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Floodplain Zoning and Mapping for Lower Kelani River, Sri Lanka

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Abstract: Flood risk mapping and floodplain zoning are emerging as practical tools to reduce flood damage. The study intended to develop floodplain zoning maps in the lower Kelani River basin using Flood frequency analysis and MIKE 11 modeling. Flood quantiles estimated for River gauging station at Hanwella and Lower Kelani basin have been used for the flood map developments. The river gauge at Hanwella to the estuary River strip has been considered for floodplain zoning using MIKE 11 modeling software. The hydrologic modeling was performed using MIKE 11 Nedbor Afstromnings Model (NAM), while the hydraulic modeling was performed using MIKE 11 Hydro-Dynamic (HD) model. MIKE 11 rainfall-runoff (RR) NAM calibration and validation Nash-Sutcliffe efficiency (NSE) results were 0.766 and 0.607, respectively. Similarly, coupled NAM and HD model on Mike-Zero platform calibration and validation NSE results were 0.917 and 0.871, respectively. The return period floods estimated to the Hanwella River gauge and Lower Kelani River basin have been availed to generate flood inundation maps. Finally, the flood plain zoning maps have been developed for the Lower Kelani River for 10-, 25-, and 50-year return periods. These maps can be use to limit cultivations and reduce crop losses during monsoons.

Keywords: Flood Plain, MIKE 11, NAM model, HD model

1. Introduction

Floodplain zoning maps and River cross-sectional boundaries are essential non-structural techniques for planning and improving agricultural fields along Rivers to avoid flood damage [1]. A floodplain zoning map often depicts the region inundated by a flood of a specific frequency, known as the 'regulatory flood' [2]. Floods have the potential to inflict fatalities, relocations, and environmental damage, all of which can jeopardize economic progress [3], [4], [5]. Assessment of the maximum flood discharge at an intended location on a River is essential for designing hydraulic structures, managing floods, and developing flood zoning maps. Fitting probability distributions can achieve maximum flood discharge to the observed annual maximum discharge data in frequency analysis or by applying deterministic models [6]. Vogel and Fennessey (1993) demonstrated that L-moment ratio estimators are not limited to small datasets and are substantially unbiased for all underlying distributions [7]. The probability-weighted moment-based L-moment method is robust to estimate the flood quantiles of an annual peak flood series. Flood quantiles and simulating hydrodynamic models have predicted the spatial extent of flooding for different return periods. Hydrologists have endeavored to build up an assortment of methods for mapping floodplains. Floodplain information can be used to determine whether a given approach is acceptable to the extent that it meets the user's objectives. In the last 50 years, research studies have identified three possible ways to integrate hydraulic modal and Geographic Systems (GIS) to interpret the result of the hydraulic model. Three possible methods of system integration may be identified as (a) loose coupling, (b) tight coupling, and (c) fully integrated [8]. Loose coupling: Hydraulic models' ASCII file transfer to the GIS system has been very popular among hydrologists and hydraulic engineers. To mimic the natural process, the complicated hydrological cycle is described more succinctly using hydrologica

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Scientists have created flood inundations in l modeling [9]. watersheds over the recent decades using hydrodynamic modeling techniques [10]. A physically based deterministic hydrodynamic model developed for MIKE 11 can provide discharge, stage, and their relationships in a River network [11]. Similarly, the MIKE 11 HD model simulation produces an ASCII file that can be transferred to the GIS system.

Sri Lanka is a tropical country in the Indian Ocean and is prone to various hazards, such as landslides, floods, and droughts. As a country based on agriculture, paddy is the main crop that provides the staple food rice to the nation. Paddy is often cultivated in flat flood plains fed by irrigation water or direct rainfall. During the monsoon season, Rivers overflow, inundating agricultural lands. This situation has been aggravating in recent decades because of how climate change affects it. This has a detrimental effect on paddy cultivation, and farmers lose their livelihoods. Information such as flood risk mapping and plain zoning is useful for farmers and authorities to plan cultivation seasons to minimize crop damage.

Colombo is one of the most populous of the 25 administrative districts in Sri Lanka and is most vulnerable to floods. The May 2016 floods affected over five million people, killing 101 and leaving 100 missing due to floods and landslides. It destroyed hundreds of hectares of farmland and homes [12]. The primary reason for such damage from floods in the Kelani River was the encroachment of the plains for urban development by filling the lands.

This research aims to provide a robust methodology that can be used to create flood zones in any part of the country. The method consists of four steps. (i) On-site flood frequency analysis; (ii) Mike 11 NAM model simulation; (iii) Integrated MIKE 11 NAM and HD model simulation; (iv) Simulation of MIKE 11 HD models to generate flood zoning maps for different return periods. The following chapters will provide detailed guidelines about this method and its application to the lower Kelani River basin in Sri Lanka.

2. Scope of the Study

As per the scope of this study, the research aims to communicate to administrative district leaders, politicians, and the general public about the importance of floodplain zoning for Sri Lanka and introduce a robust method to develop flood zoning maps for different return periods. Primarily, in the literature review, the researcher identified only a few previous studies on the selected topic in Sri Lanka [13], [14]. Out of the many methods introduced worldwide, a prominent method is selected in this research, suitable for Sri Lanka considering the data availability. The methodology has been applied to the Kelani River basin.

