ENGINEER - Vol. LV, No. 03, pp. [21-27], 2022

DOI: http://doi.org/10.4038/engineer.v55i3.7518

Flood Inundation Modelling in Greater Colombo Region Using HEC-RAS 2D

E.M.N.T. Edirisooriya, N.G.P.B. Neluwala and W.M.S.B. Weerakoon

Abstract: Floods and associated destruction occur frequently due to unplanned development activities, rapid urbanization of flood plains and frequent storms caused by climate change. Flood risk of the Greater Colombo, which is the business capital of Sri Lanka with high population and investments, has increased recently due to the high discharge of the Kelani River and high intensity rainfall in the Greater Colombo region. Therefore, it is important to develop a model capable of simulating flood inundation in Greater Colombo region under this combined effect. In this study, the two-dimensional hydrodynamic model of Hydraulic Engineering Center's River Analysis System (HEC-RAS 2D) is used to develop a flood inundation model for the Greater Colombo region including Colombo canal network. The model was calibrated and validated using the flood events in May 2016 and May 2017, respectively. The model simulates the flood water levels and inundation extents satisfactorily with coefficient of correlation of 0.98, Nash-Sutcliffe efficiency of 0.93, root mean square error of 0.12 m and percent bias of 1.2% for water levels and goodness-of-fit index of 81% for inundation extents. The developed model is a valuable tool for flood inundation forecasting in the Greater Colombo region.

Keywords: Greater Colombo floods, Flood inundation, HEC-RAS, Kelani basin, 2D modelling

1. Introduction

Flood damage accounts for one third of economic losses caused by natural hazards worldwide [1]. As a direct effect, floods may lead to economic damage, damages to eco-systems and sites of historical and cultural value. Furthermore, floods frequently lead to loss of human life and adverse health effects [2]. Indirectly, floods cause loss of economic and agricultural production and adversely affect socio-economic welfare [3]. Therefore, flood management is important for sustainable development. Flood management strategies are categorized as structural and non-structural interventions [4]. This study focuses on non-structural cost-effective strategies like flood risk zoning and flood forecasting [5].

Flood risk of the Greater Colombo region has increased with the rapid urbanization and unplanned development activities [6], [7]. The significant reasons for frequent floods during last 30 years are identified as changes in land use and poor maintenance of the drainage and canal system in and around Greater Colombo region [8], [9]. Furthermore, urbanization has decreased infiltration and increased run-off [10]. Greater Colombo region experiences flood inundation due to two hydrological phenomena: high intensity rainfall with short duration in the Greater Colombo region and high discharge in the Kelani River caused by high intensity rainfalls in the upper basin [11]. With the combination of these two scenarios, the Greater Colombo region faces the worst flood condition.

Several attempts have been made in the past to develop hydrodynamic models for the lower Kelani basin. However, most of the studies have not incorporated Colombo canal network [12], [13], [14] which is very important to simulate the flood inundation in the city. Though a recent study [11] has simulated floods in the Colombo canal network, it has not covered rest of the lower Kelani basin. Flood inundation maps covering the whole lower basin including the canal network are essential to issue early warnings and to apply mitigation measures in the vulnerable regions identified.

***Miss. E.M.N.T. Edirisooriya**, B.Sc.Eng. (Peradeniya), Dept. of Civil Engineering, University of Peradeniya, Sri Lanka. Email:edirisooriyathiloka@gmail.com*
https://orcid.org/0000-0001-6488-2194
***Eng. (Dr.) N.G.P.B. Neluwala**, AMIE(SL), B.Sc.Eng. (Peradeniya), M.Eng., D.Eng. (Tokyo), Senior Lecturer, Dept. of Civil Engineering, University of Peradeniya, Sri Lanka. Email:pandukaneluwala@eng.pdn.ac.lk*
https://orcid.org/0000-0002-1686-3412
***Eng. (Prof.) W.M.S.B. Weerakoon,** Int.PE SL, FIE(SL), C.Eng, B.Sc.Eng. (Peradeniya), M.Eng., D.Eng. (Tokyo), Senior Professor, Dept. of Civil Engineering, University of Peradeniya, Sri Lanka.*
Email:sbweera@eng.pdn.ac.lk
https://orcid.org/0000-0002-3671-6241

In this study, a two-dimensional hydrodynamic model was developed using Hydraulic Engineering Center's River Analysis System (HEC-RAS 2D) version 5.0.6 to simulate flood inundation of the Greater Colombo region including the Colombo canal network. The developed model was calibrated and verified using historical data. The model would be able to forecast flood inundation using the rainfall forecasts made available.

