RAINFALL FORECASTING FOR FLOOD PREDICTION IN THE NILWALA BASIN

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ABSTRACT

Flooding is the major natural disaster in Sri Lanka and reliable forecasts with longer lead time is a way of reducing the damages. In this study a weather model was coupled with a hydrologic model and a hydraulic model for predicting floods in Nilwala river basin in southern Sri Lanka.

WRF 3.0 (Weather Research and Forecasting) weather model was configured and used to predict rainfall over the basin 24 h into future. The model was configured by investigating the impacts of its physics options on precipitation forecasting. The impacts of microphysics schemes, cumulus schemes, land surface schemes, long/shortwave schemes and boundary layer schemes on rainfall predictions were investigated. The predictions were compared with observed point rainfall data for three rainfall events to find reasonably good physics combination. It was seen that model physics combination; Ferrier microphysics scheme, Kain-Fritsch cumulus scheme, Rapid Update Curve land surface scheme, Rapid Radiative Transfer Model longwave radiation scheme, Dudhia shortwave scheme and Yonsei boundary layer scheme yields better precipitation predictions over the basin.

Output of the weather model was coupled with hydrologic model HEC-HMS 3.3 (Hydrologic Engineering Center-Hydrologic Modeling System) with Clark's, Snyder's and SCS transformation methods. In all model runs Green-Ampt loss model was executed with recession base flow method. Before using the model with the WRF output HEC-HMS model was calibrated for historical events and Snyder's method performed better than other methods in calibration and verification. Snyder's method produced Nash-Sutcliff efficiencies greater than 70% and 50% in calibration and verification respectively.

WRF predicted rainfall for May-2003 was introduced to HEC-HMS and the generated river discharges of sub basin were ingested to the HEC-RAS 4.0 (Hydrologic Engineering Center-River Analysis System) hydraulic model for water profile computations along the Nilwala main river. Output of HEC-RAS was exported to Arc-GIS 9.2 where it was two dimensionally visualized as a flood map. Model was capable of predicting the areas as inundated regions but with underestimation of inundation depth.

1. INTRODUCTION

Flooding has been one of the most costly disasters in terms of both property damage and human casualties in Sri Lanka. Records show that major floods have occurred in Sri Lanka in the years of: 1913, 1940, 1947, 1957, 1967, 1968, 1978, 1989, 1992, and 2003 with severe loss of human lives, public and private property and the environment. Sri Lanka has 103 major river basins. Of these, 17 rivers are associated with flood problems. These 17 rivers have a catchments area of about 1,600 km^2. Kalu, Kelani, Gin, Nilwala and Mahaweli are the major rivers causing floods in Sri Lanka (Jayasekera, 2009).

Historically floods have been the most prevalent cause of death from natural disasters (Jonkman, 2005). Most of the human losses are due to floods in the tropical regions of Africa, Asia, and Central America. A reliable flood forecasting can reduce the death toll associated with floods. (Guleid et al, 2007). Operational flood forecasting has traditionally been driven by a dense network of rain gauges or ground-based rainfall measuring radars that report in real time (Guleid et al, 2007).

The basic intention of the study was to develop a flood prediction tool for the Nilwala river basin. A model having following three basic components is proposed to introduce long lead flood forecasts.
1) Atmospheric model (To predict precipitation over the basin)
2) Hydrologic model (To predict the river flow at various locations)
3) Hydraulic model (To predict the river water profile, inundation area and depth)

1.1 Nilwala River basin

Nilwala River originates at Panilkanda near Deniyaya at an altitude of 1,050 m and after traversing about 72 km the river flows to the Indian Ocean at Matara. Before falling into the sea it passes the Deniyaya town, Morawaka and Akuressa regions. Nearly 90 per cent of the area covered by the catchment of Nilwala River belongs to the Matara District. The area of the river basin is about 1,073 km^2. Figure 2 shows the location of the Nilwala river basin and the drainage network.

