J model to predict daily discharge of Paninggahan sub catchment has given satisfactory result. The model has been calibrated during a period of March-May 2006 and of January to September 2007. The result showed that the simulation was similar with the observed dis-charge. Regression analysis showed that simulation is well agreed with the observed discharge as shown with coefficient of determination (R^2) of 0.879 (Figure 6a) for the period of March to May 2006 and of 0.46 for the period of January to September 2007 (Figure 6b). This suggests that the model is appropriately be applied to predict daily discharge in Paninggahan sub catchment.

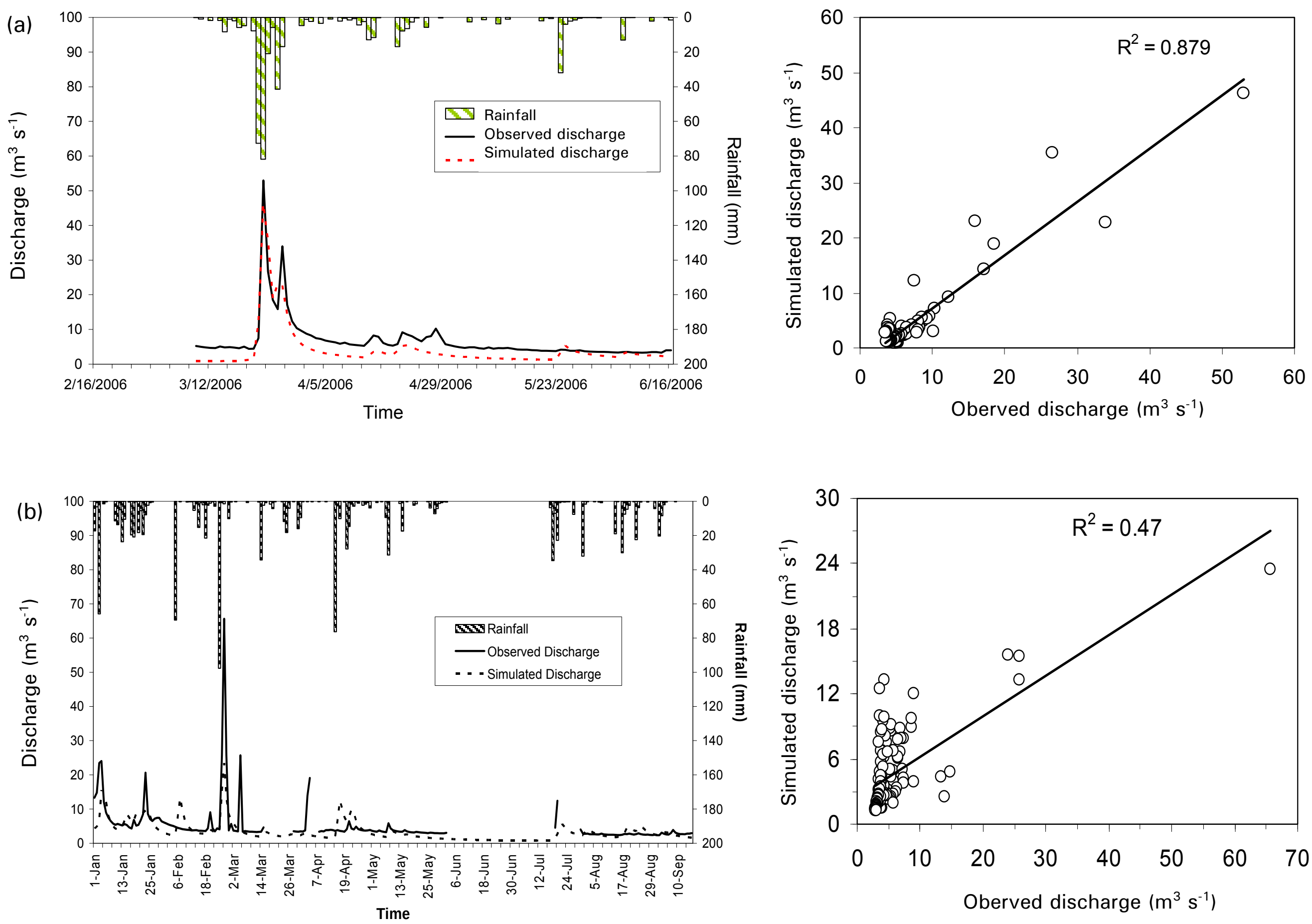

Figure 6. Daily discharge model calibration at Sabarang River of Paninggahan sub catchment during a period of (a) March to May 2006 and (b) January to September 2007

Gambar 6. Kalibrasi model debit aliran harian sungai Sabarang, sub DAS Paninggahan selama (a) Maret-Mei 2006, dan (b) Januari-September 2007

Application of H2U in modeling of instantaneous discharge needs an identification of transfer function parameter that must be measured from the map of drainage network of Paninggahan sub catchment scale 1:25.000. The characteristics of transfer function parameter of model H2U is presented in Table 2.