2. Study Area

The Kelani River, the fourth longest river in the country with 192 km length, discharges to the sea at the northern boundary of the Greater Colombo region. The Kelani River basin is located in between Northern latitudes 6° 47' to 7° 05' and Eastern longitudes 79° 52' to 80° 13' with a basin area of 2292 km^2 extending to central hills and receives an average annual rainfall of about 3,450 mm. The river basin comprises mountainous upper region and plain coastal region [15]. The river discharge depends on the bi-monsoonal rainfall received in the basin and has a significant temporal variation. The flow averages to 20 m^3/s to 25 m^3/s in the dry period (from October to February) and ranges between 800 m^3/s and 1,500 m^3/s during the rainy season (March to April and May to September). Lower Kelani River basin of 500 km^2 with the Kelani River length of 35 km at an elevation drop of 5 m from Hanwella (which is the study area, Figure 1), is subjected to frequent flood inundation [16], [17].

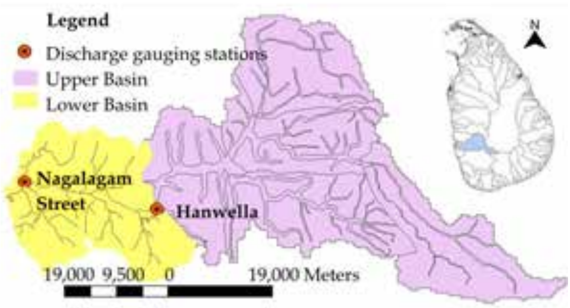

Figure 1 – Kelani River Basin with Stream Gauging Stations in the Study Area

Greater Colombo canal system with a total length of 67 km is connected to the Kelani River to drain out flood water from the Greater Colombo region. There are three outfalls to the sea from the canal system, located at Dehiwala canal, Wellawatta canal and Mutwal tunnel. There are several canal outlets to discharge flood water into the Kelani River. They include North Lock gate in the St. Sebastian North Canal, flap gates in Madiwela-East diversion canal, Kittampahuwa canal and Salalihini Mawatha canal.

3. Methodology

3.1 Model Development

HEC-RAS 2D model is a finite-volume model based on the 2D Saint Venant equations [18]. Topography and land use data for the model were derived from the 10 m accurate Digital Elevation Model (DEM) with land use classes (Source: Survey Department of Sri Lanka). Cross sections of the Kelani River and Canals (Source: Sri Lanka Land Development Corporation, SLLRDC) were incorporated to define the drainage network. Hourly tidal elevations at Colombo port and hourly river discharges at Hanwella were used as boundary conditions (Source: Sri Lanka Ports Authority (SLPA), SLLRDC and Irrigation Department) with hourly rainfalls of Hanwella and Colombo (Source: Department of Meteorology). Land classification map obtained from SLLRDC was used to define surface roughness zones.

Domain for 2D flow computation was delineated using the GIS shape file of the Greater Colombo region and the 2D mesh was created with cell size of 50 m×50 m. Mesh was refined in the regions where gradient of elevation is high such as riverbanks and where there are structures including weirs, culverts and control gates. DEM was improved to represent the continuous levies, roads and connection with canals, incorporating field measured data using the geometry editor of HEC-RAS package. The small reservoir at Thalangama (the Thalangama tank) was included with its weir crest level of 6.6 m MSL. North Lock gate and Madiwela gate were added as sluice gates and Madiwela east gate was added as a flap gate in the model. Locations of the gates are shown in Figure 2.