Figure1: Nilwala basin location and river network

The watershed is located in the wet zone of Sri Lanka and the upper part of the catchment is covered with rainforest. The mean annual rainfall of the upper basin is above 3000 mm while the lower areas receives about 1900 mm. The average monthly rainfall exceeds 200 mm during the March–June and August–December periods, but in other months it is about 150 mm (Elkaduwa et al, 1998).

2. METHODOLOGY

An atmospheric, hydrologic and inundation models coupled as shown in the Figure 2 forms the basis of the model. Following procedure is used in configuration and calibration of the model.

2.1 Weather modeling with WRF

The Weather Research and Forecasting (WRF 3.0) model used to model the weather over the basin. 45 km/15 km/ 5 km domain configuration was used in the present study. Spatial extents of domains were maintained as 1800 x 1800 km/645 x 645 km/245 x 245 km, respectively for the 1st 2nd and 3rd domains. All the domains shared the same center. Figure 3 depicts the arrangement of the three domains nested for the model runs. Initial and lateral boundary conditions for the model runs were obtained from the GFS (Global Forecast System) for three rainfall events on 10/12/2008, 20/03/2009 and 06/04/2009.

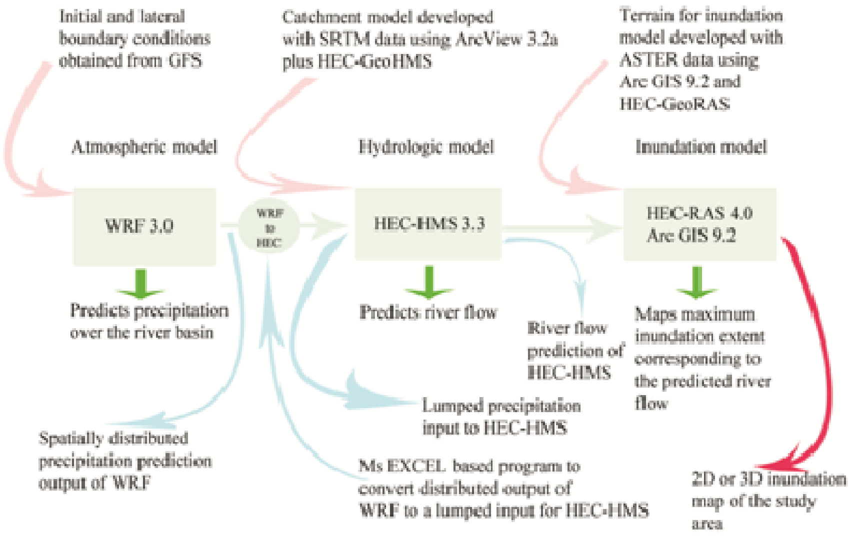


Figure 2. Flow diagram depicting the chain of model components

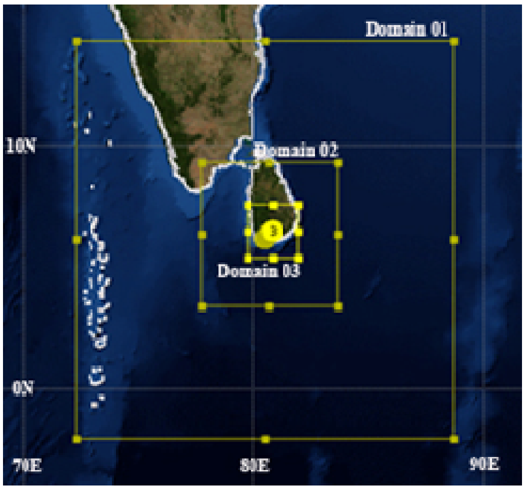


Figure 3 Arrangement of three domains in WRF Model

WRF model contains number of physics options. Under these physics options there are many schemes available for selection. This allows the modeler to use wide variety model physics combinations in predicting weather. These physics schemes can be configured to fine tune the model to produce best results for the study area. The physics options are microphysics schemes, cumulus schemes, land surface schemes, long/shortwave schemes and planetary boundary layer schemes which influence the precipitation predictions.

