

Chapter 1

Application of Hydrologic Modelling System (HEC-HMS) for Flood Assessment; Case Study of Kelani River Basin, Sri Lanka



S. Rajkumar, S. K. Mishra, and R. D. Singh

1.1 Introduction

Hydrology defines that it is a scientific study of water. It is the science that associates with the occurrence, circulation, and distribution of water of the earth and earth's atmosphere. One of the most crucial water sources of the earth is rainfall, extreme of which causes flood disaster. The rainfall characteristics are the temporal and spatial distribution of the rainfall quantity (Jain et al. 2000). The runoff estimation is a crucial aspect of watershed planning (Kumar et al. 2004). Hence the study of transformation from rainfall to runoff also referred to as rainfall-runoff modelling, watershed modelling or hydrological modelling is highly necessary for the academic background of water resources engineering for the mitigation measure against flood disaster and the future development of water resource structure.

There are numerous sources currently available for the application of rainfall-runoff modelling. However, the modern rapid developed technology and software tools assist water resource professionals to model the natural phenomena. The software tools, such as Hydrology Energy Centre-Hydrological Modelling System (HEC-HMS) and Geographical Informatics System (GIS) are simultaneously employed in such modeling tasks nowadays (Nandalal and Ratnayake 2010). The software tool requires various data for its input to run the model systematically.

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A. Pandey et al. (eds.), *Hydrological Extremes*, Water Science and Technology Library 97, https://doi.org/10.1007/978-3-030-59148-9_1

The system of hydrological modeling requires a set of meteorological data (rainfall, etc.), hydrological data (streamflow), and spatial data (topography, land use land cover and soil type) of the relevant basin. Mostly, it is obvious that precise temporal data and high quality of spatial data are not affordable. It is, therefore, a huge challenge in the application of those data with rainfall-runoff modelling. However, the lumped conceptual models which are not much expecting the higher accuracy of data is applied in this assessment. The modelling HEC-HMS is also one of the lumped conceptual model categories (Nandalal and Ratnayake 2010).

According to the available temporal and spatial data of the Kelani river basin, the objectives are (i) Application of HEC-HMS for event base modelling to simulate the Flood Hydrograph of different events in Kelani river basin. (ii) Calibration and validation of various flood simulation models of HEC-HMS. (iii) Comparison of the simulation results based on different objective functions to select a suitable model for flood simulation. (iv) Formulate real-time flood forecast at the Hanwella gauging site to provide the advance information about the flood for its management.

In order to manage the frequent occurrence of floods, the Govt. of Sri Lanka is planning to take immediate steps to safeguard the capital of the country from this frequent flood menace by adopting suitable structural and non-structural flood mitigation measures, such as (i) Diverting the flood water through a constructed channel at Hanwella gauging station minimizing the floods in the downstream, (ii) Providing embankments and levees along the both riverbanks for flood protection, and (iii) Real-time flood forecasting for the evacuation of the people from the areas likely to be affected during the floods.

For adopting measures, the flood assessments are required analyzing the rainfall-runoff data of flood events occurred in the Kelani river basin. For this purpose, it is required to understand the rainfall-runoff mechanism considering the historical rainfall-runoff events observed in the Kelani river basin. (Silva et al. 2014). Thus, the flood assessment in the Kelani River basin is very much imperative for the water managers and decision-makers since the Kelani river is frequently hit by flood due to south-west monsoon storm.

1.2 Study Area

Kalani river is the second largest river of Sri Lanka. Its catchment area up to Hanwella gauging site is 1836 km² which covers five districts namely Colombo, Gampaha, Kegalle, Ratnapura, and Nuwara-Eliya. In the catchment, the topographical elevations vary between 16 and 2320 m above mean sea level. The contributions of the flow to the river come from the rainfall mostly occur during the two distinct monsoon seasons, i.e. north-east and south-west monsoon. The Administrative Capital 'Sri Jayawardanapura' and the Commercial Capital 'Colombo' are located in the downstream of the Hanwella gauging site. The district Colombo in Western Province with the current population of 300 head per day has an area of 699 km² with a population

of 2.3 million and has population density likely to be 60 times the average population density which is 340 heads per km².