Hourly discharge at Hanwella gauging station was used as upstream boundary condition. Time series variation of the tidal level obtained from the Colombo Ports Authority was used as downstream boundary condition. Downstream boundary condition was applied at Kelani River outfall, Mutwal tunnel outfall, Wellawatta canal outfall and Dehiwala canal outfall. The effective rainfall for runoff generation was estimated as a percentage of measured hourly rainfalls at Hanwella and Colombo gauging stations considering the peak discharge. These measured data were verified using the data published by Irrigation Department of Sri Lanka [19], [20].

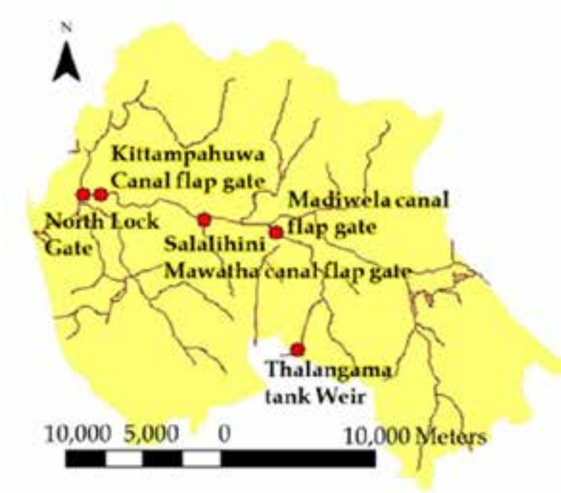

Figure 2 – Locations of Gates in the Study Area

3.2 Calibration and Validation

2016 May flood event from 15 May 2016 to 23 May 2016 was used for calibration of the model, where the observed and simulated water levels at Nagalagam street river gauging station and five locations in the canal network were compared. Manning's coefficients were adjusted during the calibration process within the recommended ranges for land use patterns [21]. Table 1 gives the Manning's roughness coefficients (n) used in the calibrated model. The calibrated model was then validated for 2017 May flood event from 24 May 2017 to 30 May 2016 using the same roughness coefficients obtained during the calibration.

Flood inundation area was compared with the observed flood maps (Source: Survey Department of Sri Lanka). Goodness-of-fit of the observed and simulated water levels at Nagalagam Street river gauging station was statistically evaluated using root mean square error (RMSE), coefficient of correlation (CC), percent bias and Nash-Sutcliffe efficiency (NSE).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad \ldots(1)$$

$$\text{percent bias} = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \times 100\% \qquad \ldots(2)$$

$$\text{NSE} = 1 - \frac{\sum_{1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad \ldots(3)$$

where,
O_i – Observed discharge
P_i – Simulated discharge
n – Number of data points
$\bar{O}$ – Mean of the observed discharge

Flood inundation areas were compared using goodness-of-fit index [22] given by;

$$\text{Fit}(\%) = (I_{obs} \cap I_{sim}) \,/\, (I_{obs} \cup I_{sim}) \qquad \ldots(4)$$

where I is inundated pixels, and subscripts 'obs' and 'sim' represent observed and simulated values, respectively.

Table 1 - Manning's Roughness Coefficients used for Land Use Types

Land use type	*n* Value
Built-up area	0.04
Bund (Canal embankment)	0.04
Canal and streams	0.01
Coconut plantation	0.04
Garden	0.04
Grassland	0.03
Jeep/ Car track	0.015
Lake	0.01
Main road	0.04
Marsh	0.01
Other plantation	0.04
Paddy	0.018
River plantation	0.03
Rubber plantation	0.04
Tea plantation	0.035
Transport and utilities	0.04

4. Results

Figure 3 shows the comparison of simulated and observed water surface elevations (WSE) at the Nagalagam Street river gauging station during 2016 May flood event. It shows a good agreement with the observed water levels at Nagalagam Street river gauging station. The observed peak water level of 2.3 m MSL has been correctly simulated but rising flood level on 16 May 2016 is slightly underestimated in the simulation. Further, the simulated water levels at the end of 22 May are slightly higher than the observed water levels by 0.25 m.