During the study the model predictions are compared with observed point rainfalls, obtained from the Department of Meteorology, Sri Lanka, for the rain gauging stations at Mapalana, Kekanadura tank, Thihagoda, Thelijjawila, Goluwatta, and Mawarella Estate. The observed point rainfall data were spatially distributed using inverse distance weighting on 5 km x 5 km horizontal grid for comparison with the predictions of WRF model for the same grid. Variation within +/- 5 mm range was considered as an acceptable forecast. Area inside the basin in which the predictions were within the above specified +/- 5 mm range was expressed as a % of the total area of the basin (Correctly Predicted Area %, CPA). This was taken as the measure of success of the predictions for different physics schemes.

2.2 Hydrologic Modeling with HEC-HMS

Rainfall is converted to runoff using hydrologic modeling of the Nilwala basin with HEC-HMS 3.3 hydrologic model. HEC-HMS is a numerical model includes different methods to simulate runoff in a watershed predicting flow and stage variation with time (USACE, 2008).

Data needed for the hydrologic component of the study basically comprised of precipitation records of the Nilwala basin, discharge data of the river, digital elevation map of the basin, location data of the rain gauges and river gauges etc. Hydrologic modeling was performed on the upper part of the Nilwala basin upstream of Pitabeddara and once the model is calibrated the same is extended to lower basin. Such approach is needed as no reliable flow gauging station below this is available.

For model calibration and verification phases, as transformation techniques Clark's method, Snyder's method and SCS (US Soil Conservation Services) method were applied in conjunction with the Green Ampt loss model. The recession base flow method was used for modeling base flow in all the cases. For the model calibration three rainfall-runoff events were arbitrarily selected as given in the following Table1.

Table1 Rainfall-runoff events selected for the calibration of the HEC-HMS model

Start date of event	**End date of event**	**Peak date of event**	**Peak discharge (m^3/s)**
14-Sep-74	20-Sep-74	16-Sep-74	125.6
5-May-75	13-May-75	07-May-75	171.8
9-May-78	20-May-78	15-May-78	279.3

For the evaluation of model performance there are various different criteria are used. In this investigation Nash–Sutcliffe efficiency index, Q Simulated /Q Observed ratio and Peak Q Simulated/Peak Q Observed ratio were used to evaluate the model performances. For model verification another set of different flood events were selected as given in Table 2.

Table 2 Rainfall-runoff events selected for the verification of the HEC-HMS model

Start date of event	**End date of event**	**Peak date of event**	**Peak discharge (m^3/s)**
10-Jun-79	18-Jun-79	14-Jun-79	105.4
10-Jul-84	17-Jul-84	13-Jul-84	128.8
25-Sep-79	30-Sep-79	27-Sep-79	199.0

The Nilwala river basin was subdivided into 10 sub basins based on the major tributaries as shown in Figure 4. Flows generated in the sub-basins had to be routed in order to convey them downstream. The Muskingum-Cunge routing technique was selected in the study and the parameters were derived from details of river cross-sections. For all the reaches the Manning's 'n' was taken as 0.030 and in flood plains 0.035.(Dyhouse et al, 1996). The predicted rainfalls from the WRF were given as spatial average of rainfall over each sub-basin to HEC-HMS.

2.3 Inundation Mapping

The flow prediction of the hydrologic model was used to map the inundation extent downstream of Pitabeddara up to Matara town. To obtain the water levels along the main river HEC-RAS 4.0 hydraulic model was used. Arc-Map was then used to prepare the inundation map.