Figure 1.1 shows the gross basin of Kalani river and the locations of gauging station over the basin. The calibration and validation process is set up with the observed streamflow data of Hanwella gauging station. Therefore, all the data processing is carried out in the upper catchment of Hanwella gauging station (Figs. 1.2 and 1.3). It is referred to as Kalani river basin in this study.

Kelani River in Sri Lanka is being contributed with runoff from both monsoon seasons rainfall, but the major share of its flow contribution is due to the rainfall during south-west monsoon season. The district Colombo frequently experiences

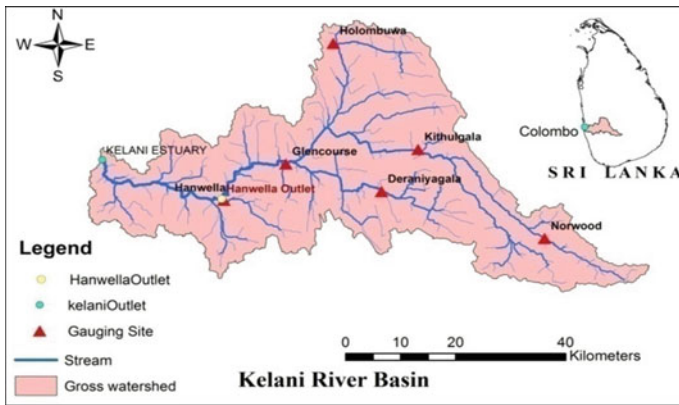


Fig. 1.1 Gross basin of Kelani river

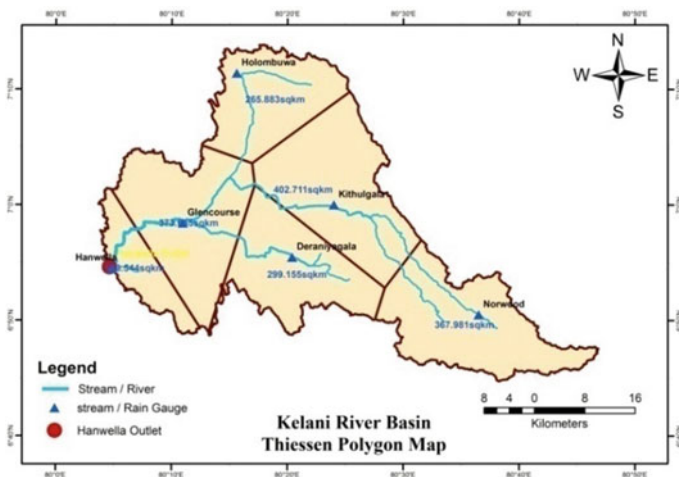


Fig. 1.2 Thiessen polygon map

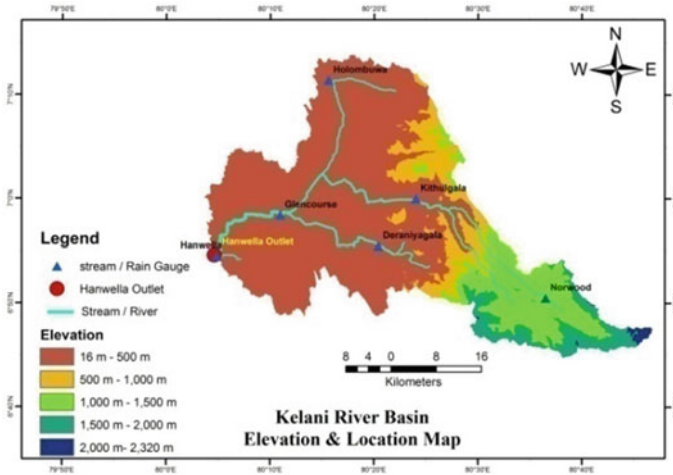


Fig. 1.3 Gauging station and elevation map

flood menace almost every year. It causes loss to the lives and severe damages to infrastructures, properties and ultimately livelihood of the communities residing in district Colombo. Thus, the economic growth of Sri Lanka dramatically reduces due to the extensive damages caused by frequent flooding.

