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Modeling effectiveness of management practices for flood mitigation using GIS spatial analysis functions in Upper Cilliwung watershed

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Abstract. Flooding is caused by excessive rainfall flowing downstream as cumulative surface runoff. Flooding event is a result of complex interaction of natural system components such as rainfall events, land use, soil, topography and channel characteristics. Modeling flooding event as a result of interaction of those components is a central theme in watershed management. The model is usually used to test performance of various management practices in flood mitigation. There are various types of management practices for flood mitigation including vegetative and structural management practices. Existing hydrological model such as SWAT and HEC-HMS models have limitation to accommodate discrete management practices such as infiltration well, small farm reservoir, silt pits in its analysis due to the lumped structure of these models. Aim of this research is to use raster spatial analysis functions of Geo-Information System (RGIS-HM) to model flooding event in Ciliwung watershed and to simulate impact of discrete management practices on surface runoff reduction. The model was validated using flooding data event of Ciliwung watershed on 29 January 2004. The hourly hydrograph data and rainfall data were available during period of model validation. The model validation provided good result with Nash-Suthcliff efficiency of 0.8. We also compared the RGIS-HM with Netlogo Hydrological Model (NL-HM). The RGIS-HM has similar capability with NL-HM in simulating discrete management practices in watershed scale.

1. Introduction

Performances of discrete management practices such as infiltration well, retention ponds in reducing surface runoff had been investigated in plot scale. But, appropriate methodologies are still required to study the performance of the measures in a watershed scale. Many studies use catchment hydrological modeling like SWAT and HEC-HMS to investigate the performance of various management practices for flood management (Yustika, 2012, Budiyanto et al. 2015). SWAT model uses HRU (hydrologic response unit) as a smallest homogeneous unit to calculate hydrological processes (Arnold, 2012). Meanwhile, HEC-HMS uses sub-catchment as a smallest unit. In both cases, the surface area of discrete management practice like an infiltration well is too small to be represented by HRU or sub-catchment having an area 10 to 100 ha. One way to overcome this limitation is by using raster as a smallest unit analysis. One discrete management practice can be represented by one raster and using

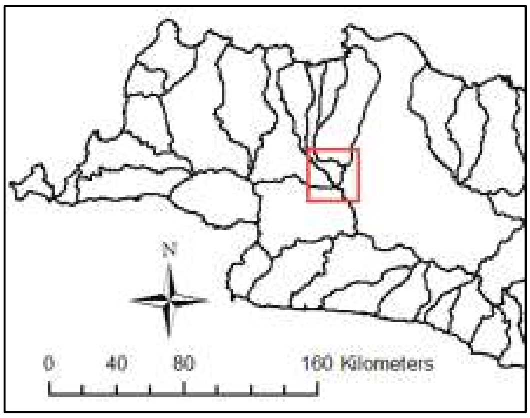
GIS function the size of a raster can easily be adjusted according to the size of structural management practices. According to Arnold (2010), the raster delineation can simulate the impact of landscape position on management and runoff in explicit spatial detail.

The aim of this research is to use raster spatial analysis functions of Geo-Information System (RGIS-HM) to model flooding event in Ciliwung watershed and to simulate impact of discrete management practices on surface runoff reduction. The main advantage of the model lies in its ability to represent individual discrete management practices such as infiltration well in its single raster representation. The main equations used in the modeling process is Manning equation relating flow velocity with slope and surface roughness of the channel. In addition, SCS-CN equation was adopted to relate land use and the proportion of rainfall becoming surface runoff. The grid size is easily adapted to represent small size discrete management practice like infiltration well. Input of the model are topographic map (DEM), land use map, soil map and rainfall characteristics. GIS provide various hydrological functions and raster spatial analysis such as flow direction, flow accumulation functions, flow travel time and zonal statistic to depict flow hydrograph.

2. Methodology

The research was conducted in upper Ciliwung watershed situated in West Java, Indonesia (Figure 1). The outlet of the watershed situated in Katulampa. The watershed experience frequent big flooding in recent years. Effective management practices in upper watershed should be implemented to reduce peak discharge. To select effective management practices, a model should be constructed to test them at the watershed scale.

