DEVELOPMENT A DISTRIBUTED RAINFALL-RUNOFF MODEL CONFIGURED FOR USE IN REGIONAL SCALE AND REAL-TIME FLOOD FORECASTING: CASE STUDY OF JAKARTA METROPOLITAN AREA (JABODETABEK)

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ABSTRACT

Development of regional scale rainfall-runoff modeling system is essential for flood mitigation in a river-delta mega city, such as Jakarta Metropolitan Area, in terms of both designing flood management alternatives and real-time flood forecasting. To take consideration on this fact, Jabodetabek region needs the proposed assessment for better preparing to anticipate the flood disaster. Indeed, many studies have been conducted in Jabodetabek. However, this study offers a new approach by constructing a distributed kinematic-wave rainfall-runoff modeling system that is applicable ranging in scale from sub-catchment, river catchment, to regional. The model is able to deal with various spatial types of rainfall, topographical and soil properties, and hydraulic structures. It has high capability for simulating the hydrological responses of multi river catchments simultaneously, running at the same time. In addition, quantitative rainfall information from ground gauges and from the Global Satellite Mapping of Precipitation (GSMaP) were utilized for modeling of actual floods and their heavy rainfall, respectively. This newly developed rainfall-runoff modeling system and GSMaP product generally provided acceptable estimated heavy rainfall movements and simulated hydrographs at specific locations during the Jakarta floods in 2007, 2013 and 2014. Moreover, the model is planned to be further developed to provide forecasts of river flows (flood), water quality and climate change impact assessment.

Keywords*: distributed hydrologic model, rainfall-runoff, regional scale, Jabodetabek, Jakarta flood*

INTRODUCTION

The question of possible climate change and the associated effects on human society is presently a major topic of public discussion. The observed weather phenomena of recent years, in particular extreme rainfall events, make clear that water and flood management must adapt to changes occurring in the runoff behavior. Because of climate change and human activities, the probability that flood and other extreme meteorological events may become more frequent in the future. Adaptation to the impacts of climate change and human disturbances in the water sector requires both enhanced understanding of the changing dynamics of climate, land-use, water, societal impacts resulting from these changes; and improved capacity for managing risks.

Natural disasters related to severe weather events such as heavy rainfall and flood often occur in Indonesia and have great impacts on human life, economy, and environment. The Jakarta Metropolitan Area, which is located in low lying area in the Capital City of Indonesia (DKI Jakarta), West Java Province, and Banten Province, is one of the regions that have been experienced with flood disaster. It consists of the surroundings regencies and cities of Jakarta-Bogor-Depok-Tanggerang-Bekasi (Jabodetabek). The geographical location and hydrotopographical characteristics of Jabodetabek are inherently prone and vulnerable to flood disaster. There are 13 rivers and many more intersecting canals. Among them, three major rivers within the Jabodetabek area are the Ciliwung River, Cisadane River, and Bekasi River. Additionally, rapid population growth and increasing migration from rural areas to cities in Jabodetabek lead to intense urbanization and increases flood risk. These cause, besides annual floods, the Jakarta Metropolitan Area experienced extraordinary flooding in every 5 years in average (i.e., 1996, 2002, 2007, 2013, and 2014). As an example, the Jakarta flood event in mid-January 2013 triggered by heavy torrential monsoonal rains was a devastating disaster and is considered the worst in the last three decades; leading to the deaths of at least 41 people, more than 100,274 homes were damaged, and over 37,000 people had been displaced with total economic and insured losses would reach IDR 32 trillion and IDR 3 trillion, respectively. More recently, areas of Bogor, Depok, Bekasi, Tanggerang, south and north of Jakarta have experienced flooding and/or been inundated by sea tidal surges.

The work in this research proposal is partially motivated by the fact that increased frequency and magnitude of floods were observed in Jabodetabek in recent years, which are believed as the consequences of human-induced land-use conversion and increased intensity and magnitude extreme events. Climate change scenarios for Indonesia across multiple General Circulation Models (GCMs) show considerable convergence on continued warning, with country averaged mean temperature increase of 2.5^{o}C projected by 2100. There is high confidence across the climate models that monsoon rains might intensify under climate change; and hence causing larger floods. From global point of view, the Intergovernmental Panel on Climate Change (IPCC, 2007) through the Fourth Assessment Report (AR4) projected that global climate change in the twenty-first century will increase both the magnitude and the frequency of floods as result of an increase in extreme meteorological events. Previously, IPCC AR3 (2001) listed out that the behavior of El Nino Southern Oscillation (ENSO) over much global tropics and sub-tropics has been unusual since the mid-1970s compared with the previous 100 years, with warm phase ENSO episodes being relatively more frequent and intensive than the opposite cool phase. The ENSO is well known as one of the major factors related with water-related disasters in Indonesia. Moreover, the effects of local environmental change due to anthropogenic land-use modification and conversion are the other main cause of hydrologic regime change, which often increases the flood risk. Land-use is another key factor controlling the associated river runoff generation especially at smaller scales (Hurkmans et al., 2009 & Pawitan, 2008).

Under these conditions, a better understanding of flood behavior and an assessment of flood control options are necessary. Additionally, there is increasingly important to investigate the impacts of climate change on rainfall extremes, assess their possible impacts on the future flood property and risk by considering urbanization growth of Jabodetabek. To provide flood control assessment and flood prediction, hydrologic models have been widely used in recent years. At the catchment scale, such a rainfall–runoff modeling system can serve as a fundamental tool for integrated basin management, allowing for assessment of flood control alternatives and real-time flood forecasting (Leavesley et al., 2002). However, relatively view studies in the past have used the finer spatio-temporal resolution of hydrologic model that applicable for both purposes; real-time flood forecasting and climate change impact assessment at regional scale such as in Jabodetabek. To effectively utilize powerful computer technology combined with online digital geographic data and meteorological measurement by radar and satellites as well as for use in a regional climate change impact study, more physically-based hydrologic models that can handle a variety of spatiotemporal data must be developed (Singh and Frevert, 2002). Distributed hydrologic models capable of incorporating a variety of spatially varying land characteristics and precipitation forcing data are thought to have great potential for improving hydrologic forecasting (Carpenter and Georgakakos, 2006).

Many studies related hydrological responses evaluation have been conducted in the Jabodetabek region. However, the aim of this study was to develop a physically-based distributed rainfall–runoff modeling system based on the kinematic wave approach and provide streamflow information for water resources planning, flood preparedness and prevention. The modeling system is configured to be applicable ranging in scale from sub-catchment, single catchment, and encompassing many river catchments at regional area. It is also set up for use either in combination with a global or regional climate model. For these objectives, this study applied three hydrologic element modules to simulate rainfall–runoff processes: the hillslope runoff module, channel runoff module, and dam reservoir operation module. Then, these modules combined systematically under the integrated modeling platform, and simultaneously predict streamflow discharge at specific locations of the river catchments.