The accuracy of the model is further verified by the statistical parameters comparing the simulated and observed water levels at Nagalagam Street river gauging station given in Table 2. The coefficient of correlation of 0.98 indicates a good agreement between observed and simulated results. Similarly, NSE of 0.93 indicates an acceptable level of match between two data sets. RMSE value of 0.12 m and percent bias of about 1.2% are low, and imply that the simulation results agree with observations.

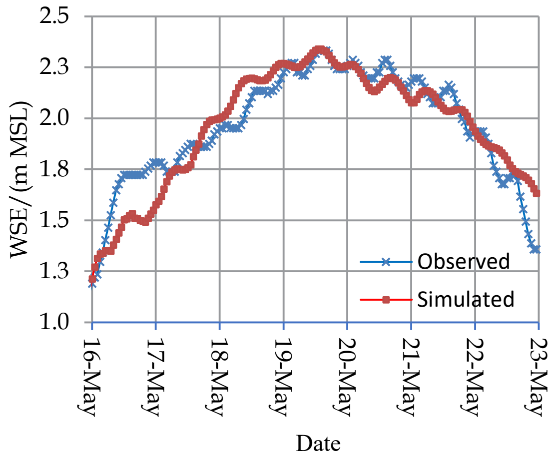

Figure 3 - Observed and Simulated Water Surface Elevations at the Nagalagam Street River Gauging Station during 2016 May Flood Event

Table 2 - Statistical Parameters in the Calibration Event

Parameter	Value
Coefficient of correlation	0.98
Nash-Sutcliffe efficiency	0.93
Root mean square error	0.12 m
Percent bias	1.22 %

Comparison of observed and simulated flood inundation extents in the Greater Colombo region for 2016 May flood event is shown in Figure 4. The overlapping areas within the observed and the simulated regions are considered for the model evaluation. Goodness-of-fit index is 87% for 2016 flood inundation simulated by the model. Therefore, the simulated flood inundation area agrees satisfactorily with the observed area.

Simulated water surface elevations in the canal network were compared with the observations, although only a very limited number of observations was available. Figure 5 shows that the model simulation has captured the peak water surface elevations of the St. Sebastian North canal satisfactorily.

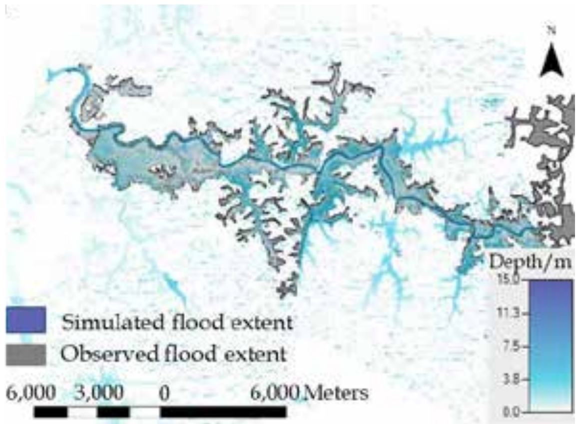

Figure 4 - Comparison of Observed and Simulated Flood Extents in the Greater Colombo Region for 2016 May Flood Event

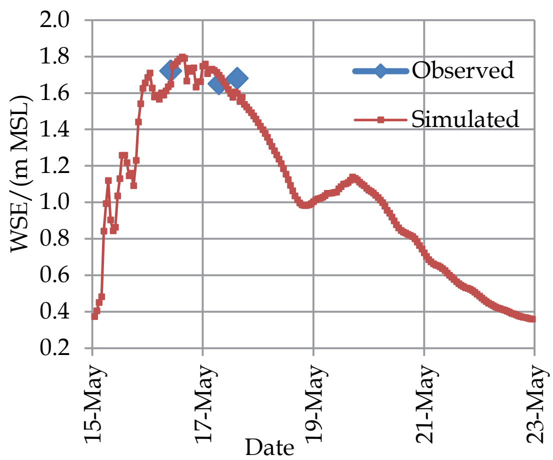

Figure 5 - Observed and Simulated Water Surface Elevations at the St. Sebastian North Canal during 2016 May Flood Event