Surface water flow is the most important component in flood modeling. During rainfall event surface runoff flowing from the upper catchment as a uniform flow and it gradually accumulates forming channel flow as it move downwards of the catchment. At the upper catchment the water flow can be considered as normal flow (stationary flow), which can be approached by the Manning equation. This flow condition is a function of a resistance, slope and hydraulic radius. At the downstream, the flow tends to be non-stationery due to the backwater in the downstream channel. This study focuses on the flood wave generated by surface runoff from the upper catchment.



Source: BPDAS Citarum Ciliwung (2008)

Figure 1. Research location in Upper Ciliwung watershed, West Java, Indonesia

Runoff volume

Runoff volume calculation is the first step in every hydrological modeling. Runoff volume is primarily determined by the proportion of rainfall becoming surface runoff in particular watershed. Proportion of rainfall becoming surface runoff is determined by hydrologic soil groups (HSG) and land use characteristics. The combined impact of HSG and land use characteristics is expressed in term of CN value. Based on Yustika et al. (2012), upper Ciliwung watershed dominated by HSG of type B. The CN values for HSG of type B are then differentiated primarily based on land use (Table 1). After determining the CN values, SCS equation is used to calculate proportion of rainfall becoming runoff using the following equation:

$S=(25400/CN)-254$ (1)
$Q= (P-0.2S)^2/(P+0.7)$ (2)
where,
Q = Runoff volume, mm
P = Rainfall, mm
S = Maximum recharge capacity of watershed
CN = Curve Number

The CN values and Manning coefficients based on dominant land use in upper Ciliwung are listed in Table 1.

Table 1. SCS curve number and Manning coefficients based on dominant land use in upper Ciliwung

Land use	Curve Number	Manning coefficient
Natural forest	0.55	0.6
Secondary forest	0.60	0.6
Mixed agriculture	0.66	0.5
Plantation	0.66	0.45
Settlements	0.85	0.012
Shrub	0.60	0.45
Bareland	0.86	0.018
Dryland farming	0.76	0.02

Source: Schwab et al. 1981

Flow velocity and travel time

Component of flow in an upper watershed consists of: a) overland flow, b) channel flow. Overland flow can be further differentiated based on its position on the slope. Channel cells are identified (using a GIS function) as those cells which have a minimum amount of >50 of upstream cells. In this model, baseflow is assumed constant.

At the upper catchment the flow was modeled based on Manning equation (DHV-MLD-Deltares 2011):

$V = \{s^{0.5} * (A/P)^{2/3}\}/n$ (3)

Where:

V = flow velocity in the cell (m3/s)
s = slope (m/m)
A = flow cross-sectional area (m^2)
P = wetted perimeter
n = Manning's coefficient

The slope is determined from DEM (Digital Elevation Model) available in grid size of 30m x 30m in the study area. The Manning's coefficient is determined according to the types the land-use for the particular cell (Table 1). Based on DHV-MLD-Deltares (2011) for overland flow where the depth relatively small compared to the width of the flow, the hydraulic radius (A/P) can be approximated by the depth of the flow in the cell. The Manning equation can be formulated as follows:

$V = \{s^{0.5} * d^{5/3}*W\}/n$ (4)

The flow travel time in the particular cell can be determined as follows.

$T = x/V$ (5)

where:

V = flow velocity in the cell
s = slope (m/m)
d = depth of the flow
n = Manning's roughness coefficient
x = flow distance
W = flow width (for overland flow, it was estimated based on its position in the overland runoff process; for channel flow it was estimated based on observations in the catchment)

GIS functions were used to determine cumulative travel time from particular cell to the outlet based on the flow direction map obtained from GIS spatial analysis. By accumulating volume of excess rainfall in each of the cells along the flow direction and their respective time to reach the outlet, the flow hydrograph at the outlet of the watershed is determined using zonal statistics of GIS functions and plotting in a hydrograph.

Rainfall data

The model requires hourly rainfall data. Rainfall data used as an input for the model was obtained from Citeko meteorological station. Discharge data for model calibration was obtained from Katulampa hydrological station.

Model validation

The model was validated using flooding data events of Ciliwung watershed in 29 January 2014. The hourly hydrograph data and rainfall data were available during period of validation.

3. Results and Discussions

Model setup

Input of the model consisted of rainfall events, spatial data (soil, land use, topography). Soil and land use data were used to derive CN value. CN value determines partition of rainfall into surface runoff and infiltration (Figure 2).