In this paper, model development and evaluation are focused, and the performances of a satellite-based GSMaP rainfall estimates during Jakarta floods are presented. In section 2, study area of Jabodetabek and geo-spatial used in the model are described. In section 3, development and evaluation of the physically-based grid-cell rainfall-runoff model including some basic equations are presented. Then, in section 4, satellite-based GSMaP rainfall estimates and its performance in representing extreme rainfall that caused Jakarta floods are presented.

STUDY AREA AND GEO-SPATIAL DATA

The Jabodetabek region was choosen as the study area. It has total drainage area of 5,795.57 km^2 covering more than 13 river catchments (see Figure 1, left). The region is prone to flooding from water draining through the cities from the hills in the south and also from coastal tidal flooding in the north. Thus, the catchments in this region have been identified as priority for flood and water resources management by the Indonesian Directorate General for Water Resources (DGWR).

The region has a tropical monsoon climate which is characterized by two distinct seasons, rainy season from November to April and dry season from May to October. Floods are frequently caused by thunderstorms with local rainfall of high intensity during rainy season, but no tropical depression (cyclone) attacks. Generally, the distribution of rainfall over space in the region reveals clearly the effect of topography with higher altitude areas recording more rainfall than the low elevation areas.

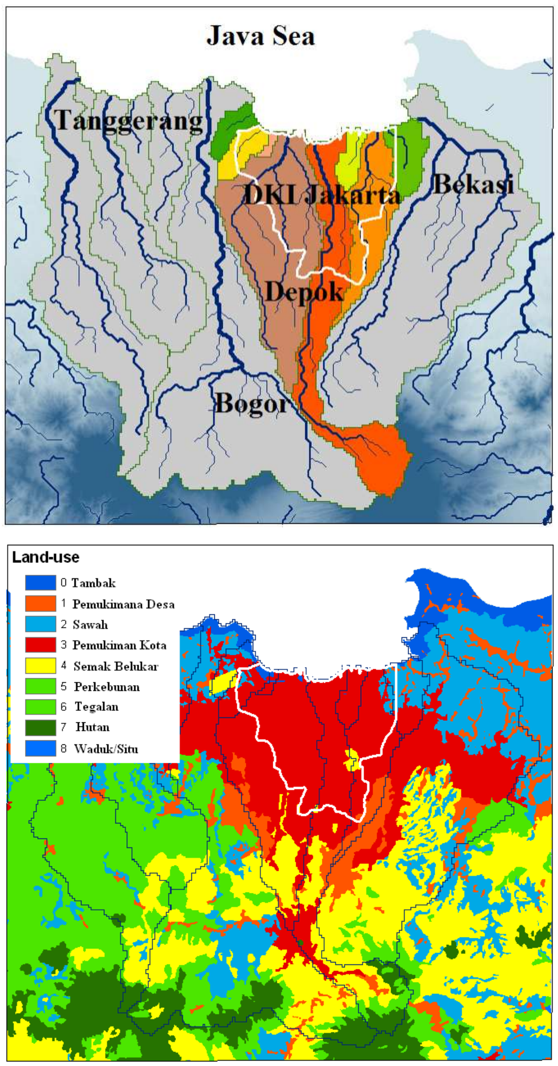


Figure 1. river networks in the Jabodetabek region (left column) and its land-use types condition (right column).

Figure 1-right shows the land-use classification map, where land use types are largely dominated by urban lands ("pemukiman kota" and "pemukiman desa") and agriculture lands ("tegalan" and "perkebunan"). Most of dense forests ("hutan") and paddy fields ("sawah") are relatively small and concentrated in several spot areas. Agriculture lands area is dominant on the upper and middle area where the elevation is from about 1000 m to 1500 m, then on the lower area than that is mostly located by urbanized lands.

Constructing the Jabodetabek's rainfall-runoff model was setup using a 90-m Digital Elevation Model (DEM) and its flow direction as well as flow accumulation data provided from HydroSHEDS global topographic-hydrographic data (http://hydrosheds.cr.usgs.gov). Figure 2-left shows the area was discretized into individual 15 river catchments, partitioned by the topographic properties. Among them, three major catchments were delineated for the Ciliwung River, Cisadane River, and Kali Bekasi River. Furthermore, each river catchment (i.e Ciliwung River catchment) has been divided into more sophisticatedly areas called sub-catchment, which were separated by a number of the hydro network points and existing hydraulic structures such as weir, small pond, and dam (see Figure 2, right). Quantitative information on the area of each river catchment is given in Table 1.

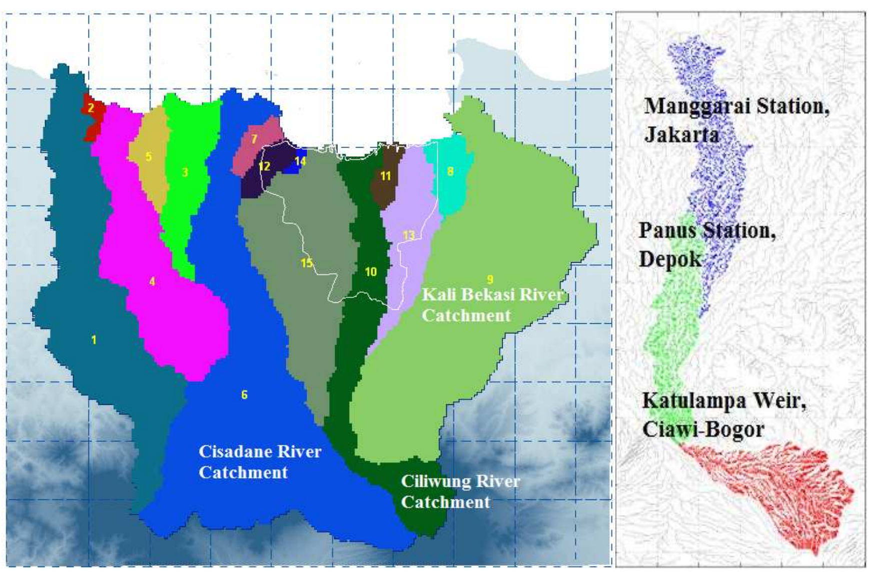


Figure 2. boundaries of the delineated river catchments in the Jabodetabek region (left column) and an example discretized catchment area into three sub-catchments at the Ciliwung River (right column).

Table 1. Calculated total area for each delineated river catchments (see Figure 2-left)

Catchment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Total Area (km^2)	811.8	20.4	209.7	514.9	88.2	1345.0	45.5	85.0	1301.1	451.4	42.2	56.4	220.4	8.4	595.1	5795.6

DEVELOPMENT AND EVALUATION OF THE PHYSICALLY-BASED DISTRIBUTED RAINFALL-RUNOFF MODEL

A modified grid-cell distributed rainfall-runoff kinematic wave model was constructed in order to increase the model capability in transforming hyetographs of abnormal rainfall into a set of flood hydrographs at specific sites within the regional scale. It is a one dimensional physically-based model type and accepts spatial information in terms of topography, soil property, land-use, and meteorological data. Original program of the grid-Cell Distributed Rainfall-Runoff Model (CDRM) was developed and programmed by the Fluvial and Marine Disaster Research Laboratory, the former laboratory of Innovative Disaster Prevention Technology and Policy Research, Disaster Prevention Research Institute (DPRI), Kyoto University (Apip *et al.*, 2012). Latest version of the original model considers dynamic water fluxes in the surface soil layer and two zones of the sub-surface soil layer as introduced by Takasao & Shiiba (1988) and enhanced by Tachikawa et al. (2004). However, the original model advantage is restricted by the fact that the model is only applicable to be run in a single river catchment. It will not be a suitable tool for performing rainfall-runoff simulations in a river catchment that subsequently discretized into a number of sub-catchments, it was also not intended for multi river catchments as well as a regulated river catchment by multipurpose dams.