Inundation mapping used digitized main river and a Digital Elevation Model from ASTER data. Along the main river cross-sections were defined. The lateral flows from tributaries were introduced to the main river at appropriate locations. The boundary condition at upstream the river at Pitabeddara was introduced as the hydrograph HEC-HMS for rainfall from WRF. The lower boundary condition was the normal depth with 0.001 energy gradient. Results from HEC-RAS were exported to Arc-GIS for two dimensional visualizations.

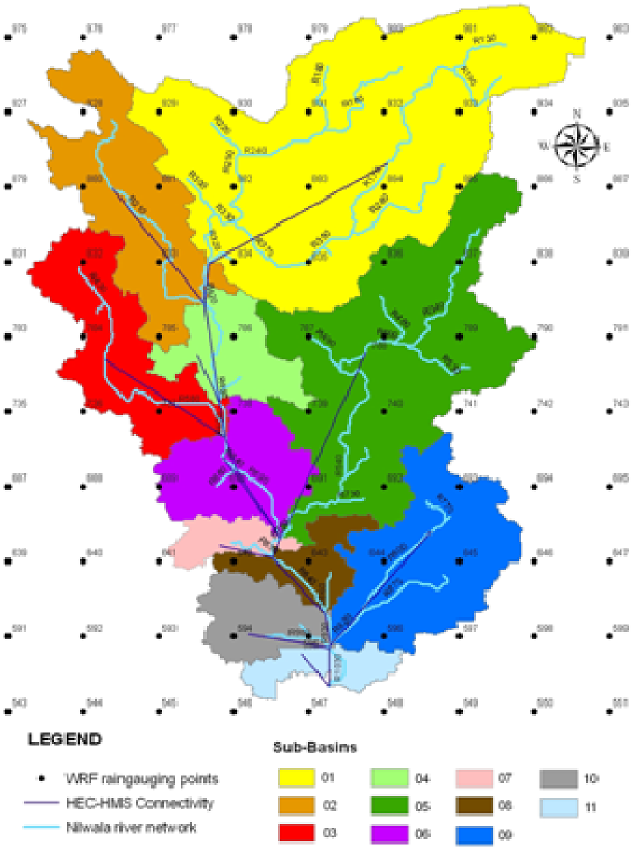


Figure 4 Sub-basin division of Nilwala Basin

Inundation corresponding to the flood event occurred on the 18-May-2003 was mapped. There flood maps were prepared for 16th,17th,18th and 19th of May-2003 with the discharges obtained from the HEC-HMS hydrologic model driven by the precipitation predicted by WRF weather model.

3. RESULTS AND DISCUSSION

Results of the investigation of impacts of microphysics schemes are given in Table 3. All the microphysics schemes (Lin et al, Kessler, Thompson, Morrison, WSM3, WSM6 and Ferrier) show high accuracy over the basin for event of 06/04/2009 while low accuracy for the event on 20/03/2009. The rain events on 10/12/2008 showed varying accuracy with different schemes. The Ferrier microphysics scheme is accepted as it was giving better results for all events.

Table 3. CPA % for different Microphysics schemes

Rain event	10/12/2008	20/03/2009	06/04/2009
Microphysics scheme	CPA %	CPA %	CPA %
Lin et al	66	55	88
Kessler	68	19	86
Thompson	40	37	88
Morrison	46	16	88
WSM3*	80	37	90
WSM6	50	13	86
Ferrier	71	84	91

*WRF 3.0 default option

When it comes to the cumulus schemes a clear pattern of prediction accuracy over the basin was not observed. The prediction accuracy changed spatially from event to event with different cumulus schemes used. The model default Kain-Fritsch cumulus scheme produced reasonably good results and therefore selected for modeling. In the case of land surface options all schemes have produced good predictions in all the three rain events. The RUC is selected as it was the most consistent scheme among the three models tested. The RRTM longwave radiation scheme with Dudhia shortwave scheme produced good rainfall predictions for the three events considered. These are the model default longwave and shortwave radiation options in WRF. Mellor Yamada and YSU planetary boundary layer schemes have shown very little influence on the spatial distribution of the accuracy of the predictions. Therefore the default scheme is selected.