3. Description of Study Area

Kelani River originates from the Sri Pada (Adam's Peak) in the central portion of Sri Lanka [15]. Kelani River, the fourth longest River in Sri Lanka, has a total basin area of 2276 km^2. The catchment lies within the wet zone, and the average annual rainfall in the wet zone is more than 2500 mm. The basin has the highest annual rainfall in the country (Malliboda 5330 mm). The river basin receives rain throughout the year, but from May to June and from October to December receives heavy rainfall. The Kehelgamu Oya, Maskeli Oya, Wee Oya, Gurugoda Oya, and Seethawaka River are the main tributaries that connect to the Kelani River. Throughout the dry season, River discharge fluctuates from 20 m^3/s to 25 m^3/s, while throughout monsoons, River discharge fluctuates from 800 m^3/s to 1500 m^3/s. The basin's upper reaches consist of three reservoirs that regulate the natural flow to generate hydroelectric power. The river is perennial. Generally, the River flow consists of clear water, but during monsoon, the river flow turns muddy. The upper part of the basin consists of a tropical forest reserve, and the lower region consists of an urban area. Generally, the basin consists of fertile soils. Soil fertility and flat terrain in the middle part of the basin are suitable for agriculture. As a result, cultivation occurs in the plains along the river and flood plains. The lower part of the river (i.e., from Hanwella to the mouth of the sea) has been taken up for study. The river section is about 32 km long. The detailed basin map is shown in Figure 1.

4. Data Used

Data was collected from various organizations and used for the study. Hydro-meteorological data and bathymetric data, i.e., rainfall, discharge, evapotranspiration, water level and River cross-section data, were obtained from the Irrigation Department, Sri Lanka. Annual Peak Flood (APF) data (1987-2014) at the Hanwella River gauge station was used for Flood Frequency Analysis (FFA). Despite the long-term data, it was not easy to select a gap-free period for all 13 rain gauges. Daily rainfall

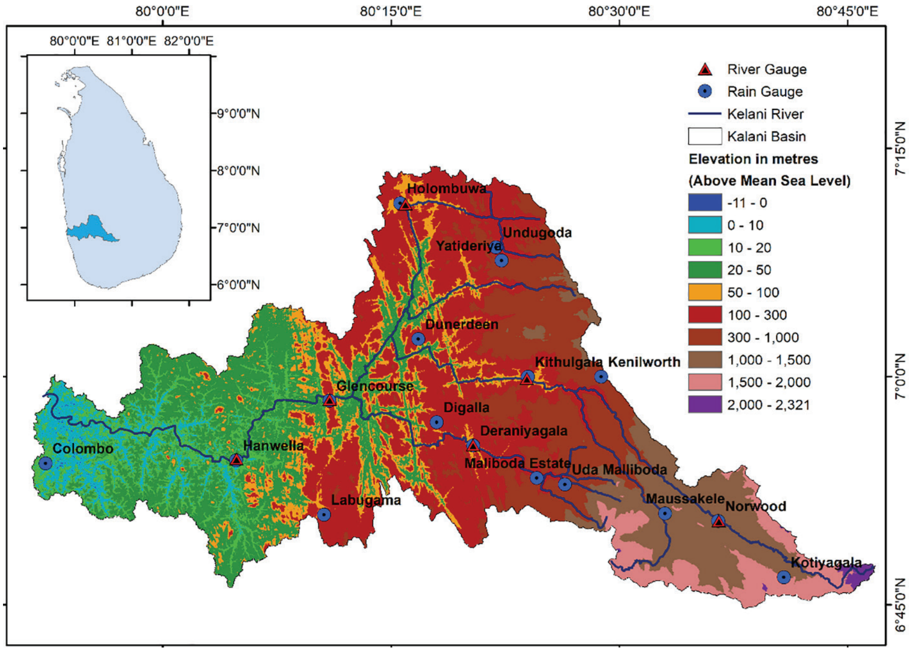

Figure 1 – Location Map of the Kelani River

data (1987-2014) were collected from 14 locations in Kitulgala, Norwood, Maussakelle, Kenilworth, Kotiyagala, Deraniyagala, Labugama, Hanwella, Holombuwa, Malliboda, Yatideniya, Nortonbridge, Colombo and Dunedin. The data period has been selected considering data availability and the absence of gaps.

The weighted average rainfall contributions from each gauge station were computed using the Thiessen polygon method with the help of ArcGIS. Figure 1 shows the locations of the gauging stations used for the study. Observed River discharge data at Hanwella and Glencourse stream gauge stations for four years, i.e., 1997 to 2000, have been used as discharge time series inputs for NAM model simulation. Bathymetric data from Glencourse to Sea mouth, have been collected from the Irrigation Department of Sri Lanka. The data screening procedure introduced by Iresh (2020) was adapted before using rainfall data for the RR modeling [16], [17].