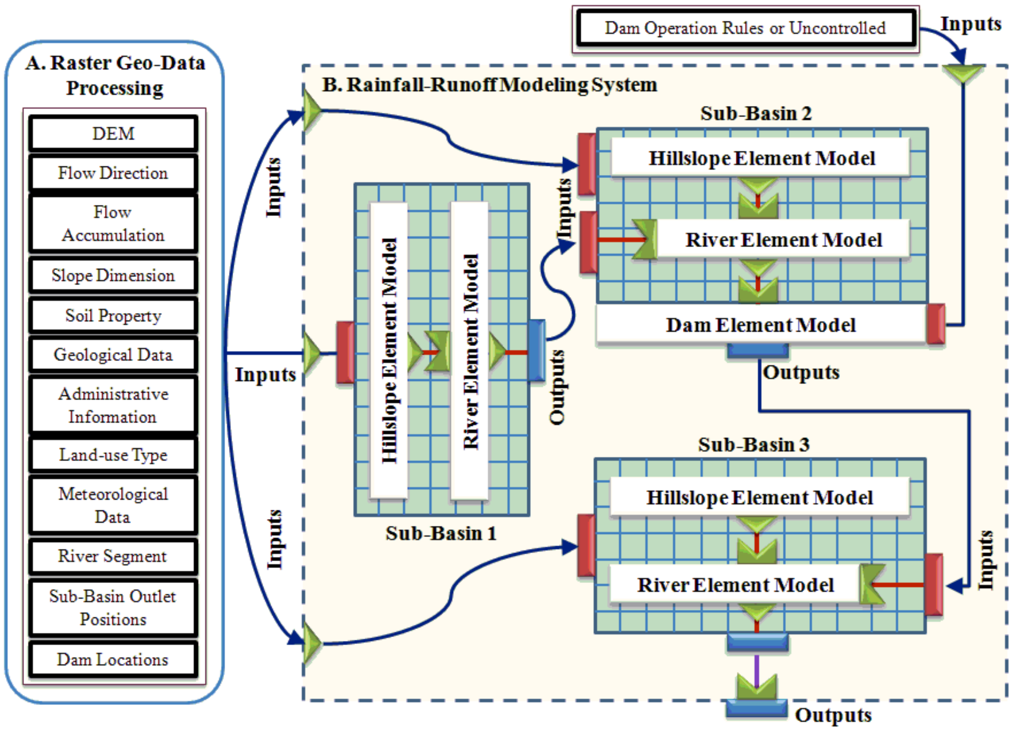


Figure 3. Modified version of the grid-cell-based distributed rainfall-runoff modeling system that is integrating three hydrological sub-models. The figure illustrates the runoff routing process for several sub-catchments within a river catchment/sub-region at the regional scale.

The Jabotabek consists of many river catchments, they are moderately controlled, and amount existing hydraulic structures such as dams, urban lakes, small ponds regulate the river flow regimes. Thus, the model is expected to be a suitable tool for performing hydrological simulations in a region that subsequently discretized into a number of catchments and sub-catchments. Herein, new algorithms for raster geo-data input processing and dam reservoir routing have been imbedded. The modified modeling system consists of two components: adding raster geo-data input processing and modificationson three main element models. Through new development, the target region is discretized into rectangular grids firstly, all spatially varying land characteristics such as topographic features, land-use, geology and soil properties, river networks, and precipitation forcing data, are represented in each grid.

The rainfall on each grid within either individual sub-catchments, catchments or sub-region is transformed to the runoff at every simulation time step (i.e. hourly). The computed outflow discharge from hillslopes drains into river grids following predefined flow direction information. The sequence of routing process between sub-catchments within a river catchment or sub-region (consists of more than one river catchment) is setup through ordering the sub-catchments code according to the drainage area values at their outlet's grids. As further process, the water flows are propagated from the sub-catchments with lowest to highest upstream drainage areas. If a dam exists among sub-catchments, the dam module is setup to be actively supported and running at their outlet grids. Additionally, if a dam exists at a sub-catchment outlet, the outflow from its down stream end grid will drain into the dam, while the simulated dam outflow inputs to the downstream sub-catchments. Figure 3 illustrates the schematic procedure of outflow routing process between sub-catchments. The rainfall-runoff process of sub-catchment system is represented by three hydrologic sub-models as summarized below.

Hillslope Rainfall-Runoff Production Sub-Model

As mentioned, river catchment topography is represented based on DEM that is divided into an orthogonal matrix of square grid-cells. Each grid-cell receives flows from upper grid-cells and rainfall on it. These grid-cells are connected to each other according to predefined eight-direction flow map. Discharge and water depth diffuse to one of the next eight adjacent grid-cells along the direction of steepest descent and routine order determined in accordance with upstream drainage area. The hillslopes flow routed and given to the river flow routing sub-model; then the river flow is routed to the outlet.

The governing equations for water flow are based primarily on the kinematic wave model. The kinematic wave approximation assumes flow is governed mainly by gravity force, proportional to the bed slope, and friction force, proportional to the friction resistance of the bed slope. The schematic diagram of the flow propagation through subsurface and surface using the kinematic wave approximation is shown in Figure 4. From Figure 4, the continuity equation describes a kinematic wave model of the model is derived as:

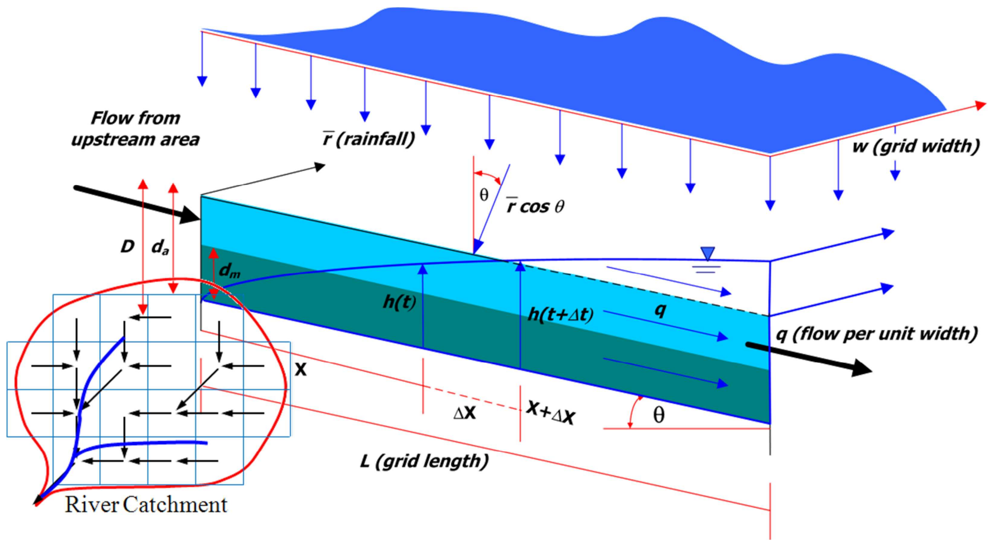


Figure 4. Schematic representation of kinematic wave model for water flow over a grid-cell (slope element) of a river catchment.