1.3 Data Availability and Data Processing

1.3.1 Temporal Data and Processing

Meteorological data (rainfall) on daily basis and hourly basis for selected extreme flood events and Hydrological data (discharge only on daily basis and water level on daily basis and on an hourly basis for selected extreme flood events) at six (06) gauging stations (shown in Fig. 1.1) namely Hanwella, Norwood, Deraniyagala, Kithulgala, Holombuwa, and Glencourse located in the upper basin have been obtained. These data have been obtained from the Dept. of Irrigation, Colombo, Sri Lanka for model calibration and validation. The event-based model calibration and validation is carried out by considering the flood events that occurred in the recent past years (Table 1.1).

The event base modelling calibration requires hourly streamflow data. Because of non-availability of this hourly data, from the observed discharge data and the corresponding stages, stage discharge relationship, which is known as Rating Curve, for the gauging station Hanwella is developed. Then from the computed equation, the hourly discharge is accounted for corresponding stages at the gauging site Hanwella.

Table 1.1 Flood events considered

Flood events	Duration in days
May 2017	14
May 2016	30
December 2014	8
June 2014	16
November 2012	9

The data of the daily gauge and corresponding observed discharge are available for the Hanwella gauging site. Those data are used to develop the rating curve in the following form using analytical as well as graphical approaches:

$$Q = a \cdot (H - H_0)^b \quad (1.1)$$

where Q is river discharge in m^3/s , H is river stage measured in m at the gauging site, H_0 represents the stage reading corresponding to the zero discharge, a and b are the constants which may be computed analyzing the available stage and corresponding discharge data. In the analytical approach, simple linear regression analysis has been carried out transforming the data in the log–log domain whereas in the graphical method the observed stage and corresponding discharges are plotted on arithmetic or log–log scales. The form of the rating curve developed using analytical approach is $Q = 31.48(H - 0.48)^{1.696}$ with ($r^2 = 0.983$) whereas it is in the form of $Q = 21.38(H - 0.48)^{1.63}$ with $r^2 = 0.941$ developed using the graphical method. The rating curve, developed by analytical method, is used to convert the hourly observed gauge values to the hourly discharge values for all the flood events considered for analysis. The hourly average rainfall values for all those flood events are computed from the hourly rainfall values observed at six rain gauge stations using the option of Thiessen polygon method (as shown in Fig. 1.2) available in HEC-HMS programme.

1.3.2 Processing of Spatial Data

The digital elevation model (DEM) and Satellite Image of 30 m resolution, which is available in the United States Geological Survey (USGS) website have been downloaded. The DEM is the fundamental input of the HEC-GeoHMS tool to develop the basin model of this study area and the soil data map. The satellite image has been employed to develop land use land cover map. Figures 1.4 and 1.5 illustrate the spatial distribution of land use/land cover and soil type of the Kelani river basin, respectively.