5. Methodology

This study used ArcGIS and DHI-MIKE 11 software to generate flood maps for different return periods. Hanwella River gauge station in the Kelani River basin has been used to conduct an extensive study to determine the return period flood using the APF series. Initially, APF data outlier analysis [18], trend analysis [19], [20], and serial independence (randomness) analysis were estimated prior to using data for the FFA. The best-fit distribution for the APF series has been estimated using the L-moment diagram method introduced by Hosking and Wallis (1993) [21]. The DHI-MIKE 11 NAM model was developed for the Glencourse to Hanwellasub-basin and the model was calibrated and validated. Subsequently, daily flow series was developed for the lower Kelani River basin (Hanwella to Sea) using the calibrated model parameters and observed rainfall and evaporation data. FFA was conducted for the Lower Kelani River basin to estimate the return period flood. Glencourse to Hanwella, River strip flow data and bathymetric data were utilized to calibrate and validate the hydrodynamic model. Finally, DHI-MIKE 11 HD model was simulated with FFA return period floods to generate the flood zoning maps for different return periods using calibrated Manning's 'n'. The step-by-step method adopted in developing flood zone maps is presented in Figure 2.

5.1 Flood Frequency Analysis

One of the assumptions of FFA analysis is that annual maximum flood peaks are independently and identically distributed [22]. FFA is a recommended statistical method developed to estimate the flood quantile using the APF series. The Hanwella gauge station observed APF series and Lower Kelani basin simulated daily River flow data have been utilized to assess the return period floods of 10, 25, and 50 years. Statistical parameters of the APF have been estimated for the series and used for the flood frequency analysis. The FFA conducted by Iresh (2019) [15] has been used for this research as input data for hydrodynamic modeling.

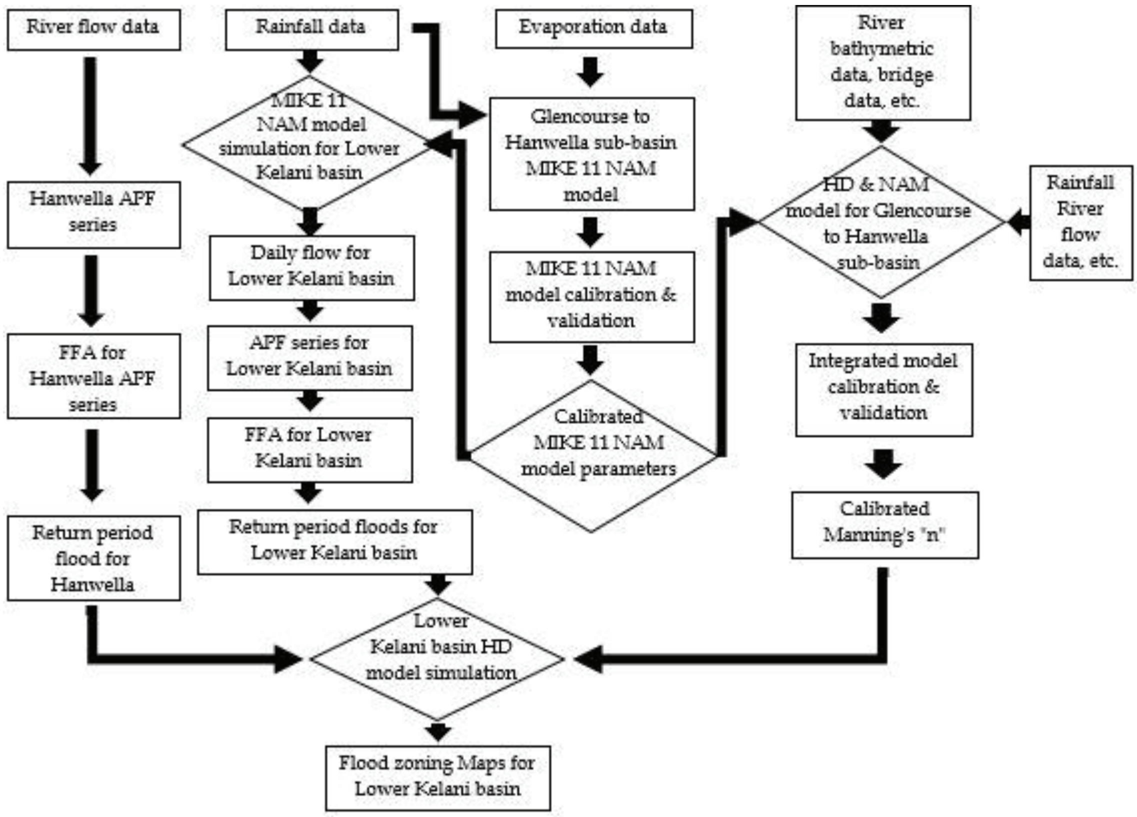

Figure 2 - Methodology Flow Chart Adopted for Flood Zoning Map Development

For information on the flood frequency analysis details, the reader may refer to Iresh (2019).

5.2 Mike 11 NAM Model Simulation

MIKE 11 RR NAM is a deterministic conceptual lumped modeling tool requiring moderate data inputs, developed by the Danish Hydrological Institute (DHI), Denmark. Since its creation in 1973, NAM has been used worldwide in various climate and hydrological settings to simulate runoff from precipitation events [23]. The RR model has been developed for Glencourse to Hanwella sub-basin and lower Kelani basin using hydro-meteorologic data.