$$q(x + \Delta x)\Delta t - q(x)\Delta t + r \cos \theta \ \Delta x \ \Delta t = (h(t + \Delta t) - h(t))\Delta x \quad (1)$$

finally the continuity equation could be obtained as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r(t) \cos \theta$$ with initial and boundary conditions

$$\begin{cases} h(x,0) = H_i(x), & 0 \le x \le L \\ h(0,t) = H_B(x), & t > 0 \end{cases} \quad (2)$$

Where t is the time, x is the distance of water flow, L is the slope length, θ is the slope angle, r is the rainfall intensity, H_i is the initial water depth, H_B is the water depth at the upstream end of the grid-cell, d_m is the equivalent unsaturated soil depth, and D is the total soil layer.

Specific stage-discharge relationship considering the unsaturated (capillary pore) and saturated (non-capillary pore) flows as well as surface flow with uniform thickness was developed as illustrated in Figure 5. Its derived from a combination between field capacity model and subsurface-surface kinematic wave runoff model. When micro soil pores are filled with water, the soil water content higher than a threshold value of field capacity water content, the soil is termed unsaturated flow; when the water is contained in micro and macro soil pores, the soil water content exceeds a threshold value of free water content, the soil is termed saturated.

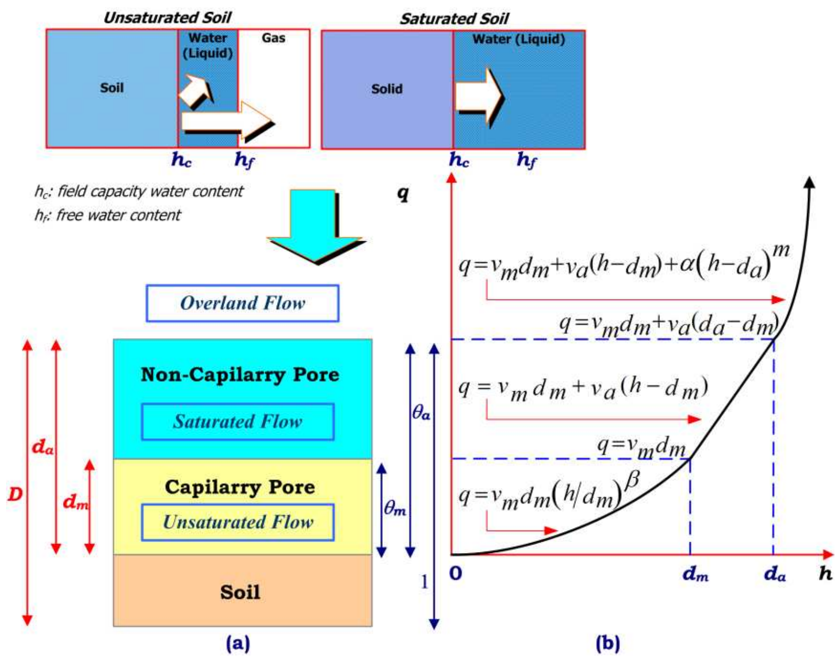


Figure 5. (a) Concept of hillslope soil layer structure and (b) stage-discharge, *h*-*q*, relationship for each soil layer and water flow zone.

The basic assumption used in the model that the flow lines and the hydraulic gradient are parallel and equal to the slope, respectively. The model simulates three lateral flow mechanisms within a permeable soil layer including (1) subsurface flow through capillary pore, (2) subsurface flow through non-capillary pore and (3) surface flow on the soil layer. At each grid-cell, when the water depth is lower than d_m, for the maximum volumetric water content in the unsaturated flow $\theta_m(d_m = D \times \theta_m)$, flow is simulated by Darcy law with degree of saturation $(h/d_m)^\beta$ and an unsaturated hydraulic conductivity k_m. If the water depth increases and exceeds d_m, the exceeded water flows as saturated subsurface flow that is described by Darcy law with saturated hydraulic conductivity k_a. Once the water depth is greater than d_a, the total soil layer D times effective porosity $\theta_a(d_a = D \times \theta_a)$, the water flows as surface flow, which is simulated by the Manning's equation. These processes in each slope grid are modeled with a kinematic wave approach using function for the stage-discharge (*h*-*q*) relationship and its flow equations for each soil layer as illustrated in Figure 5. Some variables in these equations formulated by the following equations (Tachikawa *et al*. 2004):

$$v_m = k_m i,\ v_a = k_a i,\ k_m = k_a/\beta,\ \alpha = \sqrt{i}/n \quad (3)$$

Where q is discharge per unit width, h is water depth, i is the topography gradient, k_m is the saturated hydraulic conductivity of the capillary soil layer, k_a is the hydraulic conductivity of the non-capillary soil layer, d_m is the depth of the capillary soil layer, d_a represents the depths of the capillary and non-capillary soil layers, β is the exponent constant of unsaturated flow (=3), v_m and v_a are the flow velocities of unsaturated and saturated sub-surface flows, respectively, n is the Manning's roughness coefficient varies as a function of land-use type, and k is a constant (= 5/3). An advantage of the model is that the stage-discharge relationship of each grid-cell reflects the topographic and physical characteristics (i.e., land-use and soil type) of its own grid.

Model parameters in the stage-discharge relationship are D, θ_m, θ_a, k_a, and n. The Lax-Wendroff finite difference scheme applied to solve the one-dimensional kinematic wave equation on every node in a grid-cell. The Lax-Wendroff finite difference scheme determines the partial derivates at point (i,j+1) in terms of the quantities at adjacent points (i-1,j), (i,j), and (i+1,j) as illustrated Figure 6.

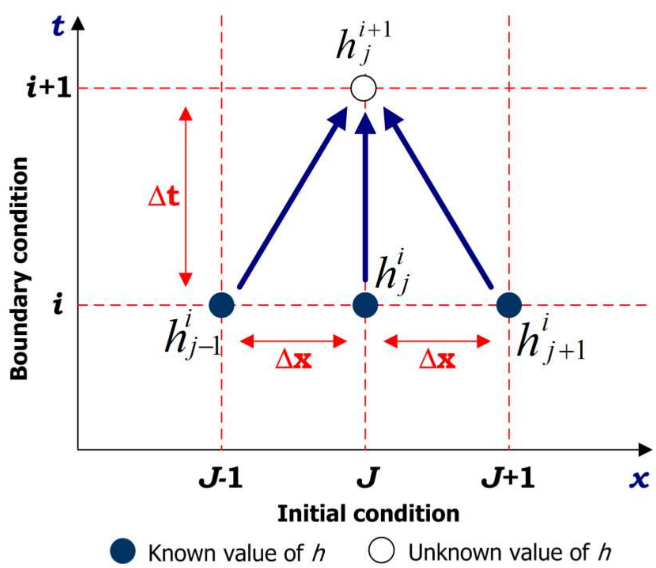


Figure 6 Lax-Wendroff scheme for solution of the kinematic wave equation.