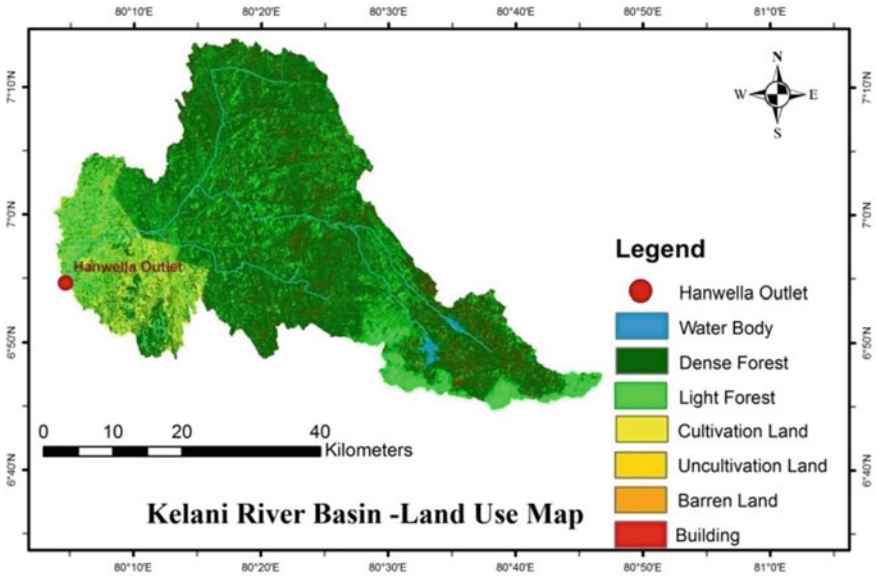


Fig. 1.4 Land use land cover map

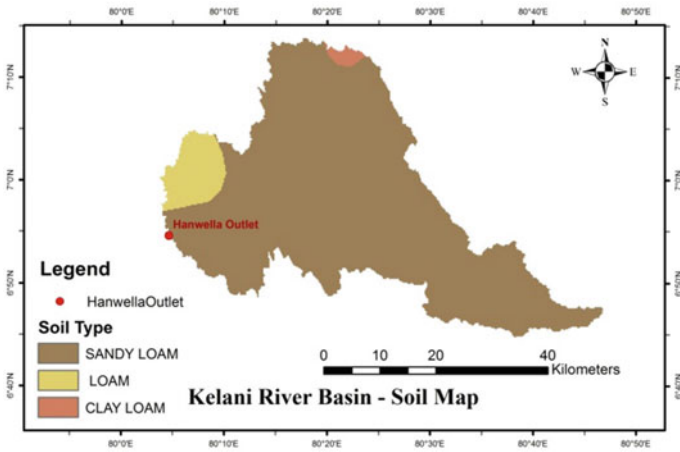


Fig. 1.5 Soil map

1.4 Methodology

The entire modelling exercise has been carried out using software namely HEC-GeoHMS and HEC-HMS. HEC-HMS process along with the steps for its calibration and validation is illustrated in the form of flow chart as shown in Fig. 1.6.

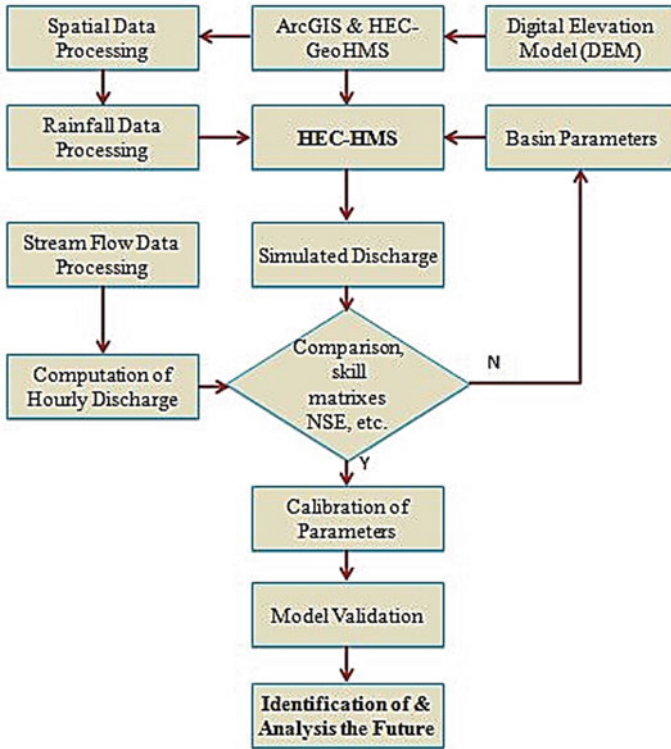


Fig. 1.6 Flow chart for HEC-HMS process

1.4.1 HEC-Geo HMS and HEC-HMS

HEC-Geo HMS is Geospatial Hydrological Modelling System, the extended supplementary application tool of ArcGIS and used to develop basin model and its characteristics from the raw digital elevation model (DEM). Then the developed basin model in HEC-Geo HMS is imported to HEC-HMS for its further application. HEC-HMS is the simulation software developed to simulate all types hydrological processes of river basin (Sampath et al. 2015) It is available as online resource software designed by the US Army Corps of Engineers (USACE) with updated versions and treats user-friendly manner. The model consists of the following components:

Basin Model and Meteorological Model

Basin model is developed by HEC-GeoHMS as a single basin and used for the calibration and verification process. The required basin characteristics such as longest flow path, river lengths, upstream and downstream elevations and slopes of each river segments are obtained via this HEC-GeoHMS application process. Meteorological model is created by selecting the gage weight option available in this HEC-HMS

model. Gage weights, which have been estimated from Thiessen polygon method, are used for this option.