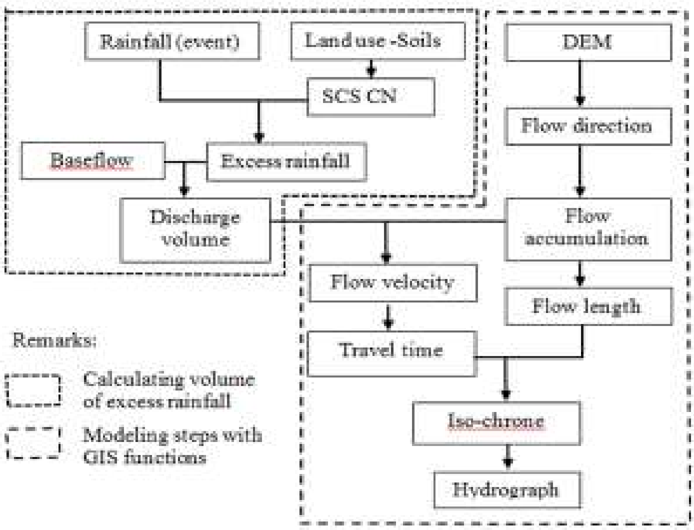


Figure 2. Components of the runoff model

Table 2. The hourly rainfall data from Citeko meteorological station and water level in Katulampa during flood event in 29January 2014.

Date	29 January 2014								30 January 2014						
Hour	17	18	19	20	21	22	23	24	01	02	03	04	055	06	077
Rainfall (mm)	0	0.1	2.7	5.2	45.5	63	25	1.3	0.2	2.8	0.1	0.1	2.5	8.5	3.5
Water level (m)	80	80	80	80	80	130	190	230	200	190	180	150	140	130	120