The NAM model was simulated by continuously accounting for the moisture content in three different and mutually interrelated storages. These storages represent the overland flow, interflow, and baseflow components [23]. Precipitation, in the form of snow, can be accounted as the fourth storage component. However, snow storage has not been considered since snow does not occur in the Kelani River basin. The NAM model simulation required nine parameters describing the three storage components: groundwater storage, root zone, and surface storage. The parameters of the NAM model for the Hanwella gauging station have been calibrated using the input areal rainfall time series developed using the Thiessen polygon method, as shown in Figure 3. 1997 to 1998 was taken as the calibration period. Model calibration efficiency has been estimated statistically as well as graphically. The model has been validated from 1999 to 2000. Observed runoff and predicted runoff performance statistical indices were analyzed during model calibration and validation. Model performance statistics such as R^2 (Coefficient of determinant), Nash Sutcliff efficiency (NSE), Root Mean Square Error (RMSE), Percent Bias (PBias), and RMSE Standard Deviation (Std. obs) ratio (RSR) have been estimated.

5.3 NAM Model Sensitivity Analysis

NAM model sensitivity analysis was carried out during model parameter calibration. NSE and RMSE were estimated each time a parameter changed, while the other parameters were kept constant. The estimated NSE and RMSE against the respective model parameter values have been graphed graphically to identify the sensitive parameters. The simulated runoff for each parameter value from the lower to the upper margin was changed for low flow. The peak flow variation of the time series and the parameter effect on flows was analyzed.

5.4 MIKE ZERO HD Model Simulation

MIKE 11 HD model is a popular model with an implicit finite-difference scheme for computing unsteady flows in Rivers and estuaries [23]. The HD model is a one-dimensional unsteady non-uniform flow simulation model with flow applications such as subcritical and supercritical flow conditions through the numerical scheme that adapts according to the local flow conditions (in time and space) [23]. The HD model setup requires four input files to simulate a model. Each input file contains a specific format with hydrometeorological or morphological data requirements.

Model input files required for the MIKE 11 HD model simulation are presented below.

(1) River Network editor (nwk11 format).
(2) Cross-section editor (xns11 format).
(3) Boundary data editor (bnd11 format).
(4) HD parameter editor (hd11 format).

The input files have been prepared using collected data such as bathymetric data, upstream and downstream boundary conditions, and River network data. The river (Lower Kelani River) network has been developed including all the bridges across the Lower Kelani River (Hanwella to Sea). There are ten bridges across the Lower Kelani River. The names of these bridges are Hanwella Bridge, NawagamuwaThotupola Bridge, Kaduwela Bridge, Outer Circular Expressway Bridge, Pattiwila Bridge, Peliyagoda Railway Bridge, New Kelani Bridge, Japan Friendship Bridge and Mattakkuliya Bridge. Bridge details were collected from field surveys. The HD parameter wave approximation was considered 'fully dynamic'. The initial conditions of global value were kept as the water depth zero at zero discharge for downstream boundary condition. Observed flow series at Hanwella was used as upstream boundary condition for the river hydrodynamic model calibration and validation. Bed resistance was considered a Manning's 'n'global value. After preparing the required file formats, the files have been uploaded to the HD model for simulation.

5.5 Integrated MIKE NAM and HD

The NAM and HD models have been combined and simulated for the Glencorse to Hanwella River belt. The lateral inflow time series upstream of the catchment with downstream discharge (Q) and water level (h) relation has been taken as boundary conditions for the simulation. The model simulation generates a water level time series for each cross-section.

Model calibration is estimating the appropriate values of model parameters to produce observed values with acceptable accuracy.

The model parameters were changed to generate this consistent result. The parameters of the integrated NAM and HD models have been calibrated utilizing the observed water level time series at the Hanwella River gauge.

5.6 Flood Plain Zoning and Mapping

The calibration parameters of the HD model (Manning's 'n'), and the estimated flood quantiles at the Hanwella gauge site and Lower Kelani basin have been used to generate the flood maps for the river strip of Hanwella to the sea.

To develop the flood plain maps, MIKE 11 HD models have been simulated for each return period flood, such as 10, 25, and 50 years. The HD parameter editor map tool has been used to generate flood maps. Despite the HD model being a one-dimensional dynamic model, it can generate two-dimensional grid base maps with *dfs2* (Distribution File System 2) file format. Further enhanced digital maps for the different floods in the return period have been generated using ArcGIS tools.

Table 1 – Summary of Flood Quantiles Estimated for Hanwella River Gauge (adapted from Iresh (2019))

Station	Q_{mean}(m^3/s)	Return Period Flood (m^3/s)		
		10	25	50
Hanwella	846.62	1231	1436	1586

Table 2 – Summary of Flood Quantiles Estimated for Lower Kelani Basin, Downstream of Hanwella

Station	Q_{mean}(m^3/s)	Return Period Flood (m^3/s)		
		10	25	50
Lower Kelani basin	260	390	450	500

6. Results and Discussion

6.1 Flood Frequency Analysis

Flood frequency analysis has been conducted for the Hanwella APF series, and Lower Kelani River basin. The flood quantiles estimated by Iresh (2019) [15] have been used for the flood plain map generation. Table 1shows the flood quantiles estimated for Hanwella River gauge, whereas Table 2 shows the flood quantiles estimated for Lower Kelani River basin.