Model calibration has been applied for storm event on April 11-12, 2006 and on January 14, 2007. The model has given very satisfactory result, which is shown by the value of similarity coefficient of 96% and 87% respectively for April 11-12, 2006 and January 14, 2007 events (Figure 7a and 7b). For April 11-12, 2006 event, the calibrated model parameters to obtain appropriate simulation are:

- Index of infiltration (Φ) to determine excess rainfall is 0.14 mm minutes^{-1}.
- Time lag between peak of excess rainfall and peak of simulated discharge is 114 minutes.
- Mean flow velocity for channel network and hillslope are 7.5 and 0.08 m s^{-1} respectively.

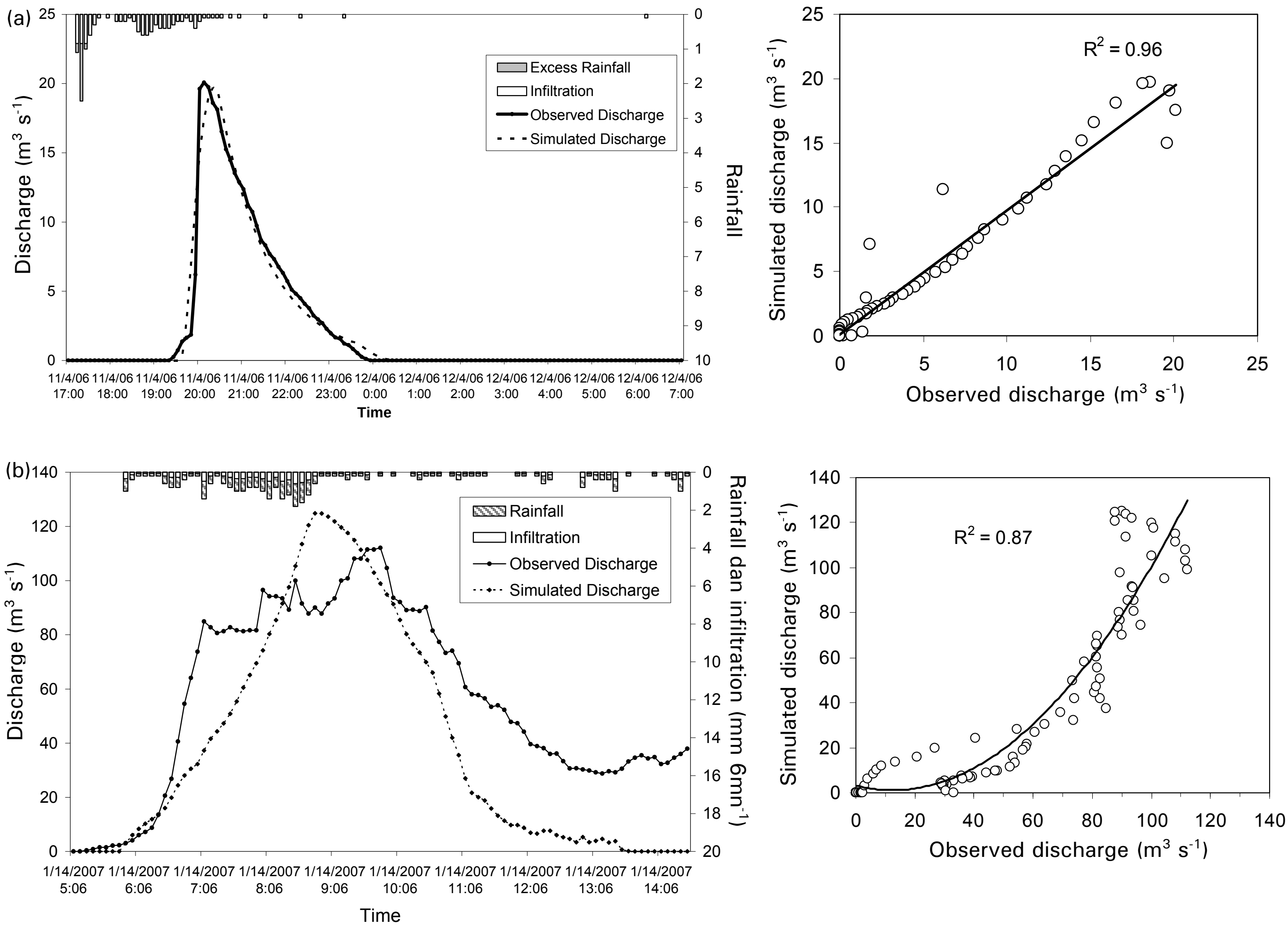

Figure 7. Instantaneous discharge model calibration of Sabarang River of Paninggahan sub catchment, episode (a) April 11-12, 2006 and (b) January 14, 2007

