Holistic Dynamics of Urban Pond Infrastructure for Flood Risk Mitigation – A Case Study on Jaffna Municipal Council Area

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***Abstract*—The frequency of flood occurrence in the Jaffna Peninsula mainly depends on rainfall intensity, conditions of natural drainage, associated terrain, and hydraulic structures. Jaffna Municipal area has also been facing recurrent severe flood events in the past years. Since it is situated in the dry zone, the seasonal rainfall occurs in the second inter-monsoon and North-East monsoon periods with daily rainfall often exceeding monthly average rainfall under extreme conditions and there is no proper management of drainage network or associated pond cascades. However, in the past, these cascade pond systems were used to retain the upstream rainwater and enrich groundwater storage through recharging before it reaches the outlet. In the present study, a pond cascade model was developed by using the HEC-ResSim computer simulation application to compare the efficiency of flood mitigation of cascade systems and individual ponds. The HEC-HMS computer application was used to find runoff from the catchment. The flood inundation area was identified by the HEC-RAS 5.0.7 modeling. According to the results obtained from the model calibration based on the 2017-year rainfall event and 10-year return period flood event, the flood inundation area of the individual pond approach was 0.366. When the cascade pond behavior was introduced, it was reduced to 0.2352 km^2. The obtained results obviously say that the flood inundation area was reduced by the pond cascade system because a considerable amount of flood was retained in upstream ponds. The inundation area was decreased by 0.1308 km^2. It is possible to reduce the flood inundation area further based on the results by increasing the pond capacities. In conclusion, the flood inundation can effectively be reduced by ensuring the holistic behavior of the pond cascade system meanwhile increasing the groundwater recharge.**

Keywords— HEC-ResSim model, Holistic flood management, Pond cascade system

I. Introduction

The frequent occurrences of natural hazards have been a major challenge to Sri Lanka. Sri Lanka is affected by rising temperatures, higher variability of monsoonal rainfall and an increase in climatic extreme events such as floods or droughts. During peak rainfall conditions, many poorly designed urban areas are facing flooding issues [1]. Urbanization has the potential to have an unknown impact on the future sustainable functionality and management of the water-harvesting and storage systems [2]. Their effects are felt in the Jaffna district as well [3]. The average Jaffna district rain fall is 1230 mm (1950-2011) [3]. Normally, during the North East monsoon and second inter monsoon period rainfall was received in Jaffna district. Even though the peak rain fall is observed during the second inter monsoon period which was much higher than annual rainfall leads to the occurrence of flood. Flooding in the urban areas always affect the economy in a negative way [2]. People are facing commercial, social consequence and economic negative issues due to the flood.

14.06% of the Jaffna peninsula's population lives in the Jaffna Municipal Council (JMC) area, and JMC has the highest population density [4] of 2986/ km^2. The highest number of people in this area is facing flood issues compared with the other divisional secretariats in Jaffna district. In JMC in the 20th century, there are more than 100 ponds, but now it is reduced to 47 ponds [5]. Because most of the ponds are abundant due to increasing the population, urbanizations, and people are using reservation areas for their own purposes. To avoid this situation from getting worse further and to maintain this available number of ponds as it is, this particular area was selected for this case study.

Freshwater is getting scarce due to the rapidly increasing world population. Hence, effective management of water resources is becoming one of the most important issues in this era [6]. When considering this effect in the Jaffna district, during the dry season, water scarcity will occur due to the absence of streams and rivers. Exiting ponds help to recharge the groundwater and reduce this water scarcity. Therefore, proper methodology should be found to protect the existing ponds surrounding the municipal areas. In this case, the most suitable method is pond cascade system, which help to increase the retention and detention periods of ponds. In a cascade system, the upper part of the water is already used before sent to the outlet. The upstream ponds in the catchment area can detain a considerable amount of stormwater, which will cause a retardation in the flood wave [7].

Some water resource proposals were prepared in previous years, but they were not implemented for various reasons. Webb prepared the "Jaffna peninsula lagoon scheme" report in 1942, and action was taken in 1945 to design two barrages across Thondamanaru and Upparu. But it failed due to slow process [8]. The second proposal was to construct on a reservoir at Elephant- pass lagoon, which was prepared by S. Arumugam. This method also had some setback, which damaged the bund because of subsoil settlement [8]. And recently, another proposal was made on the water supply from Kilinochchi Iranaimadu reservoir. But, Kilinochchi community raised the concerns about their own water problem [10].