Assuming that at time t (time line j, j-1, and j+1), the values of h are known, the problem is to determine the unknown quantity at point j at time t+Δt, (j,i+1). Derivation of the finite difference form from kinematic wave model $h(x_j,t_i)$, $q(x_j,t_i)$, and $r(x_j,t_i)$ obtained:

$$h_j^{i+1} = h_j^i + \Delta t\left\{r_j^i - \frac{q_{j+1}^i - q_{j-1}^i}{2\Delta x}\right\} + \frac{(\Delta t)^2}{2} - \left[\frac{\partial r}{\partial t} - \frac{1}{\Delta x}\{R(j+1/2,i) - R(j-1/2,i)\}\right] \quad (4)$$

with $j = 0, 1, 2, \ldots\ldots, n\text{-}1$, $\Delta x = L/n$, $x_j = j\Delta x$, for $j = n$, the finite difference form in Equation (4) can be expressed as:

$$h_n^{i+1} = h_n^i + \Delta t\left\{r_n^i - \frac{q_n^i - q_{n-1}^i}{2\Delta x}\right\} \quad (5)$$

The numerical stability of the computation depends on the relative grid size (Δt, Δx). An insufficient condition for stability of an explicit scheme is the Courant condition. For the kinematic wave equations, the Courant condition is:

$$\frac{\Delta x}{\Delta t} \geq \frac{dq}{dh}$$
$$\frac{\Delta x}{\Delta t} \geq f_*'(x_j, t_i) \qquad j = 0, 1, 2, \cdots, n \quad (6)$$

in which f'_* is the kinematic wave celerity that is specific for each layer of flow zone.

River Channel Runoff Production Sub-Model

The river channel of catchment is modeled as a network of river grids, connected with a number of grid-cells. Production of river network is arranged by two means; either using real drainage network information or using approximated stream network based on the minimum numbers of grid-cells to delineate a river segment grid. River channel rainfall-runoff sub-model has been developed to compute runoff movement processes, in which water flow discharges from hillslopes are regarded as the lateral inflow of the river runoff model. Here, one-dimensional kinematic wave approach is kept to route the runoff from one grid-cell to the next in the river as follows:

$$\frac{\partial h_w}{\partial t} + \frac{\partial q}{\partial x} = q_L + r(t)\cos\theta$$
$$q = \alpha h^k \qquad (7)$$

herein h and q are defined as the river water depth and its discharge per unit width, respectively; q_L is the lateral inflow into the river from hillslopes; α and k are defined as like in hillslope sub-model.

Dam Reservoir Routing/Operation Sub-Model

The flux of dam reservoir volume in hydrological modeling is mostly approximated using linear storage function approach. In the new modified model, the storage function method was adopted for formulating a simple dam reservoir routing and operation sub-model. used a simple form of infinite difference to express the change in dam storage over a time interval as given by:

$$S^{t+1} = S^t + \left(\frac{Q_{in}^t + Q_{in}^{t+1}}{2} - \frac{Q_{out}^t + Q_{out}^{t+1}}{2} \right) \Delta t \qquad (8)$$

Where S is the dam storage; Q_{in} is the inflow into the dam; Q_{out} is the dam outflow or release; t and t+1 indicate the current and next time step, respectively. This method assumes a variation in horizontal water surface and called as *Level pool routing*. It could be used for uncontrolled dam outflows. Once the dam inflow, initial conditions, and dam reservoir characteristics (i.e., the relationship of the dam water level and the dam storage, *H*-*S*) are known, the dam outflow can be accounted. In addition, the dam inflow is affected by the natural upstream flows.

The dam outflows, however, may be uncontrolled, controlled, or a combination between both systems. In example, a multipurpose dam during a flood period is operated manually under a control by considering the state of the dam reservoir, dam inflow, rainfall in the upper area of the dam, operational status of other related dams, and the downstream flood condition. Here, the dam release is determined according to the operation rule, spillways are used to release the water.

The rainfall-runoff model's performance evaluation was carried out at the number of sub-catchment outlets. In which, adjustment of final parameters of each sub-catchment was conducted by performing Monte-Carlo-type simulations on the basis of best model performance. In this study, only the Manning Roughness coefficient and effective soil depth are spatially distributed according to the land-use and soil depth, respectively, whereas other parameters are spatially uniform over the region. For the comparisons of model outputs with the observations, Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) was chosen as the objective function:

$$NSE = 1.0 - \frac{\sum_{j=1}^{M}\left(O_j - S_j\right)^2}{\sum_{j=1}^{M}\left(O_j - \overline{O}\right)^2} \quad (9)$$

where M is the number of ordinates in a simulation period, O and S are the observed and simulated streamflow discharges, respectively, while $\overline{O}$ is the average of observed discharges.

Model Performance Evaluation

The performance of the physically-based distributed rainfall-runoff model described has been evaluated by applying the model to the rainfall-runoff response in an actual flood event; in this case the Ciliwung River catchment is selected as the case. Hourly rainfall-runoff data in time series is available in this catchment for the case of 2007 Jakarta flooding. The hydrological dataset on the period January-February 2007 was selected as an example for the evaluation of the model in the Jabodetabek, particularly at the Ciliwung River catchment. Since in that year during 29 January - 7 February, 2007, a relatively large flood event with a peak discharge of more than 500 m^3/s occurred at Depok Station. Hourly measurements from nine automatic rain gauges and two water discharge at the sub-catchment outlets, Katulampa-Ciawi and Panus-Depok, were available. The area rainfall distribution was estimated by the Thiessen Polygon method. Figure 2 (right) and Figure 7 (left) show the delineated sub-catchments, the density of rain gauge networks and estimation of coverage area of each rain gauge location based upon Thiessen Polygon method, respectively. The model calibration was performed at 1-hour time step for the rainfall and hydrological dataset with the total model parameter set as mentioned in the previous section.

The simulated flood events at each sub-catchment outlet for model evaluation phase are shown in Figure 9. The predicted runoff (streamflow discharge) is compared with the observed one. The model is generally successful in representing broad trends in water discharge in both outlets, but simulated water discharge tends to underestimated along times of falling limb of hydrograph for the case of Katulampa Station, the range of modeled water discharge is somewhat lower than observed. As a reason, the streamflow discharge at Katulampa station constrained by a weir (bendung), which is not modeled yet in the simulation. Incorporation weir function and its operation rule is a way to provide more acceptable hydrographs in this outlet point. A summary of this flood runoff event is given by the model efficiencies, NSE, are more than 0.75 for each sub-catchment outlet. In summary, we may be able to recognize that the model prediction from an example flood event is closer to the observed value.