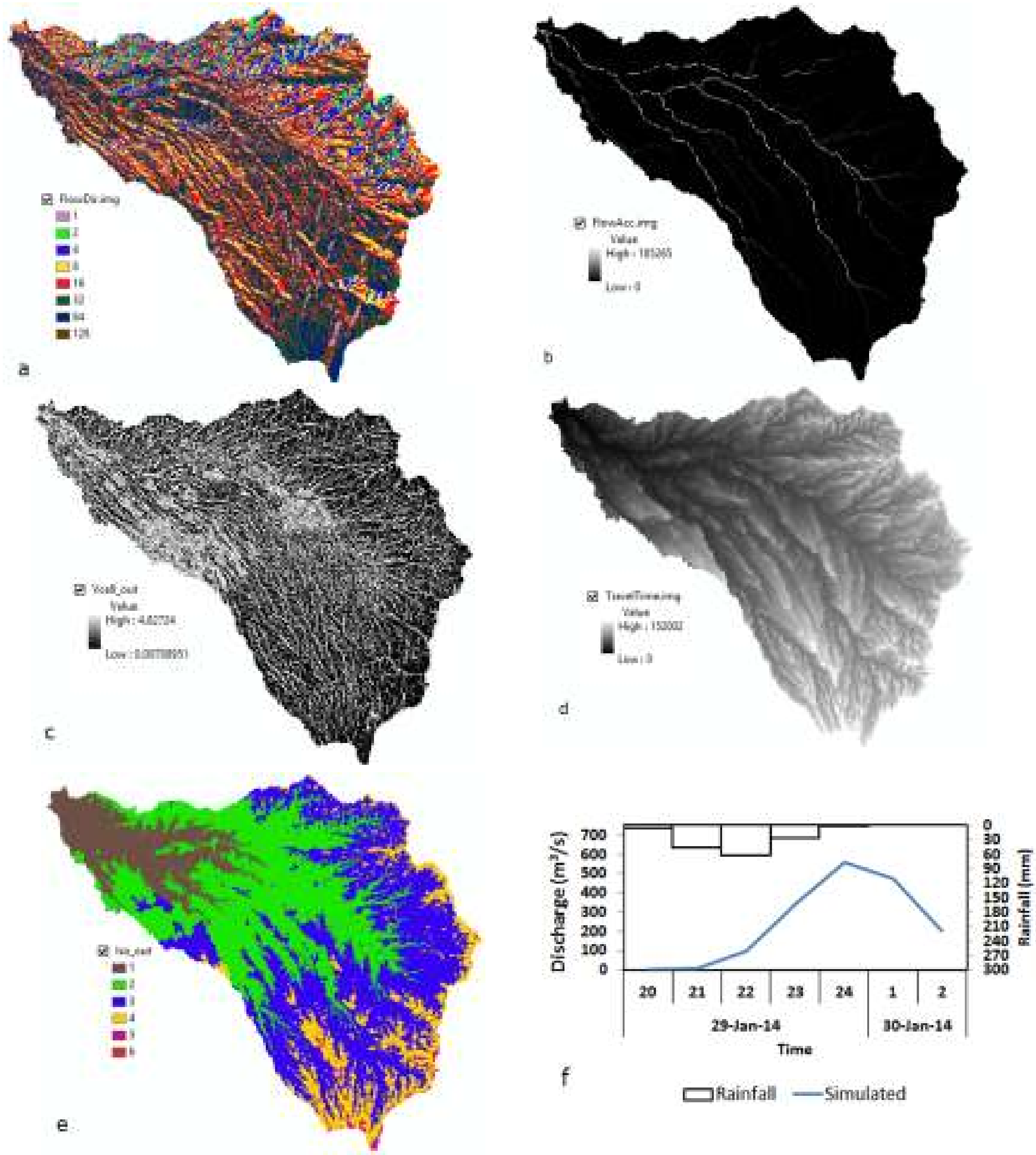


Figure 3. Flow direction map (a), flow accumulation map (b), flow velocity map (c), Travel time (d), Iso-chrone (e) and output hydrograph (f)

As the input for the model, we used hourly data available from Citeko rainfall station. We didn't use rainfall data from other two stations found in the watershed (Gunung Mas and Katulampa), since both stations had only daily rainfall data which couldn't be used to simulate hourly flood event. The hourly rainfall data from Citeko meteorological station in the upper Ciliwung and respective water level in Katulampa outlet during flooding event is shown in Table 2. The flood peak discharge occurred at 24.00 on 29 January 2014 generated by rainfall event started form 19.00 PM (Table 2).

Topography data or DEM was used to delineate the catchment and to derive flow direction (Flow_dir) and flow accumulation (Flow_acc) maps using GIS functions. Based on the Flow_dir, Flow_acc and rainfall data, the model calculated rainfall excess, flow velocity, flow volume excess, travel time, and Iso-chrone (Figure 3 a,b,c,d,e) using Equation 1 and 3. The final output of the model is discharge hydrograph at the outlet of the catchment at Katulampa (Figure 3 f).

Validation and Simulation

The flood event was initiated by single rainfall even started from 20.00 to 23.00 PM in 29 January 2014 with hourly amount of rainfall were 5, 46, 64, 25 mm consecutively. The flood started the rising limb 1.5 hour after rainfall initiation. The flood peak discharge (~525 $m^3 s^{-1}$) occurred at 23.30 AM on 29 January 2014 was accurately simulated by the model (Figure 4). The time period for rising limb and its trend were simulated by the model with good agreement with observed data. But, the magnitude of simulated discharge during the rising limb was underestimated by the model with decreasing trend toward the peak discharge. The decreasing limb one hour after the peak discharge was slightly overestimated by the model.

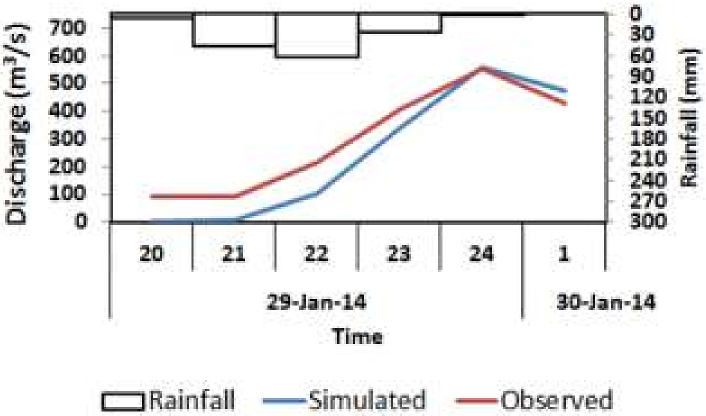


Figure 4. Simulated and observed peak discharge during flood event on 29 January 2014 in Katulampa outlet

The model was validated using observed hydrograph data recorded at Katulampa station during flood event in 29 January 2014 (Fig.1). The validation results were expressed as Nash-Sutcliff efficiency (NSE) (Nash and Sutcliff, 1970). In overall, the R^2 between observed and simulated discharge was 0.97 and the Nash-Suthclife Index amounted to 0.81. Both statistical indicators showed that the model can be used for prediction.