Base Flow Model

The following three base flow model's options are available in HEC-HMS to serve the model running for each event:

- Constant, monthly varying base flow
- Exponential recession model
- Linear reservoir model.

In this application, exponential recession model option is used for the base flow model. Initial discharge, recession constant and threshold discharge are the parameters for this option. The base flow is separated from the ordinates of hourly flow hydrograph in order to obtain the hourly direct surface runoff hydrographs for each flood event.

Loss Model

There are numerous runoff volume models also known as loss models are applicable in HEC-HMS modelling.

- Initial and constant rate loss model
- Deficit and constant rate loss model
- SCS curve Number (CN) Loss Model
- Green and Ampt Loss Model
- Soil Moisture Accounting (SMA) Loss Model.

In the application of loss model, the method initial loss and constant rate is used. This method includes two parameters, such as initial loss and constant loss rate. Those parameters depend on the physical properties of the river basin soil, land use and the antecedent moisture condition in the basin. The calibrated loss model is used to estimate the excess rainfall hyetograph subtracting the losses from the average rainfall hyetograph for each flood event.

Direct Runoff Model (Transform Model)

The HEC-HMS programme facilitates various transform models to estimate the direct surface runoff hydrograph from the excess rainfall hyetograph. The following three transform models are used in HEC-HMS:

- Clark UH model
- SCS UH model
- Snyder UH model.

Clark UH Model

The use of Direct Runoff model—Clark UH (Clark 1945) is requires the following input as initial parameters in addition to the time—area diagram (Singh et al. 2014).

- Time of concentration T_c
- The storage coefficient, R .

The properties of time-area histogram or time-area percent curve of the basin.

The time of concentration T_c and the storage coefficient R are estimated from observed flood hydrograph available to employ as initial parameter values. There is an option available in the software to compute the ordinates of time-area diagram synthetically. Alternatively, the time-area diagram developed for the basin may be supplied as input replacing the synthetic time-area diagram. In this study, the time area diagram has been developed using ArcGIS software tool adopting Kriging Interpolation method.

SCS UH Model

For this model, only one parameter, known as basin lag, is available under direct runoff model. The initial value of the parameter is found from the observed flood hydrograph.

Snyder UH Model

For this model two parameters, Peaking Coefficient C_p and Standard lag t_p are available under direct runoff model. The initial value of this parameter C_p is taken as 0.3 which is minimum of its possible values described in HEC-HMS technical reference manual. The Standard lag t_p is taken from observed flood hydrograph.

1.4.2 Calibration of Model

Calibration of the model is done in two ways such as manual calibration (trial and error) and computer automatic calibration (optimization). However, the initial parameters of the individual model should be fed before simulating the model. Certain parameters have been estimated from observed flood hydrograph and some have been obtained from temporal and spatial data processing. The calibrations of the model have been done based on the various goodness of fit measures derived from the observed and simulated hydrographs in HEC-HMS programme. Based on these measures, the suitable methodologies are selected. The algorithms developed inside this modelling software estimate the optimum model parameters based on the various good of fit measures as an Objective Function. The choice of objective functions depends upon the necessity of the analysis. In the HEC-HMS, there are two options available for optimization which is based on search method. Those are Univariate-Gradient Algorithm and Nelder and Mead Algorithm.

1.4.3 Comparison of Three Direct Runoff Models

Although there are plenty of objective functions available in this software, NSE, Percentage Error Peak, Percent Error Time to Peak and Percent Error Discharge volume (Volume Deviation D_v) are applied for the quantitative approach of model evaluation.

Nash–Sutcliffe Model Efficiency Coefficient is defined as

$$NSE = 1 - \left[\frac{\sum_{i=0}^n (Q_{obs}(i) - Q_{com}(i))^2}{\sum_{i=0}^n (Q_{obs}(i) - \bar{Q})^2} \right] \quad (1.2)$$

where Q_{obs} , Q_{com} and \bar{Q} are the observed, simulated and observed mean discharge over the n hours, respectively. And the optimal value of NSE is 1.