Gambar 7. Kalibrasi model aliran sesaat sungai Sabarang, sub DAS Paniggahan pada (a) 11-12 April 2006 dan (b) 14 Januari 2007

Table 2. The main characteristics of transfer function in channel network and hillslope for Paninggahan sub catchment

Tabel 2. Karakteristik utama parametr fungsi alihan pada jaringan hidrografi dan lereng untuk sub-DAS Paninggahan

Parameter	Unit	Paninggahan sub catchment
Channel Network		
- Mean hydraulic length ($\overline{L}$)	m	13,250
- Maximum hydraulic length (L_{max})	m	20,050
- Strahler's catchments order (n)	-	5
Hillslope		
- Mean hydraulic length ($\overline{l_o}$)	m	331
- Maximum hydraulic length ($l_{o\ max}$)	m	1,150

The use of discharge data for land and water management planning

Land and water management planning need data and information about potential of water resources, where the discharge data is an important parameter to be included. Since in many cases there is lack of instruments installed in the catchment, the use of prediction model of discharge becomes valuable. Predicting discharge in un-gauging catchments must be prioritized for water resources management planning especially in quantifying the use of water for crops irrigation in Singkarak basin.

For water management planning, water resource availability is key factor to succeed irrigation practices for agriculture. Discharge data either recorded or estimated from the model can be used for estimating available water for irrigation. For seasonal based cropping system, two major cropping patterns have been observed in Singkarak basin area, those are rice-rice-rice for paddy based cropping system and chili-onion-maize for dry land crops based cropping system. From the research conducted at the same site with the present study, Nurwindah (2008) reported that under paddy based cropping system, water requirement at the initial crops at September, January, and May is higher compared to other crop stages. For dry land crops based cropping system, the available water from the existing rainfall amount is enough to cover water requirement for crops. Especially at November and December, the supplemental irrigation was not needed. This suggests that the available water resource that reflected from the discharge data is enough to cover water requirement for irrigation. Based on the discharge data during the period of March to May 2006 at Sabarang river, the maximum discharge was more than 50 m^3s^{-1} and the minimum discharge was 3.6 m^3s^{-1}, while the base flow was about 4-5 m^3s^{-1}. Under the rainfall of more than 100 mm at the upstream area and more than 60 mm at the downstream area, the maximum discharge occurred.

In addition, discharge data is also very valuable for estimating the volume of water discharging and increasing water level in the lake of Singkarak and to some extend is for estimating the operation of hydro-electric power. The use of hydrograph data may provide information on the characteristics of river flow. In Singkarak basin, especially in Sabarang river, it was indicated that rapid flow during storm event was characterized, meaning that the catchment may not be able to retain water longer. This implies that Paninggahan catchment needs to be re-greened. Tree crops based cropping system is recommended to be powerful alternative in land use planning.

CONCLUSIONS

1. GR4J and H2U models are valid for predicting daily and instantaneous flow from hillslope areas in Paninggahan catchment to the lake of Singkarak, West Sumatra. These valuable models need to be validated periodically (3-5 years) prior to dynamic behavior of flow, land use, and land management system in the catchment.
2. Application of both hydrological models in Paninggahan sub catchment during a period of March to April 2006 has given satisfactory result. The GR4J model has been calibrated and has given the value of similarity coefficient of 87.9%, while calibration of H2U model applied for storm event has given the value of similarity coefficient of 96%.
3. The success of predicting discharge using both models is valuable to support planning program in land and water management for farming system development in the Singkarak basin and to some extend for other un-gauging catchments.
4. The water management strategy can be planned based on the available water resource that is reflected by the discharge data. For appropriate crops production, irrigation practices can be applied for two different paddy and dry land crops based cropping systems. For paddy based cropping system, irrigation water should be higher at initial crops in September, January and May, while for dry land based cropping system, supplemental irrigation may also be implemented except for November and December.

5. Based on hydrograph data, the discharge increased rapidly just after rainfall event happened indicating that the catchment retention is low. Land use planning may also be integrated in the land and water management, especially for basin conservation practices through regreening.
6. Since installing the hydro-meteorological station is not easy and is not cheap for farmers community, combining model application and validation is recommended for confidential data and information gained from the prediction in justifying the community in negotiation with other stakeholders in the Singkarak basin.

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