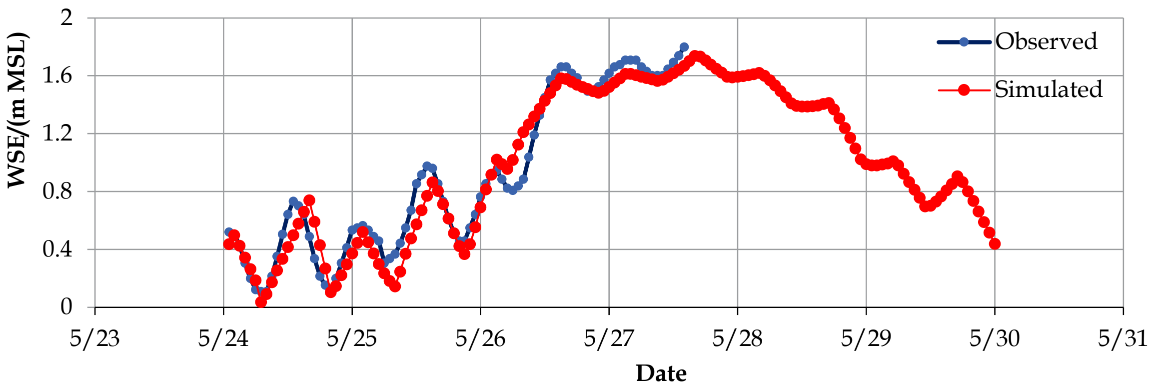

Figure 6 - Observed and Simulated Water Surface Elevations at Nagalagam Street River Gauging Station during 2017 May Flood Event

2017 May flood event was used for validating the model. During the 2017 May flood event, a rainfall of 425 mm was recorded at Hanwella gauging station and 69 mm of rainfall at Colombo rain gauging station in a period of 48 hours. The simulated water levels at the Nagalagam Street river gauging station shows good agreement with the observed water levels as depicted in Figure 6, although the observations are available only up to the flood peak. The simulated peak water level is only 0.03 m less than the observed peak water level. Simulated flood inundation extent shows good agreement with the observed flood extent according to goodness-of-fit index value of 81%. Table 3 gives a summary of calculated statistical parameters under the validation process. According to the statistical parameters (i.e., CC, NSE, RMSE, percent bias) the model simulated results show a high accuracy.

Table 3 - Statistical Parameters in the Validation Event

Parameter	Value
Coefficient of correlation	0.98
Nash-Sutcliffe efficiency	0.95
Root mean square error	0.13 m
Percent bias	4.5%

Figure 7 shows the agreement of observations in St. Sebastian North canal. Though only limited observations are available, Figure 7 shows that model could satisfactorily capture the flood peak and shape of the flood hydrograph in St. Sebastian North canal.

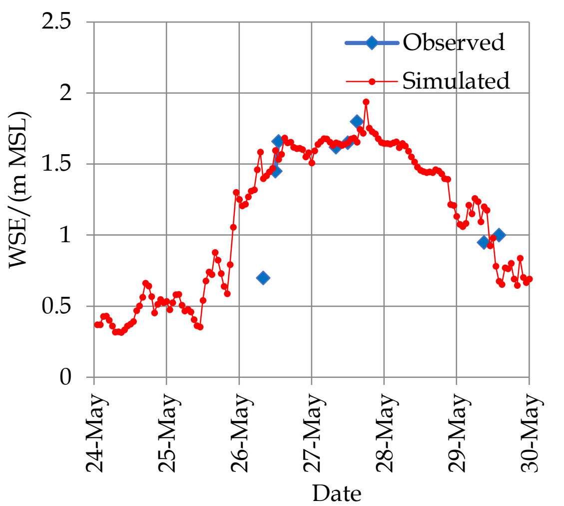

Figure 7 - Observed and Simulated Water Surface Elevations at St. Sebastian North Canal during 2017 May Flood Event

5. Conclusions

A two-dimensional flood inundation model for the Greater Colombo region was developed using HEC-RAS 2D 5.0.6 model. The model was calibrated and validated using the water level observations and flood inundation maps available for the flood events in 2016 and 2017 in the Greater Colombo region.