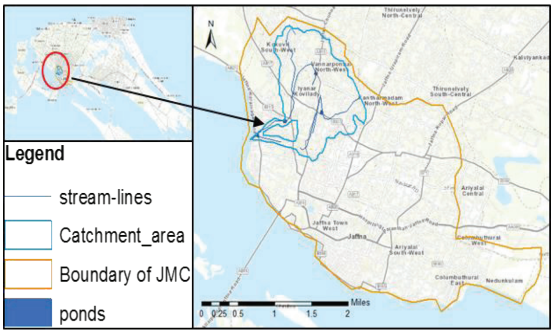

Fig. 1. Jaffna municipal council area with Kompayan kulam cascade

II. Materials and Methodology

The research methodology was developed based on the effective flood management system for the Jaffna municipal council area. Therefore, the methodology was focused on finding the flood inundation area of existing conditions of ponds and after ponds connected to the cascade system. Then, check the way of methodology hypothesis and conclusions also compare with two scenario analysis. Research methodology starts with comprehensive literature view which helps to identify the study area characteristics, problems and suitability of the proposed methodology. After that, the required data were collected and important to analyses the data. TABLE *II* shows the required data collection details. In here 10-year return period was considered and year 2017 rainfall data was used for the inflows. For this study, HEC-HMS 4.2, HEC-ResSim 3.1, HEC-RAS 5.0.7 computer modelling software were used. From the HEC-ResSim 3.1 was used to identify the excess water which comes from the spill (this cause to the flood) during the rainy season for individual ponds and pond behave as a cascade.

A. Study Area: Kompayan Kulam Cascade

There are 47 ponds in the study area. Among them, the Kompayan kulam cascade has 4 ponds. According to the post flood inundation map, stream network and availability of the required data this pond cascade system was selected.

Kompayan kulam cascade is located at the south-west part of the Jaffna municipal council area. Among the 4 ponds, Kompayan kulam has a large catchment area and helps to contribute to the large runoff generation of the cascade. The total catchment area of the cascade is 1.169 km^2. The entire catchment area belongs to the Jaffna municipal council. The selected cascade is in hydrological zone II (Dry zone) [9] and the catchment area of Kompayan kulam belongs to agro-ecological zone of DL3(which represents the climate, soil and terrain condition, DL3 – Receiving lowest annual rainfall in dry zone) [9]. The monthly evaporation values of ponds were taken from the nearest gauge station of Thondamanaaru [8]. TABLE *III* shows the monthly evaporation value. All ponds have an uncontrolled outlet (natural spill) and the cascade out is Jaffna lagoon. Fig. 1 shows the location of selected cascade which is in the Jaffna municipal council area. TABLE *I* is given the ponds detail of the Kompayan kulam cascade.

TABLE I. POND LOCATION OFCASCADE

Pond Names	JMC No	Location of the cascade
Anjutha kulam	20	Upstream
Nachchimar kovil kulam	19	Upstream
Kompayan kulam	40	Downstream
Rajali kulam	18	Downstream

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B. Data and Data Checking

There are several data need to analyze with Global mapper, Arc GIS, HEC-HMS 4.2, HEC-ResSim 3.1 and HEC-Ras 5.0.7 computer software analysis. Google Earth pro help to verify the location of the pond and catchment area.

C. Developing Watershed Area and Stream Network

Global Mapper created a stream network and watershed area using a Digital Elevation Model (DEM) with a resolution of 30m. From the stream network and watershed area, the catchment areas of the induvial ponds and cascade pond were identified. Fig. 2 shows catchment area with outlet.