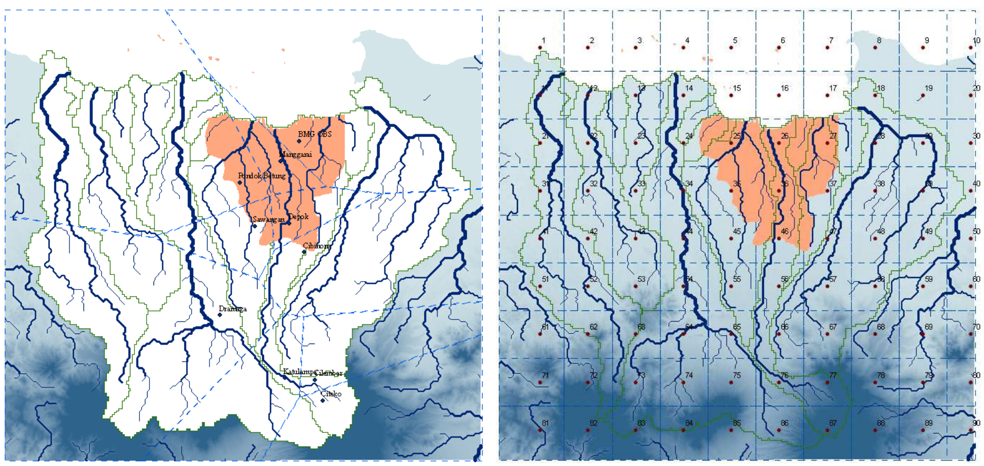
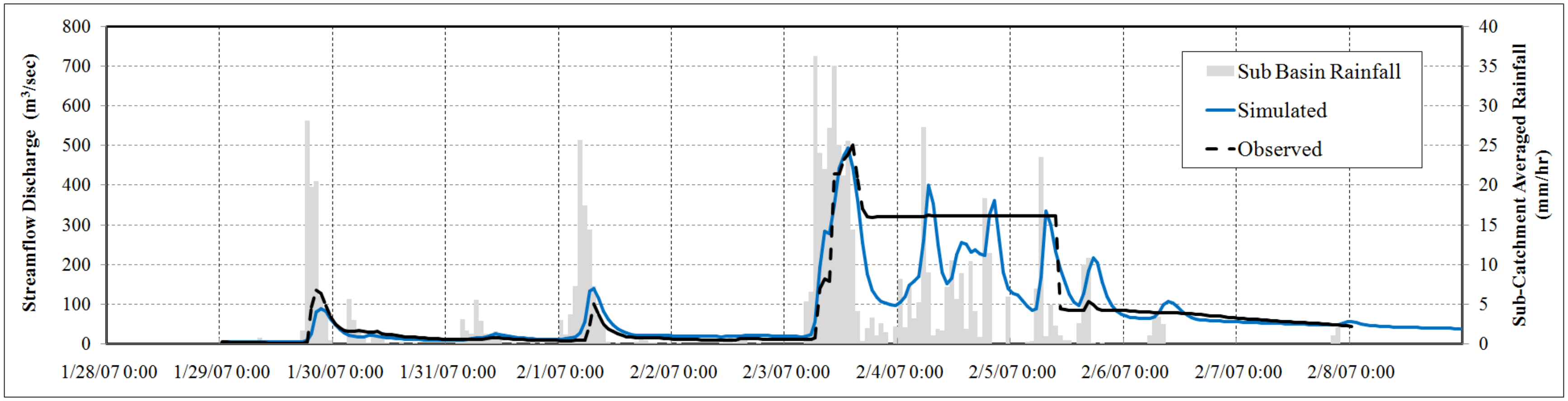


Figure 7. Thiessen polygon of the used automatic rainfall observation points (on the left) and GSMaP grid points (on the right) in the Jabodetabek region.

Figure 8. Photographs of the Jakarta flood situation on January 2013 (top photographs) and January 2014 (below photographs). These photos were taken from online daily newspapers.

(a) At Katulampa-Ciawi, Bogor



(b) At Depok

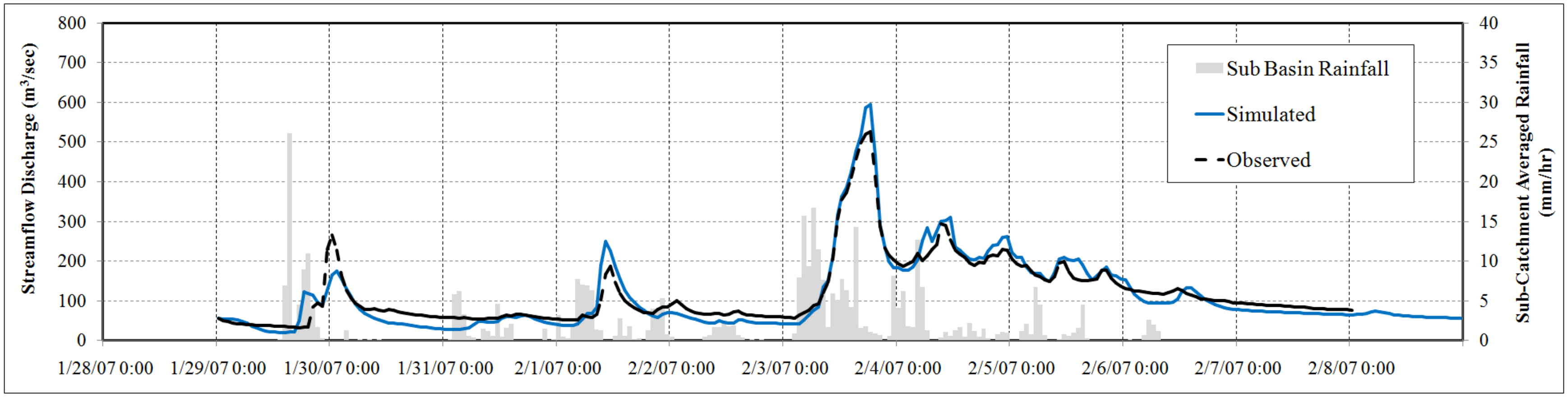


Figure 9. Simulated and observed hydrographs (river discharge) comparisons at Katulampa-Ciawi Station (upper figure) and Panus-Depok Station (bottom figure), Ciliwung River catchment during Jakarta flooding on January-February 2007.