The model calibrated considering the water levels and inundation extents in May 2016 flood at Nagalagam Street using the accepted Manning's coefficients simulates the flood of May 2017 satisfactorily with RMSE of 0.13 m, coefficient of correlation of 0.98, Nash-Sutcliffe efficiency of 0.95 and bias of 4.5% for water level and the goodness-of-fit index of 81% for inundation extents. Model simulated water levels in canal network are also in agreement with the observations.

The developed flood inundation model is a useful tool a) for flood inundation forecasting in the Greater Colombo region under the combined effect of high discharges of the Kelani River and high intensity rainfall in the region and b) for planning flood mitigation interventions in the Greater Colombo region.

6. Recommendations

Further studies can be carried out to couple the developed model with a rainfall forecasting system to forecast the floods in Kelani River basin to minimize flood damages. This model can also be extended to identify optimum gate operating rules for the canal network, locations and capacities of pumping stations in the flood mitigation planning in the Greater Colombo region.

Acknowledgement

The authors wish to extend their sincere gratitude to NORAD WaSo-Asia Project for providing financial assistance for conducting this research study.

References

1. Bosello, F., Iglesias, A., Termansen, M., Jeuken, A., Winsemius, H., De Cian, E., & Garrote, L., "Economy-Wide Impacts of Climate Mitigation and Adaptation Strategies Across European Regions", *In Adapting to Climate Change in Europe*, 2018, pp. 245-271, https://doi.org/10.1016/B978-0-12-849887-3.00005-8.

2. Hajat, S., Ebi, K. L., Kovats, R. S., Menne, B., Edwards, S., & Haines, A., "The Human Health Consequences of Flooding in Europe: A Review", *Extreme Weather Events and Public Health Responses*, Springer, Berlin, Heidelberg, 2005, https://doi.org/10.1007/3-540-28862-7_18.

3. Jonkman, S. N., "Global Perspectives on Loss of Human Life Caused by Floods", *Natural Hazards*, Vol. 34, No. 2, 2005, pp. 151–175, https://doi.org/10.1007/s11069-004-8891-3.

4. Dawson, R. J., Ball, T., Werritty, J., Werritty, A., Hall, J. W. & Roche, N., "Assessing the Effectiveness of Non-Structural Flood Management Measures in the Thames Estuary under Conditions of Socio-Economic and Environmental Change", *Global Environmental Change*, Vol. 21, No. 2, 2011, pp.628-646, https://doi.org/10.1016/j.gloenvcha.2011.01.013.

5. Patro, S., Chatterjee, C., Singh, R. & Raghuwanshi, N. S., "Hydrodynamic Modelling of a Large Flood-Prone River System in India with Limited Data", *Hydrological Processes*, Vol. 23, No. 19, 2009, pp. 2774-2791, https://doi.org/10.1002/hyp.7375.

6. Ranagalage, M., Morimoto, T., Simwanda, M. & Murayama, Y., "Spatial Analysis of Urbanization Patterns in Four Rapidly Growing South Asian Cities Using Sentinel-2 Data", *Remote Sens*ing, Vol. 13, No. 8, 2021, 1531, https://doi.org/10.3390/rs13081531.

7. Dissanayake, P., Hettiarachchi, S. & Siriwardana, C., "Increase in Disaster Risk due to Inefficient Environmental Management, Land Use Policies and Relocation Policies. Case Studies from Sri Lanka", *Procedia engineering*, Vol. 212, 2018, pp.1326-1333, https://doi.org/10.1016/j.proeng.2018.01.171.

8. Dammalage, T. & Jayasinghe, N., "Land-use Change and its Impact on Urban Flooding: A Case Study on Colombo District Flood on May 2016", *Engineering, Technology & Applied Science Research*, Vol. 9, No. 2, 2019, pp. 3887-91, https://doi.org/10.48084/ETASR.2578.