According to the results of hydrologic modeling performances, the Snyder's transformation technique in HEC-HMS produced the best results for the Upper Nilwala basin in calibration and verification phases. Results of model validation with Snyder's transformation technique are given in Table 4.

Table 4. Results of model validation with Snyder's transformation

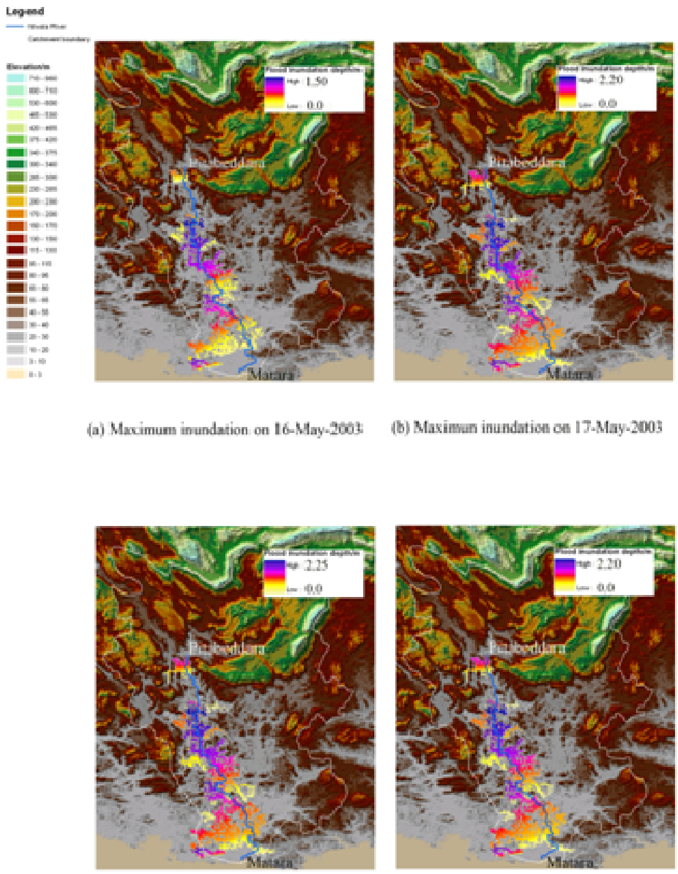
Model performance evaluation criterion	Rainfall-Runoff event (date of peak)		
	14-Jun-79	13-Jul-84	27-Sep-79
Nash–Sutcliffe efficiency %	76.14	51.31	57.75
Q Simulated /Q Observed	1.29	1.27	1.09
Peak Q Simulated/Peak Q observed	1.03	0.78	0.76

The inundation maps developed for the stretch of Nilwala River from Pitabeddara to Matara are shown in figure 5. Depths of inundation and corresponding areas affected have been given in table 5.

Table 5 Depths of inundation and corresponding areas affected

Depth of inundation/ m	Inundated area km 2			
	16-May	17-May	18-May	19-May
0.0-0.5	28.3	16.9	16.2	16.6
0.5-1.0	15.7	30.1	30.1	31.1
1.0-1.5	12.2	14.7	15.3	14.4
1.5-2.0	0.0	13.1	13.8	10.5
2.0-2.5	0.0	0.5	1.2	0.4
Total inundated area km ^{2}	56.1	75.3	76.7	73.1

The model was capable of predicting the inundated areas correctly as shown in Figure 5. The combined WRF – HECHMS model has underestimated the river discharge which was about 1000 m^3/s (Pacific, 2007) on the 18-May-2003 at Pitabeddara, according to the Department of irrigation but the corresponding discharge has been determined by the model as $664 m^3/s$. This is attributed to the model accuracies and improvement of the procedures is continuing.