6.2 MIKE 11 NAM Model Calibration and Validation

The final values of calibrated NAM model parameters for the Hanwella gauging station are presented in Table 3. Calibrated model parameter values are within their specified range. The NAM model calibration has been finalized with the highest possible R^2 value of 0.766. The observed and simulated flow difference was 0.03%. Graphical comparisons between observed and simulated accumulative runoff showed high compatibility. The runoff hydrograph of observed and simulated runoff almost matched all the runoff events.

Critical aspect of the calibration was the time to peaks, which coincided with observed and simulated, whereas in some runoff events, peak values coincided with moderate accuracy with simulated values. Figure 4 shows the observed and simulated runoff hydrographs and accumulative runoff after calibration.

The model was validated from 1999 to 2000, with the coefficient of determinant 0.57. The observed and simulated flow difference was 2.5%, indicating that the developed model parameters performed well. The observed and simulated runoff hydrograph and the accumulative graph are given in Figure 5. Table 3 shows the calibrated NAM model parameters.

Observed runoff and predicted runoff performance statistical indices were analyzed during model calibration and validation. Model performance statistics such as R^2, NSE, RMSE, PBias, and RSR have been estimated and presented in Table 4. NSE statistical index during model calibration indicated that the model performance for simulation runoff for catchment was outstanding (If $0.75<NSE\leq1.00$, $0\leq RSR<0.5$, and $PBias<\pm10$ consider very good for streamflow [24]). However, during validation, NSE indicated a little lower value than calibration. Nevertheless, still, it gives the model a satisfactory model (If $0.5<NSE\leq0.65$, $0.60<RSR\leq0.7$, and $\pm15\leq PBias<\pm25$ consider satisfactory) [24].

PBias, during calibration and validation, showed good performance, indicating simulation data have not deviated unsatisfactorily from observed data. Both times PBias gave negative values, indicating that model simulation has an overestimation bias. Similarly, PBias figured very close to zero, which indicates that the model simulation was closer to the optimum. NSE and RMSE against the respective model parameter values have been graphically plotted. L_{max}, CQOF, TG, and CK_{12} are the most sensitive parameters.

Table 3 – Summary of NAM Model Parameter Values for Model Calibration

Parameters	Description	Unit	Value Range Lower to Higher	Model Parameter Final Value
U_{max}	Maximum water content for surface storage	mm	20 - 0	11.686
L_{max}	Maximum water content in lower zone/root storage	mm	50 - 300	118.604
CQOF	Overland flow coefficient	-	0 - 1	0.963
CKIF	Interflow drainage constant	mm	200 - 999.26	221.881
CK_{12}	Timing constant for overland flow and interflow	hour	3 - 49.99	49.908
TOF	Overland flow threshold	-	0 - 0.99	0.585
TIF	Interflow threshold	-	0 - 0.989	0.128
CKBF	Timing constant for base flow	hour	1004.45 - 3998.48	3030.661
TG	Groundwater recharge threshold	-	0 - 0.99	0.062