TABLE II. DETAILS OF DATA COLLECTION

No	Data	Sources
1	30m Dem file	United State Geological Survey
2	Pond contour maps and pond survey map	Strategic Cities Development Project (SCDP), Jaffna
3	Existing canal network	SCD Project, Jaffna
4	Daily rainfall data	Meteorology Department(2002-2018)
5	Evaporation Data	Irrigation Department guideline(Ponrajah, 1984)

TABLE III. MONTHLY EVAPORATION VALUES (mm)

Jan	Feb	March	April	May	June
115.5	113.1	133.5	139.3	171.0	164.6
July	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
151.8	153.0	156.1	135.0	107.6	111.6

D. HEC-HMS Modelling for Runoff Calculation

In this study area year, 2017 daily rainfall data from Jaffna city rainfall gauge station records were used. Fig. 3 shows the rainfall pattern of the year 2017. In Sri Lanka, two rainfall-runoff computer models were used. They are the HEC-HMS and ‘abcd' model. Here, the catchment was considered as a lumped model or semi-distributed according to the requirement. Even though distributed modelling has a higher computational cost and is more difficult to model, that’s why it is not commonly used. Due to the precipitation, the net runoff from the catchment area was calculated by HEC-HMS 4.2 computer modelling software. Because flood is a dynamic event. Therefore, when calculating the runoff rational method cannot be used, and HEC-HMS modelling is considered the unique characteristics of the catchment area.

HEC-HMS is one of the hydrological models to convert rainfall data into a runoff by using rainfall data and catchment characteristic, even if there is no hydrometric data. And help to find the meteorological and physical properties of catchments such as precipitation, evapotranspiration, infiltration, surface runoff and baseflow. In 1992, the U. S Army Corps of Engineers Hydrologic Engineering Center (HEC)discovered the Hydrologic Modelling System (HEC-HMS). HEC-HMS 4.2.1 is used for this project, and it is user-friendly runoff modelling software. Based on the catchment characteristics and pieces of literature, methods were selected. Fig. 4 shows the result of inflow, baseflow, precipitation loss and outflow of Kompayan kulam catchment.

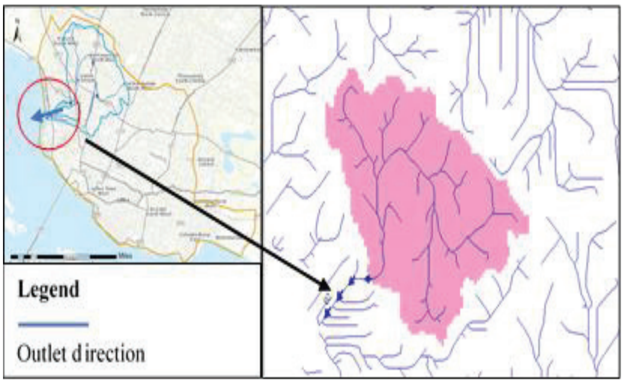

Fig. 2. Catchment area with outlet

TABLE IV. POND DETAILS OF THE KOMPAYAN KULAM CASCADE

Pond Names	Pond capacity(m^3)	Maximum depth(m)
Kompayan kulam	3186.54	1.5
Rajali kulam	2476.55	1.5
Nachchimar kovil kulam	4243.87	2.0
Anjutha kulam	2327.57	2.0

E. HEC-ResSim Modelling

This is a simple water balance approach. There are three separate modules in the HEC-Res Sim.

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Such as watershed setup, reservoir network and reservoir simulation. In the first module, input the data of reservoir locations, drawing of the streamlines, and creation of several configuration points were done. Reservoir network is used to edit the elements which are reservoir, junctions, reaches, diversions and can be used to create different alternatives. Here, the reservoir properties of pool elevation, pool area spill type, spill elevation, outlets and operation set were applied. The selection of alternatives depends on operation set, time series data, network and initial conditions. Reservoir simulation helps to create several alternatives with the desired time window. Due to this, the period where the highest amount of spilled water occurred can be identified. Also run the model for the different alternatives. In each simulation different types of alternatives with a specified time window can be analyzed. Here, all the reservoirs are designed as uncontrolled spills. Because some ponds were only functioning during the rainy period and excess water caused the flood. TABLE *IV* is given the details of capacity and maximum depth of ponds.

In the modelling, first the individual ponds were modelled separately, and cascade pond system was modelled. Fig. 5 shows individual pond modelling. In this case, inflow to the reservoir was taken from the HEC-HMS results, the reservoir storage was calculated from the area values for each elevation which can be taken from the pond survey data and possible losses which are evaporation and seepage were inserted. The seepage value was considered to be 5% of the available pond storage [9]. Finally, net outflow from the reservoir can be found from the modelling .