(a) Maximum inundation on 16-May-2003 (b) Maximum inundation on 17-May-2003

(c) Maximum inundation on 18-May-2003 (d) Maximum inundation on 19-May-2003

Fig. 5 Inundation during the May 2003 flood

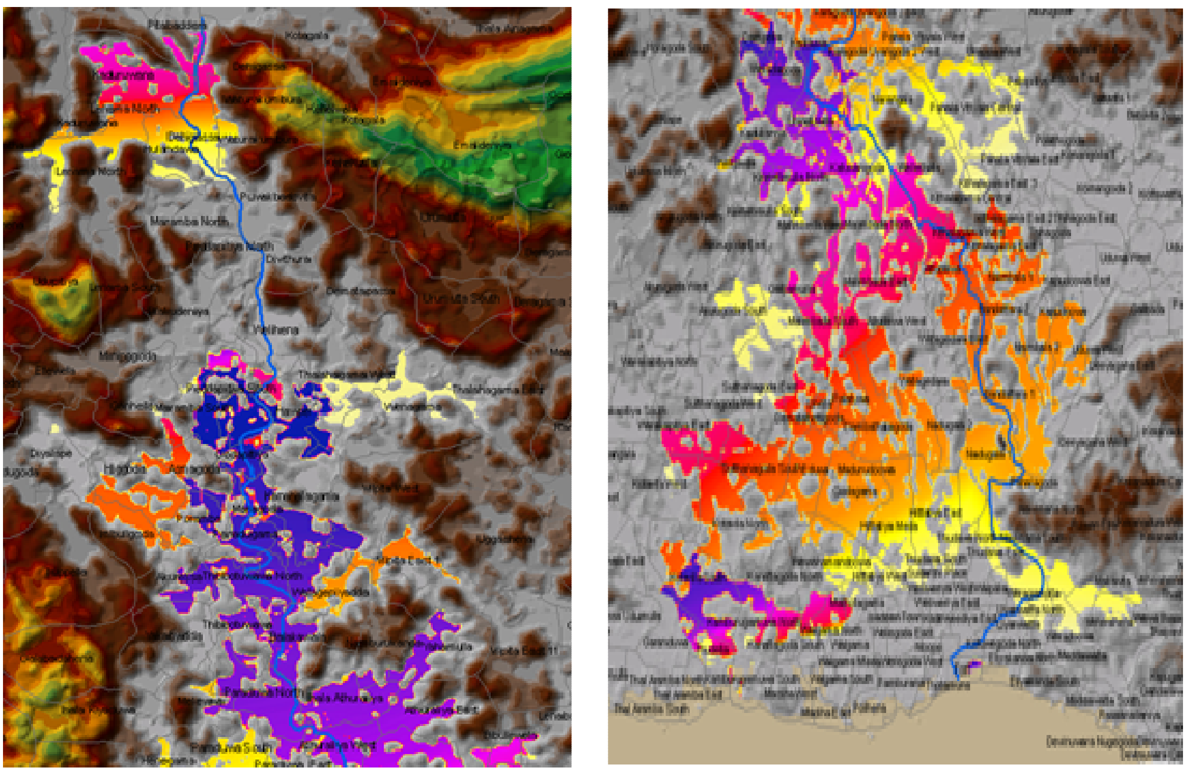


Fig 6 Maximum Inundation downstream of Pitabeddara

4. CONCLUSIONS

WRF Model and HECHMS model configuration for accurate flood prediction was thoroughly studied. It could be concluded that the model physics combination consisting of Ferrier microphysics scheme, Kain-Fritsch cumulus scheme, RUC land surface scheme, RRTM longwave radiation scheme, Dudhia shortwave scheme and YSU planetary boundary layer scheme has yielded better precipitation predictions over the Nilwala river basin. However, the total rainfall failed to generate the observed runoff indicating the model under estimated the total rainfall. The model was capable of predicting the inundation area with reasonable accuracy. This technique can be used to downscale GCM results to predict floods within reasonable accuracy.

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