Impact of infiltration well in reducing flood peak discharge

After validation with good result, the model was used to simulate impact of infiltration in reducing flood peak discharge. Some 125 infiltration well were placed in agriculture land use such as mixed farming and dry land farming (Figure 5). Surface area of each infiltration well equals to single raster size which is 900 m^2. Total area of simulated infiltration well was 125 x 900 m^2 = 112,500 m^2 or equivalent to 11.25 ha which was on only 0.0008% of upper Ciliwung watershed. The simulated infiltration wells reduced 0.67% peak discharge (Table 3). The impact of those infiltration wells in reducing flood peak discharge was still minor, but the simulation showed that RGIS-HM was cable in integrating discrete management practices like infiltration well into the flow modeling. Result of this simulation showed that: a) discrete management practice like infiltration well can be represented by individual or combination of several rasters, b) this model can be used to determine numbers of infiltration wells required to reduce peak discharge into the targeted level. Raster size can easily be adjusted to accommodate the size of discrete management practice. This kind of adjustment is not possible using other hydrological models such as SWAT and HEC-HMS.

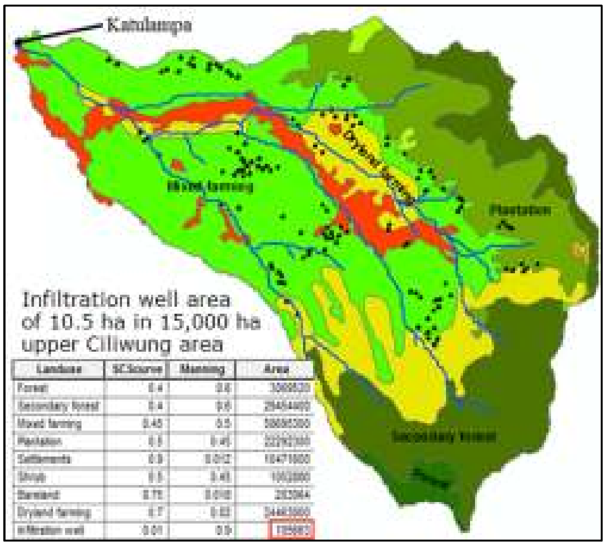


Figure 5. Simulated infiltration wells (black dots) with total surface area 10.5 ha in upper Ciliwung watershed with area of 15,000 ha.

Table 3. Impact of infiltration wells on flood discharge in Katulampa before and after infiltration well constructions

	Discharge (m3/s)		
Hour	Before	After	% Reduction
1	0.0	0.0	0.00
2	7.8	7.8	0.00
3	98.7	98.4	0.34
4	337.6	336.0	0.48
5	555.7	552.0	0.67
6	476.1	474.4	0.36
7	206.8	206.3	0.24
8	41.3	41.3	0.02
9	3.6	3.6	0.00

Netlogo Hydrological Model (NL-HM)

Netlogo is a multi-agent modeling environment for simulating natural and social phenomena. It is particularly suited for modeling complex systems evolving over time such as flood discharge hydrograph. The Netlogo world consists of agents. There are four types of agents: turtles, patches, links, and the observer. All of the agents can carry out their own activity simultaneously. The patches are similar to the grid representation of the landscape and the water flow is being the turtles. Netlogo can import GIS data using GIS extension serving as the background of the patches including DEM data providing elevation for every patches. Therefore, Netlogo can be used to simulate surface water flow using GIS extension function of the Netlogo as follows:

```
extensions [ gis ]
globals [ road-dataset
          flow-dataset ]
patches-own [ p_catchment]
to setup
ca
  ;load all gis datasets
  set road-dataset gis:load-dataset "data/catchment.shp"
  set flow-dataset gis:load-dataset "data/riv1.shp"
  ;drawing polyline data from a shapefile
to display-watershed
  gis:set-drawing-color blue
  gis:draw road-dataset 1
end
;drawing polyline data from a shapefile
to display-flow
  gis:set-drawing-color blue
  gis:draw flow-dataset 1
end
```