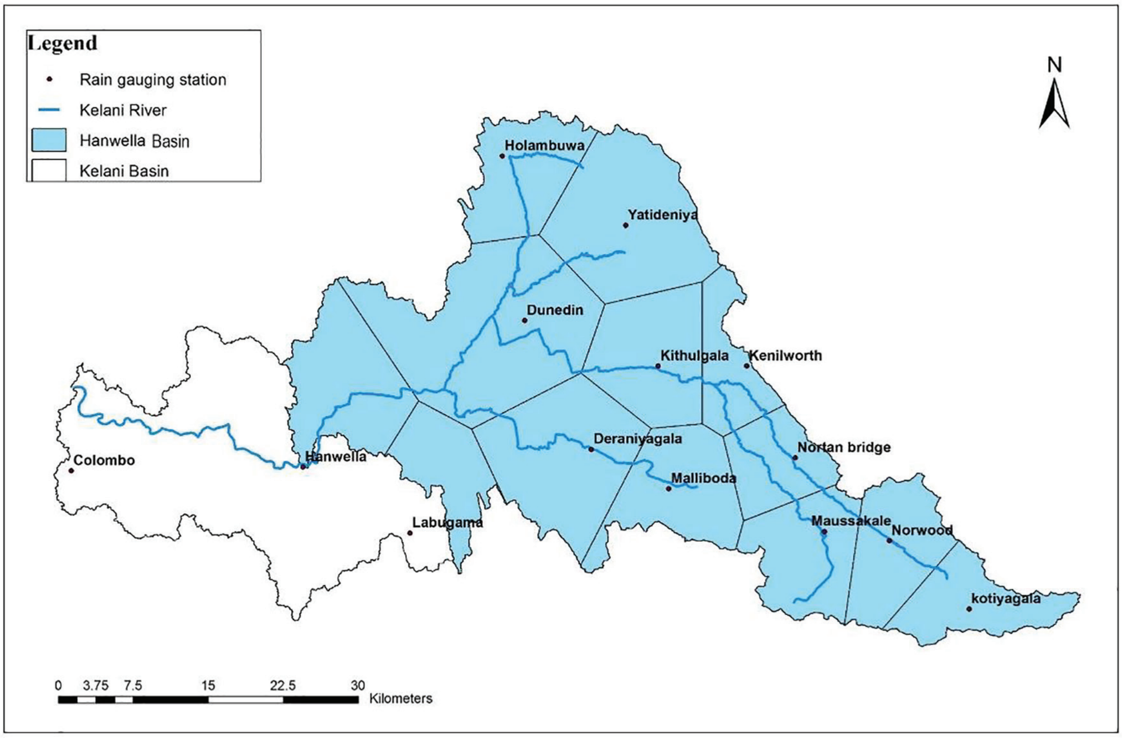

Figure 3 - Thiessen Polygon Developed for Hanwalla River Gauge Station

Table 4 – Summary of Model Calibration and Validation Performance Statistical Indices

Statistical Indices	Values	
	Calibration	Validation
RMSE	72.517	50.37
NSE	0.766	0.607
PBias	-0.034	0.86
RSR =RMSE/Std.$_{obs}$	0.484	0.627

6.3 MIKE 11 NAM and HD Model Simulation

All the calibrated parameters of MIKE 11 NAM (for Hanwella basin) have been used for the integrated model (Glencourse to Hanwella) simulation. MIKE 11 HD models was calibrated with upstream Glencourse gauge runoff time series as an open boundary to the boundary editor. HD model time-series output water levels in Hanwella have been graphically plotted with Hanwella gauge observed water level data and compared. Also, the predicted water levels and observed water levels were compared using statistical methods. The model parameters were improved by adjusting and comparing the values graphically and statistically. Statistical parameters such as RMSE, R^2, NSE, and PBias have been estimated to assess the predicted and observed water level time series. Calibrated parameter was validated for a period outside of the calibrated time. The model was calibrated with one single parameter, which was Manning's constant. HD model simulated with unsteady flow, fully dynamic wave approximation to obtain calibration. The model was calibrated with Manning's 'n' value of 0.02 for the flow path. Model performance evaluation for model calibration and validation NSE results were 0.917 and 0.871, respectively. Validation results indicate that the coupled model was calibrated and validated satisfactorily.

Calibrated Manning's 'n' value of 0.02 has been used for the Lower Kelani River MIKE 11 HD model simulation. Hanwella and Lower Kelani River basin FFA results were used for the HD model simulation as an upstream open boundary to the boundary editor. Flood maps were generated for return periods of 10, 25, and 50year.