Volume Deviation

$$D_v = \left| \frac{(V_{obs} - V_{com})}{V_{obs}} \right| \times 100\% \quad (1.3)$$

where V_{obs} and V_{com} are the observed and simulated volume of runoff over the n hours, respectively. And the optimal value of D_v is 0.

Percent Error in Peak

$$Z = \left| \frac{Q_{obs(peak)} - Q_{com(peak)}}{Q_{obs(peak)}} \right| \times 100\% \quad (1.4)$$

where $Q_{obs(peak)}$ and $Q_{com(peak)}$ are the observed and simulated peak discharge of runoff over the n hours, respectively. And the optimal value of Z is 0.

The NSE was reported as best performance criteria of simulation so far (Cuen et al. 2006). However, in addition to the NSE, percent error in peak, percent error in time to peak, percent error in discharge volume of each direct runoff model was compared in this study individually, of the number of extreme flood events considered.

1.5 Analysis and Results

1.5.1 Calibration and Validation

For the calibration and validation of HEC-HMS model for Kelani river basin, five number of extreme flood events occurred in the basin, are considered. The details about those flood events are given in Table 1.1. The flood events of May 2017, May 2014, December 2014 and June 2014 are employed for calibration by automatic

option also referred to as optimization and the event of November 2012 is employed for validation.

All flood events considered to run the model have been observed during the period of south-west monsoon. The initial loss has been taken as zero as the soil moisture used to be saturated during the south-west monsoon season due to continuous rainfall usually observed in the basin. The constant rate is computed by equating the excess rainfall volume with direct runoff volume from the observed flood hydrograph with separation of base flow. This constant loss rate is found to be approximately 1 mm/hr which is considered as an initial estimate for HEC-HMS for running the optimization option. The imperviousness value in percent is required in the model as input to complete the loss model setup. Land use land cover map (shown in Fig. 1.4), developed in ArcGIS, provides the percent of impervious area as a function of land use. The basin predominantly covers with vegetative of light forest and dense forest with around 85% of the area. Only a small extend of basin covers with urban buildings. This imperviousness percent is obtained as 4% of the land use land cover map.

In addition to that the constant rate may be estimated if the soil type existing over the basin is known. The constant loss rate is the function of soil type of the basin. The soil map is prepared using ArcGIS by downloading the soil base data from the on-line resource of Food and Agriculture Organization (FAO) and shown in Fig. 1.5. This covers predominantly by sandy loam with 93% of the basin area. The range of loss rates for different soil class is described in the Technical Manual of HEC-HMS. However, a suitable value from this applicable range has been adopted to setup in the model as an initial parameter for the constant loss rate.

The direct surface runoff hydrographs are computed separating the base flow from the observed flood hydrograph for each flood events. For this method of base flow separation, the initial value of the recession constant is derived as 0.9 whereas the initial values of the initial discharge and threshold discharge are obtained as 39 m³/s and 214.8 m³/s, respectively from the observed flood hydrograph to employ as base model initial parameters.

For Clark model, the initial parameter values of Tc and R, taken as 18 hrs and 50 h, respectively, extracted from observed direct surface runoff hydrographs of various flood events. The percent curve for the time-area diagram has been computed using Kriging Interpolation method and used in HEC-HMS software. Figure 1.7 shows the isochrones of Kelani river basin developed using the Kriging interpolation technique option of ArcGIS. For SCS UH model, the initial parameter value of Lag time is obtained as 2350 min from the observed flood hydrograph. For Snyder UH model, initial parameter value of Cp is taken as 0.3 from the technical reference manual of HEC-HMS whereas initial parameter value of standard lag is taken as 22 h from the observed flood hydrograph.