SATELLITE-BASED GSMAP RAINFALL ESTIMATES AND ITS PERFORMANCE IN REPRESENTING EXTREME RAINFALL THAT CAUSED JAKARTA FLOODS

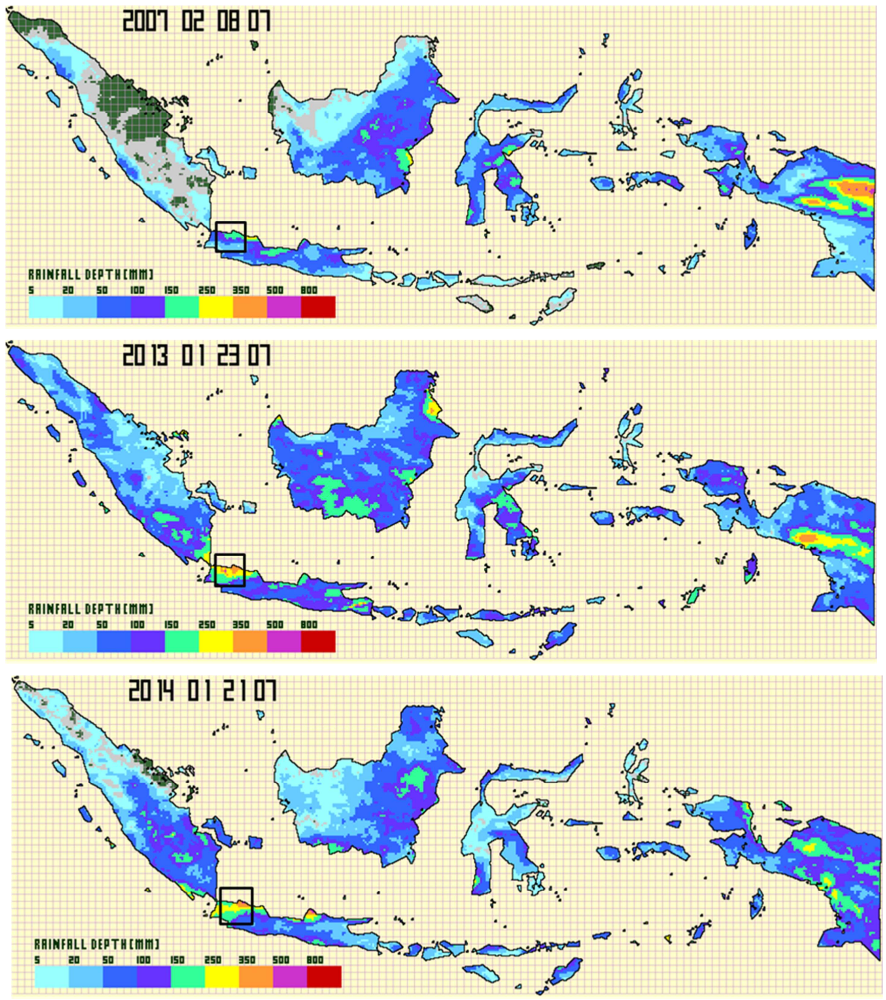


Figure 10. Spatial distribution of predicted cumulative rainfall during Jakarta floods in 2007 (29 January 2007 at 01 a.m to 8 February 2007 at 07 a.m), 2013 (13 January 2013 at 01 a.m to 23 January 2013 at 07 a.m), and 2014 using GSMaP rainfall products (11 January 2014 at 01 a.m to 21 January 2014 at 07 a.m).

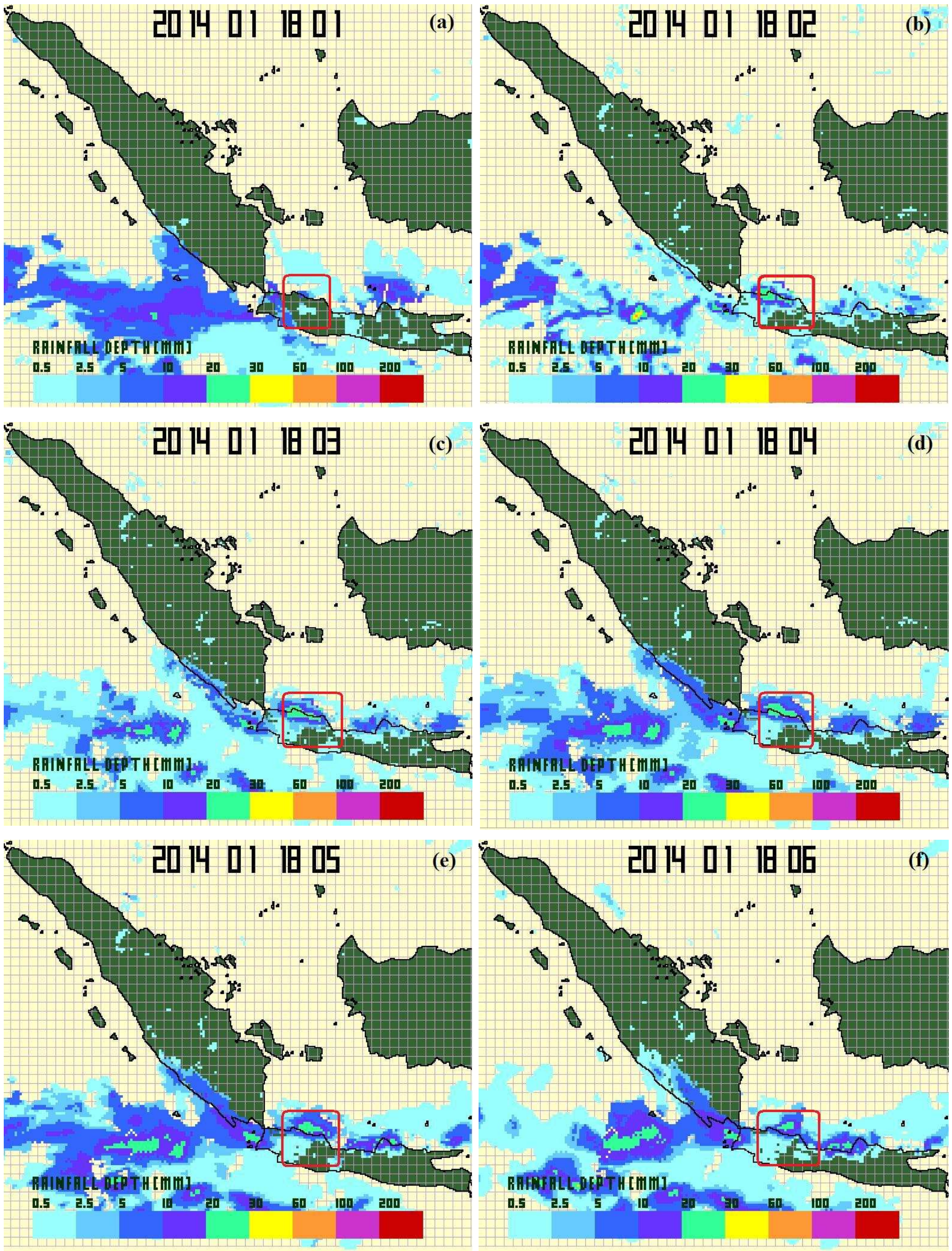


Figure 11. Example display of rainfall field movements over the Jabodetabek (including Java & Sumatera islands) estimated from GSMaP satellite images on 18 January 2014 from 01.00 a.m to 06.00 a.m that caused Jakarta Flood 2014.