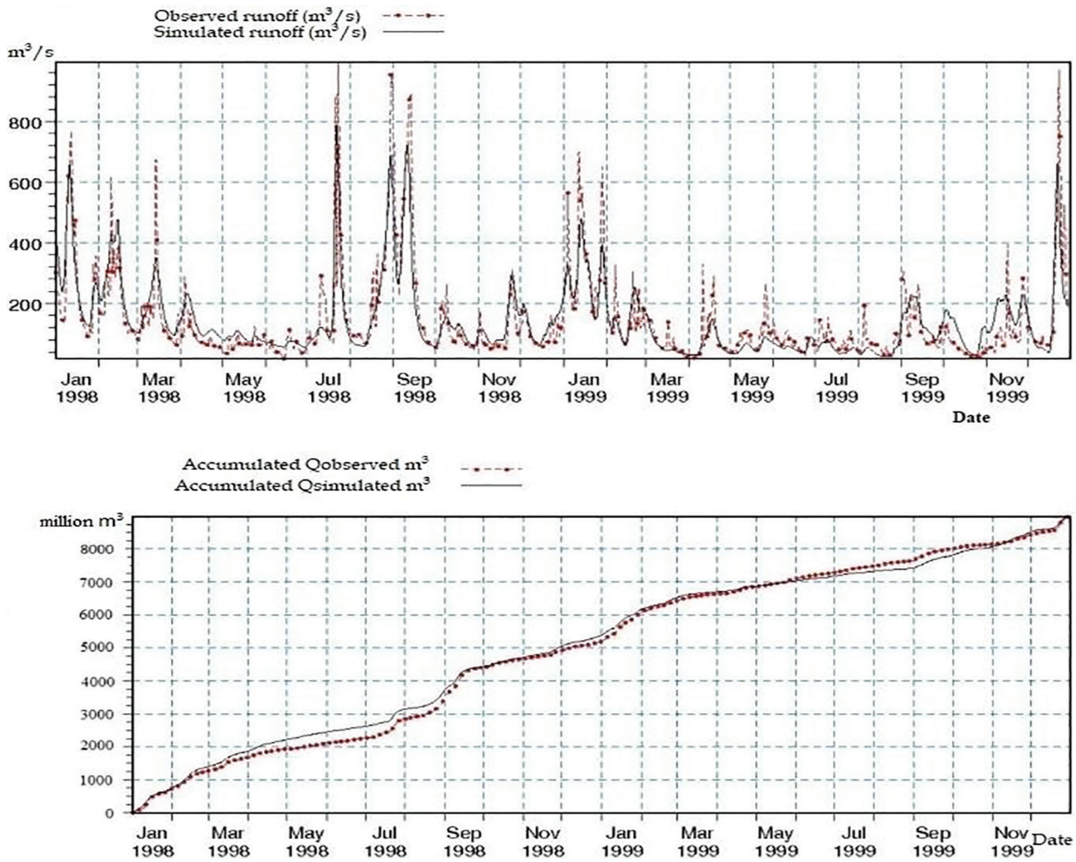

Figure 4 – Observed and Simulated Runoff Hydrographs and Accumulative Runoff after Calibration

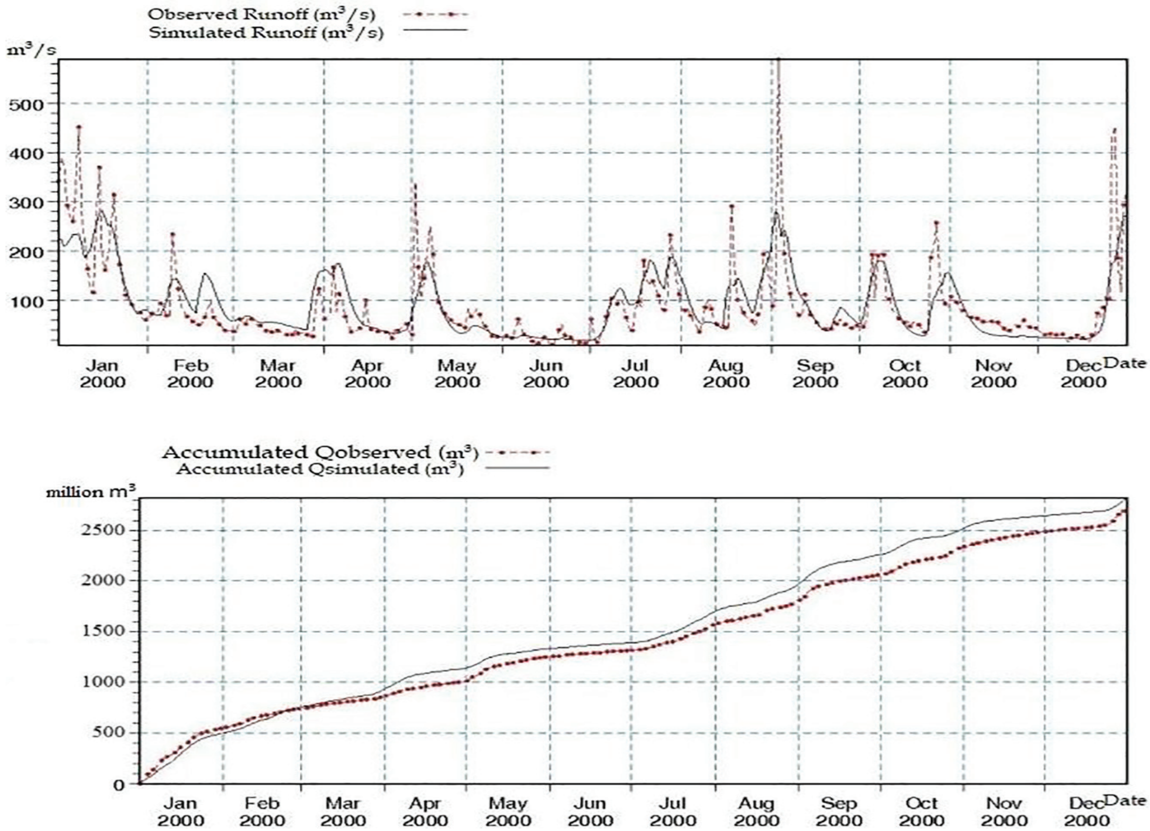

Figure 5 – Observed and Simulated Runoff Hydrographs and Accumulative Runoff after Validation