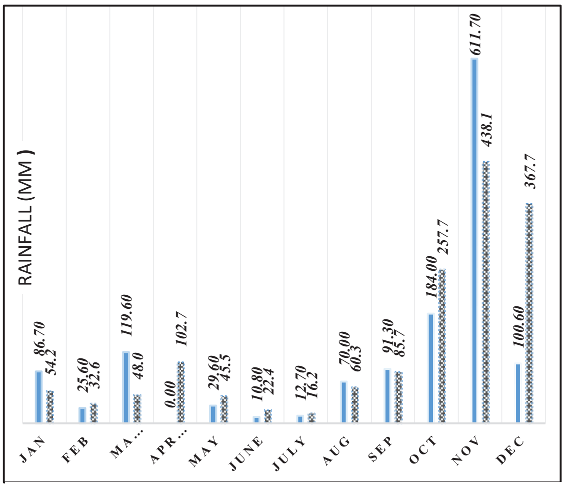

Fig. 3. Monthly rainfall pattern

F. HEC-RAS Modelling for Flood analysis

The HEC-RAS 5.0.7 tool kit was used to find the flood extension area for individual ponds and simulate their behavior as a cascade. The flow area of the ponds was identified by using a 30m DEM file of the Jaffna municipal council area, which was shown in Fig. 7. The location of ponds and catchment area was verified by Google Earth Pro.

The total 1.169 km^2 catchment area was divided into four divisions according to the amount of spill from the ponds. During the modelling, some boundary conditions were followed. Such as pond outlet being considered as an upstream point and the lowers elevation of the flow area being considered as a downstream point. Unsteady flow analysis was carried out throughout the analysis. Upstream point data was taken from the HEC-Res Sim results of individual and cascade ponds.

III. Result and analysis

A. Individual pond analysis

Considering individual ponds analysis with a 10-year return period of flood events and the 2017 rainfall pattern, the total flood inundation area was identified as 0.366 km^2, which was 33.03% of total catchment area. TABLE *V* summaries flood inundation areas, and Fig. 6(a) depicts individual pond inundation areas.

B. Holistic behavior of ponds

Considering the cascade modelling for flood analysis, all ponds were modelled separately. Here, the flow area was created from one upstream pond to another near to the downstream pond. According to this, the upstream point and downstream point was selected. Due to this, the considerable amount of spilled water can be reduced to reach the downstream point. During the analysis, the 0.2352 km^2 area was identified as a flood inundation area. It was 21.22% of the total catchment area. Fig. 6(b) shows the inundation area of cascade connectivity.

C. Result comparison

Considering 10-year return period of flood events, the result obtained from the individual ponds and cascade pond system was that a considerable amount of flood inundation area was reduced from the total flood area when the ponds

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behave as a cascade. During the analysis to get the inundation area of individual ponds, it was found to be 0.366 km^2 but was decreased to 0.2352 km^2 because of the pond cascade connectivity. Therefore, 0.1308 km^2 area was saved from the flood.

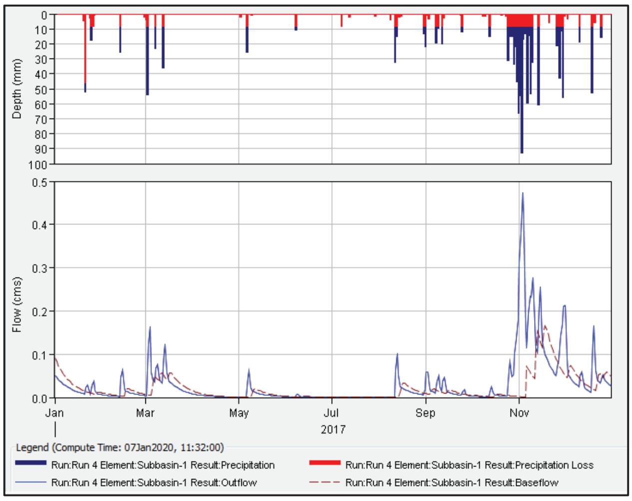

Fig. 4. Inflow, baseflow, precipitation loss and outflow of Kompayan kulam catchment.