9. Hewawasam, V., & Matsui, K., "Equitable Resilience in Flood Prone Urban Areas in Sri Lanka: A Case Colombo Divisional Secretariat Division. Global Environmental Change", *Global Environmental Change*, Vol. 62, 2020, https://doi.org/10.1016/j.gloenvcha.2020.102091

10. Chu, M. L., Knouft, J. H., Ghulam, A., Guzman, J. A. & Pan, Z., "Impacts of Urbanization on River Flow Frequency: A Controlled Experimental Modeling-Based Evaluation Approach", *Journal of Hydrology*, Vol. 495, 2013, pp.1-12, https://doi.org/10.1016/j.jhydrol.2013.04.051.

11. Moufar, M. M. M. & Perera, E. D. P., "Floods and Countermeasures Impact Assessment for the Metro Colombo Canal System, Sri Lanka", *Hydrology*, Vol. 5, No. 01, 2018, pp. 1–20, https://doi.org/10.3390/hydrology5010011.

12. De Silva, M. M. G. T., Weerakoon, S. B., Herath, S., Ratnayake, U. R. & Mahanama, S., "Flood Inundation Mapping along the Lower Reach of Kelani River Basin under the Impact of Climatic Change", *Engineer*, Vol. 45, No 02, 2012, pp.23-29.

13. Komolafe, A. A., Herath, S. & Avtar, R., "Development of Generalized Loss Functions for Rapid Estimation of Flood Damages: A Case Study in Kelani River Basin, Sri Lanka", *Applied Geomatics*, Vol. 10, No. 1, 2018, pp.13-30, https://doi.org/10.1007/s12518-017-0200-4.

14. Gunasekara, I. A., "Flood Hazard Mapping in Lower Reach of Kelani River", *Engineer*, Vol. 31, No. 05, 2008, pp.149-154.

15. Vuillaume, J. F., Dorji, S., Komolafe, A., & Herath, S., "Sub-Seasonal Extreme Rainfall Prediction in the Kelani River Basin of Sri Lanka by using Self-Organizing Map Classification", *Natural Hazards*, Vol. 94, No. 1, 2018, pp. 385–404, https://doi.org/10.1007/s11069-018-3394-9.

16. De Silva, G., Weerakoon, S. B. & Herath, S., "Event Based Flood Inundation Mapping Under the Impact of Climate Change: A Case Study in Lower Kelani River Basin, Sri Lanka", *Hydrology Current Research*, Vol. 7, No. 1, 2016, https://doi.org/10.4172/2157-7587.1000228.

17. Abeysinghe, N., "Morphometric Analysis of Watersheds in Kelani River Basin for Soil and Water Conservation", *Journal of the National Science Foundation of Sri Lanka*, 2017, pp. 273-285, http://doi.org/10.4038/jnsfsr.v45i3.8192.

18. USACE, *HEC-RAS River Analysis System Hydraulic Reference Manual Version 5.0*, Institute for Water Resources, Hydrologic Engineering Center, California, USA, 2016.

19. Hettiarachchi, P., Alwathugoda R. M. M. R., Piyasena, K. K. A., Weligepolage K., Amarasekara J. D., Somawickrama, D. A., *Hydrological Annual Report 2016/2017*, Department of Irrigation, Sri Lanka, 2017, pp. 65, Retrieved from https://www.irrigation.gov.lk/images/pdf/downloads/Hydro_Annual/2016-17n.pdf.

20. Alwathugoda, R. M. M. R., Piyasena, K. K. A., Weligepolage, K., Amarasekara, J. D., Gunawardana, A. D. S., Somawickrama, D. A., *Hydrological Annual Report 2017/2018*, Department of Irrigation, Sri Lanka, 2017, pp. 65, Retrieved from,https://www.irrigation.gov.lk/images/pdf/ downloads/Hydro_Annual/2017-18.pdf

21. Chow, V. T., *Open-Channel Hydraulics,* McGraw-Hill, New York, 1959, pp. 109-113.

22. Horritt, M. S., "A Methodology for the Validation of Uncertain Flood Inundation Models", *Journal of Hydrology*, Vol. 326, 2006, pp. 152-165, https://doi.org/10.1016/j.jhydrol.2005.10.027.