Operational flood prediction has commonly relied on a dense network of automatic rain gauges or ground-based rainfall measuring radars that report in real-time. However, a common problem of using rainfall for flood real-time prediction has been scarcity of rain gauges. Recent advances in satellite-based precipitation observation technology and increasing availability of high-resolution satellite products are providing opportunities to develop a satellite-based real-time prediction system. The use of a rainfall product derived from satellite images is one of the alternatives for poorly gauged areas such as the Jabodetabek region. The main satellite data set used in the present study was the GSMaP (Global Satellite Mapping of Precipitation) product (http://sharaku.eorc.jaxa.jp/GSMaP_crest/) prepared by the JAXA Precipitation Measuring Mission (PMM) Science Team.

The Jabodetabek region is covered densely by GSMaP rainfall grid points, roughly of 90 nodes (Figure 7, right). Further, the performance of GSMaP rainfall estimates was evaluated during the Jakarta flooding in 2007, 2013 and 2014. According to the rainfall duration and spatial distribution, the GSMaP estimates well capture relatively higher cumulative rainfall depth over the Jabodetabek region than other areas for each flooding case (see Figure 10). However, especially for high rainfall intensity, the GSMaP estimates underestimate the magnitude of rainfall when compared with the observed data of specific stations, indicating a negative bias. In summary, these results indicate that the GSMaP rainfall product is reasonable ways by which to predict the spatial distribution of rainfall over this study region. The movement of satellite-based rainfall fields could be used to detect a particular extreme rainfall event and used it as the model input for flood prediction and forecasting (see Figure 12).

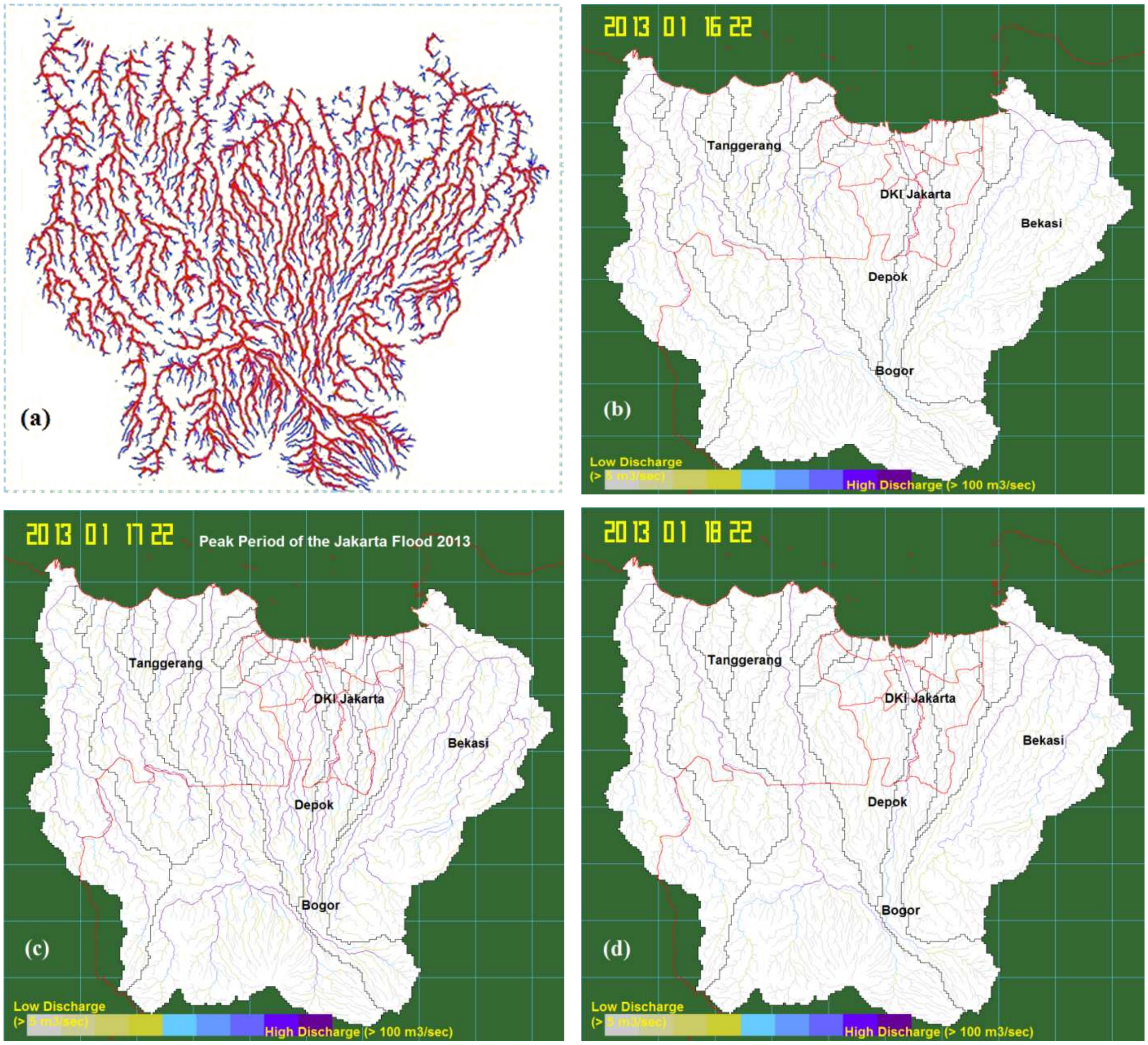


Figure 12. (a) drainage path and river networks used in the model and (b-d) example views of the model output that showing spatially-distributed information of river discharges during flood periods in Jabodetabek on mid-January 2013 (i.e.,16 January at 10 p.m; 17 January at 10 p.m; and 18 January at 10 p.m), GSMaP satellite rainfall product was used in this flood simulation.

To verify the capability of the proposed methodology for real-time flood prediction and warning, the model was applied to past flood event on January 2013 and was forced using the satellite-derived, near real-time hourly GSMaP rainfall product (GSMaP NRT). The performance of the model in detecting the streamflow propagation of this actual flood at entire river catchments could be evaluated. Figure 12 shows several views of the spatiotemporal dynamic of the simulated streamflow discharges over the study region. The spatial distribution of the rainfall, topographic components, land use, and soil condition influence the propagation of the flood flow. The process drains rainwater through the soil layer out to river channel systems, giving acute streamflow peaks on 17 January as it really happened in the case of January 2013 flooding. Overall, the results demonstrate the potential applicability of the modeling system for flood disaster prediction and warning as well as for use in regional climate model for climate change impact assessment on the future flood risk.

SUMMARY

This study developed a grid-cell-based (distributed) kinematic wave rainfall-runoff model for a regional scale (multi river catchments). The model has high capability to simulate the hydrological responses simultaneously for entire river catchments at a region such as in the Jabodetabek region. The developed model was evaluated and tested during the Jakarta floods on January-February 2007 and January 2013. The developed system captured the temporal patterns and multiple peaks of the observed hydrographs at specific locations. Exploration and evaluation on the potential capability of the system for real-time flood forecasting and associated water-related problems prediction and warning as well as climate change impact assessment on flood risk should be directed as interesting points for further advancement of the developed model. Additionally, utilizing radar information technology and near real-time satellite-derived rainfall products such as GSMaP with deterministic or stochastic rainfall prediction, the capability of the model can be examined for short-term real-time flood forecasting and warning at the regional scale.

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