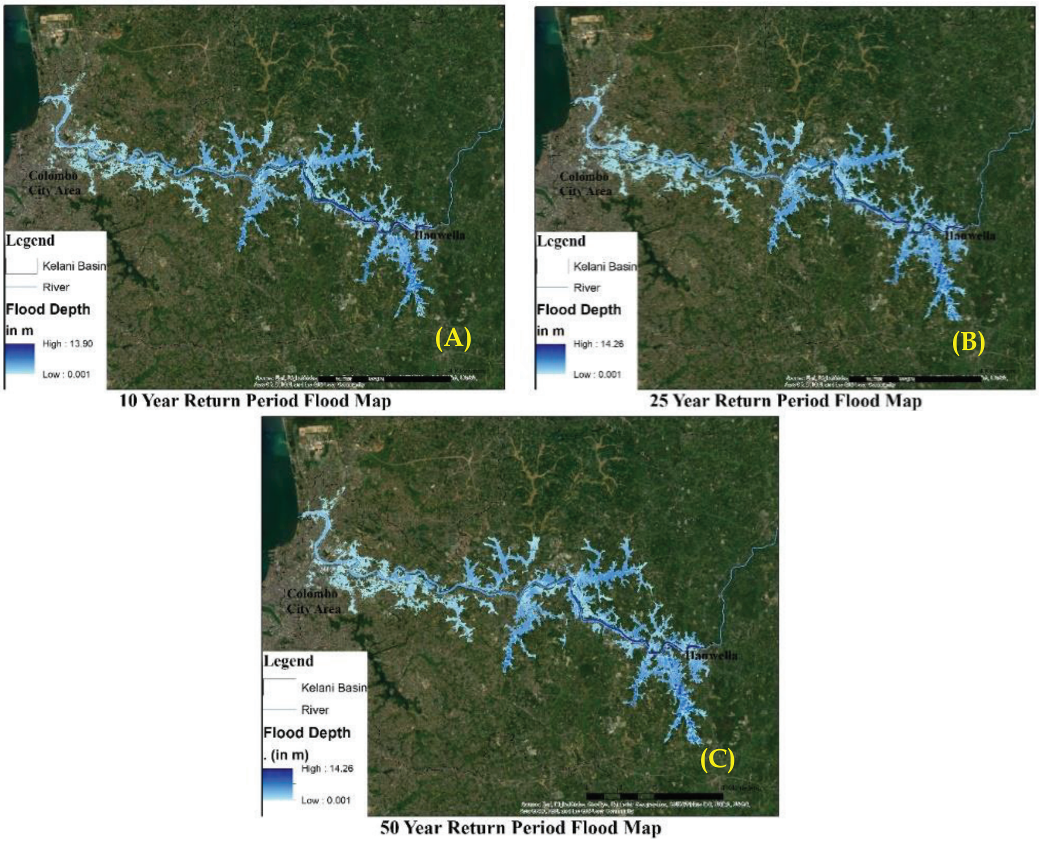

Figure 6 – Return Period Flood Plain Maps (Hanwella to Colombo) (A) 10 Year Return Period; (B) 25 Year Return Period; (C) 50 Year Return Period

Enhanced digital maps for the different return period floods have been generated and presented in Figure 6. The study identified that the 10-, 25- and 50-year return period flood inundation areas were 35.1, 38.6, and 40.3 km^2, respectively. The three return periods do not show significant differences, but flow depth has significant differences along the river. It implies that the terrain of the area has a steep slope. Though the condition differs from existing, accurate maps can be generated if short-interval cross-sections with long floodplains exist. The 50-year return period flood map has been validated using the 2016 flood maps developed by the Irrigation Department. An explicit analytical comparison has not been done as the 2016 flood map was developed by the Irrigation Department using information collected from the field after about 6 months and only a visual comparison was done. 2016 flood event return period is higher than the 50-year return period flood, the flood inundation area overlapping each other consistently in the Colombo city area. However, there are areas where the two flood maps do not overlap each other, this is due to the fact that the 2016 flood map was developed by the Irrigation Department using collected field data after the flood event.

7. Conclusion

This study provides a viable method for the development of floodplain zones, and this method can be used to develop floodplain zone maps for any basin. The developed flood zoning maps can be used to manage agricultural lands during monsoon periods and minimize damage due to floods. The data required for the study were very voluminous, which was the main disadvantage of the study. The other important factor was the HD model parameter used for the Lower Kelani (downstream of Hanwella) may not be representing the real River characteristics. However, the assumption that Manning's roughness in the river from Glencourse to Hanwella is the same as Manning's roughness in the Lower Kelani River is an optimistic approach in the absence of data to calibrate the real condition.

Due to the tidal impact to the Nagalagama Street River gauge, the gauge data has not been used for the MIKE 11 NAM model development. Accuracy and intervals of the cross-sections used for the Lower Kelani HD model simulation were also highly important for the accuracy of the flood inundation area.

These results will be helpful for irrigation managers and Local councils to introduce restrictions for land developments and agricultural activities. Similarly, these flood zoning maps can be used to introduce insurance schemes for investors, land users, and farmers through insurance companies. Insurance schemes can be introduced for various flood-zones which will benefit the farmers and investors. Hence it will be a motivation to the investors and younger generation to take up new developments and agriculture. Flood zoning maps provide the areas affected by floods of different probabilities. Similarly, flood zoning maps can be used to reduce flood risk in agriculture, industry, and residential development. Also, flood zoning maps present the potential impact of floods on humans (health and life), the economy, infrastructure, and the environment. These maps are the tools for integrated flood risk management. Community awareness about high-risk areas to low-risk areas and the development of structural and non-structural measures are mitigatory actions that can be introduced through flood zoning maps. Crops such as paddy or flood-resilient crops can be cultivated in areas most vulnerable to flooding. Whereas, cash crops not resistant to flooding can be grown on lands with low flood risk. Also, floodplain zone maps can be used to prevent farming and development in high-risk floodplains and to prevent crop and property damage. Additionally, it will help to create more green space and increase infiltration.

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