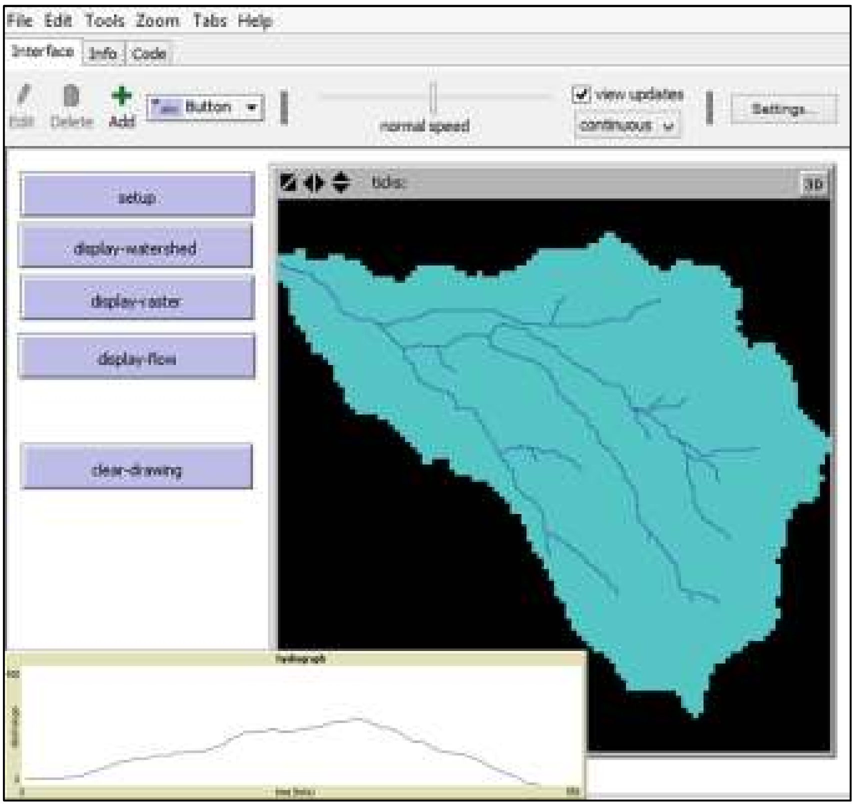


Figure 6. Example of Netlogo model and hydrograph for upper Ciliwung

To simulate water flow hydrograph, both equations mentioned in the methodology (Equation 1 and 3) can be easily incorporated into the script below. Result of the script execution using Netlogo-interface is shown in Figure 6. The interface showed upper Ciliwung watershed boundary, the channel flow and resulting discharge hydrograph.

```
to go
; calculating runoff volume using SCS equation
  let cd gis:raster-sample channel-distance self
  ifelse cd < in-channel-dist
  [ set color blue ]
     if (landuse != 0)
        [ let cn curve-number landuse
          if (cn != 0)
            [ let s (25400 / cn) - 254
              let temp q rain- 0.2 * s
              set q (temp * temp) / (rain + 0.7) ] ] ] ]
………..
end
```

Using Netlogo script it is easy to assign infiltration well in to selected patches. It is also possible to differentiate resistance and storage condition between upper and lower patches of the watershed. Other strength of NL-HM compares to RGIS-HM is its ability to perform dynamic simulation of flood hydrograph (Fig. 6). The only disadvantages of NL-HM is its longer processing time compared to that of RGIS-HM for larger watershed.

4. Conclusions

Modeling flood discharge using GIS spatial function (RGIS-HM) showed good Nash-Suthcliff index of 0.8. Despite its underestimation during the rising and decreasing limbs, the model was very successful in determining the flood peak discharge. The main advantage of the model compared to existing model such as SWAT and HEC-HMS models is its ability to simulate small and discrete management practices like infiltration well having size smaller than 1 ha by assigning its attributes to a single raster. This capability enables RGIS-HM to be used to test performance of discrete management practices like infiltration well in watershed scale.

Netlogo modeling environment can also be used to model and to simulate peak flood discharge and the impact of discrete management practices. Its strength lies in its simple and easily constructed script and also its dynamic visualization capability. The disadvantage is the increased processing time for a large watershed.

5. Acknowledgements

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