The HEC-HMS programme has been run optimizing the various parameters considering the option of Clark Model as a transform model. Similarly, SCS UH and Snyder UH models are also calibrated using the HEC-HMS programme. The parameter values obtained from the calibration of four events are averaged out and used for the validation for the fifth event for all three transform models. Table 1.2 shows the values of the average parameters obtained from calibration of the three

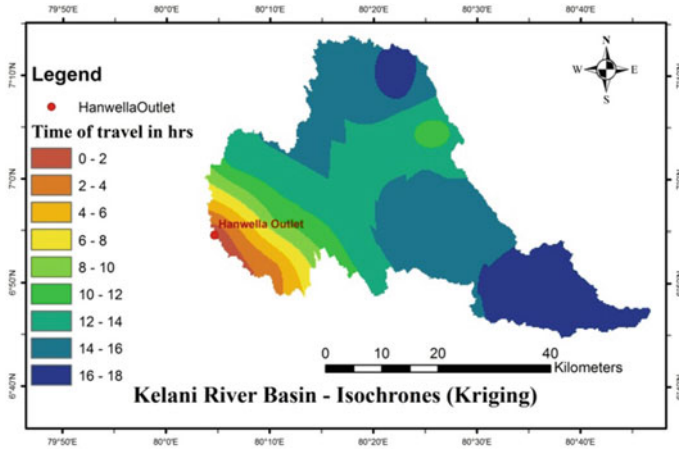


Fig. 1.7 Isochrones of Kelani river basin (Kriging interpolation method)

Table 1.2 Average of the parameters obtained from calibration of three transform models

Parameters	Average of optimized (auto-calibrated)
Clark UH—Time of concentration T_c in hrs	13.0
Clark UH—Storage coefficient R in hrs	39.0
SCSUH—Lag time in minutes	1868.2
Snyder UH—Peaking coefficient	0.3
Snyder UH—Standard lag in hrs	14.9
Recession—Initial discharge in m^3/s	45.8
Recession—Recession constant	0.8
Recession—Threshold discharge in m^3/s	206.3
Initial and constant—Initial loss in mm	0.0
Initial and constant—Constant rate mm/hr	0.9

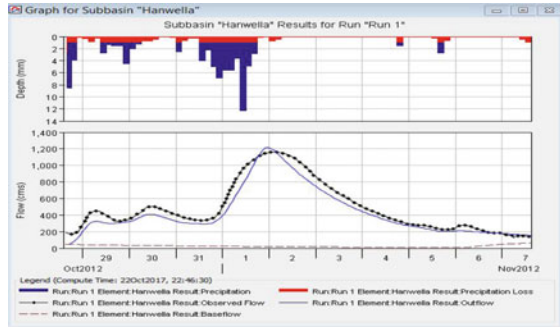
different transform models for four flood events. These average values are used for validating the fifth event.

The performance of the three transform models is judged based on the comparisons of the different goodness-of-fit criteria computed from the simulated and observed

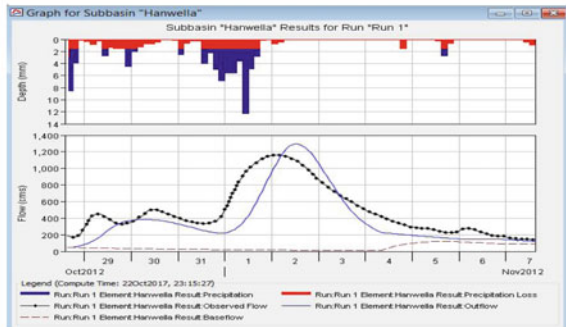
flood hydrograph of the flood event at Hanwella gauging site considered for validation. Figure 1.8a, b and c illustrate the rainfall-runoff simulation of Hanwella gauging station after validation for the Clark UH, SCS UH and Snyder UH direct runoff model, respectively.

From the Fig. 1.8a, b and c, it is observed that the Clark UH model performed very well as the simulated flood hydrograph closely matches with the observed flood

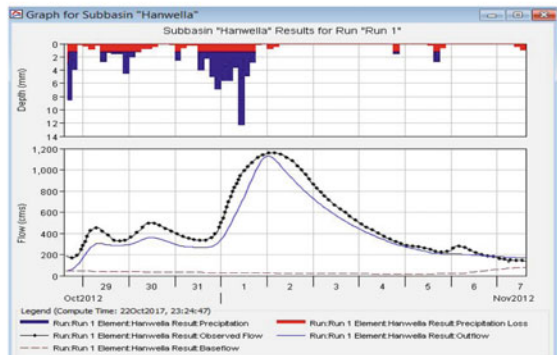
Figure 1.8 a Simulation by Clark UH. b Simulation by SCS UH. c Simulation by Snyder UH



(a)



(b)



(c)

Table 1.3 Nash–Sutcliffe model efficiency (NSE) values obtained from calibration and validation

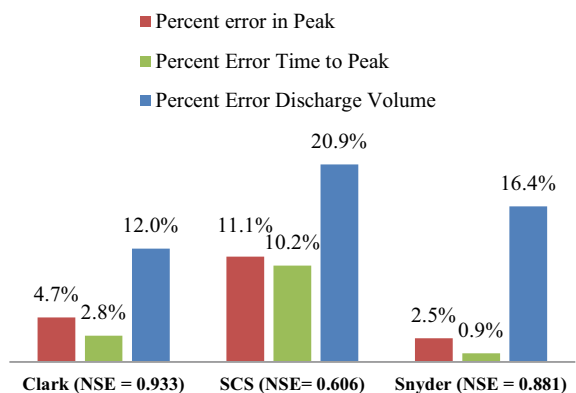
Computation	Event	Direct runoff model		
		Clark UH	SCS UH	Snyder UH
Calibration (optimization)	2017 May	0.97	0.468	0.97
	2016 May	0.88	0.62	0.84
	2014 Dec	0.96	0.76	0.96
	2014 Jun	0.94	0.52	0.98
Validation	2012 Nov	0.93	0.61	0.88

hydrograph during the validation as compared to the other two models, i.e. SCS UH and Snyder UH models. The performance of the SCS UH model is poor as compared to the other two models. To judge the performance of transform models based on the NSE, their computed values obtained during calibration and validation are given in Table 1.3. From the Table 1.3, it is also observed that the performance of the Clark UH model is best based on the NSE values computed as its value is 0.93, which is highest, whereas it is 0.88 and 0.61 for Snyder UH and SCS UH models.

The values of the various Goodness of fit criteria such as NSE, percent error in peak, percent error in time to peak and percent error in discharge volume are compared for the three transform models as shown in Fig. 1.9.

Figure 1.9 shows the value of percent error in discharge volume is minimum for Clark UH model as compared to the other two models. It indicates better simulation of the flood hydrograph. However, the values of percent error in peak and percent error in time to peak for Clark UH model is slightly higher than that of Snyder UH model. Nevertheless, Clark UH model has resulted in the best simulation of the flood hydrograph based on the computed values of NSE for the three models considered for analysis during the validation.

Fig. 1.9 Comparison of Percent Errors from different transform models for the flood events used for validation



1.6 Conclusions and Recommendations

The conclusions are drawn, and recommendations made from the study are as follows:

- (i) ArcGIS software used the USGS satellite's data at 30-m resolution for preparing the land use and land cover map, soil map, and isochrones maps. However, better maps may be generated if the high-resolution data are used.
- (ii) HEC-GeoHMS used for basin modelling is capable of preparing basin maps and providing physiographic and other important geomorphological characteristics of the basin. These maps are the input for HEC-HMS.
- (iii) HEC-HMS has the capability of flood simulation using various transform models including Clark model, Snyder model and SCS-CN model. The HEC-HMS has been successfully applied for simulating the five flood events observed in Kelani river basin (up to Hanwella Gauging Site). From the results, Clark model is recommended for simulation of flood events for this basin.
- (iv) The calibrated and validated model may be applied for the estimation of design flood for taking suitable structural measures to protect the important cities and installations in the downstream of Hanwella Gauging site. It may also be used for non-structural measures, such as real-time flood forecasting to issue flood warning to stakeholders to take necessary actions to evacuate the people, likely to be affected due to floods, for saving their lives and properties.

Acknowledgements The authors would like to acknowledge the opportunities provided by Indian Water Resource Society (IWRS) and Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee 247667 to present this paper in the International Conference on "SUSTAINABLE TECHNOLOGIES FOR INTELLIGENT WATER MANAGEMENT" during February 16 to 19, 2018. The authors also thank to the Department of Irrigation, Sri Lanka for providing the required data for the study.

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