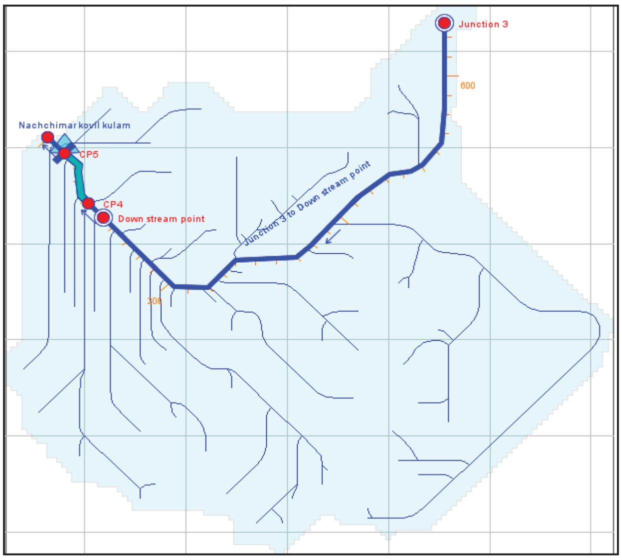

Fig. 5. Individual pond modelling of Nachchimar kovil kulam (Reservoir network)

IV. Discussion

For this study year, 2017 rainfall data was used to identify the flood inundation area. Because it is a major post-flood event in Jaffna district, it has created a huge negative impact on the social, economic, and environment of the people who are living in the Jaffna municipal council area.

The obtained results obviously show that the flood inundation area was reduced by the pond cascade system. Because a considerable amount of flooding was retained. The inundation area was decreased by 0.2352 km^2, which is 35.7%. It is possible to reduce flood inundation areas further from this result by increasing the capacities of ponds. And it can be achieved further by obtaining the maximum use from the ponds in the study area, which only functioned during the rainy season and had poor maintenance.

According to the results obtained, upstream ponds (Anjutha kulam, Nachchimar kovil kulam) reduce the flood inundation area when they behave as cascade ponds rather than when it acts as an individual pond. However, Kompayan kulam which is located at the downstream, increases the flood inundation area of cascade pond system more than the individual ponds. Because spill water from the upstream ponds gets collected in this pond. Therefore, the capacity of the pond is not capable of excess water. And upstream ponds do not have adequate capacity to retain the flood water. This issue can be resolved by increasing the pond capacity with the availability of land extent. This study mainly focuses on flood mitigation but does not consider the drought effect in Jaffna district.

TABLE V. FLOOD INUNDATION AREA OF INDIVIDUAL PONDS AND CASCADE POND SYSTEM

Ponds	**Sub-catchment area (km^2)**	**Flood affected area for individual ponds (km^2)**	**Flood affected area of cascade pond (km^2)**
Rajali kulam	0.0892	0.0459	0.0207
Kompayan kulam	0.6240	0.0506	0.0527
Nachchimar kovil kulam	0.1480	0.0876	0.0687
Anjutha kulam	0.2478	0.1865	0.0981

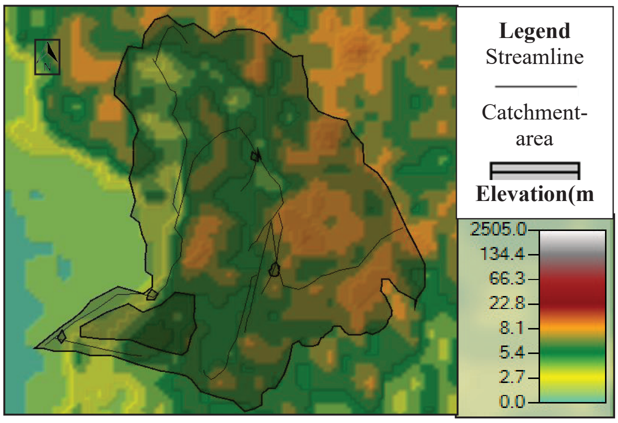

Fig. 7. DEM with syudy area

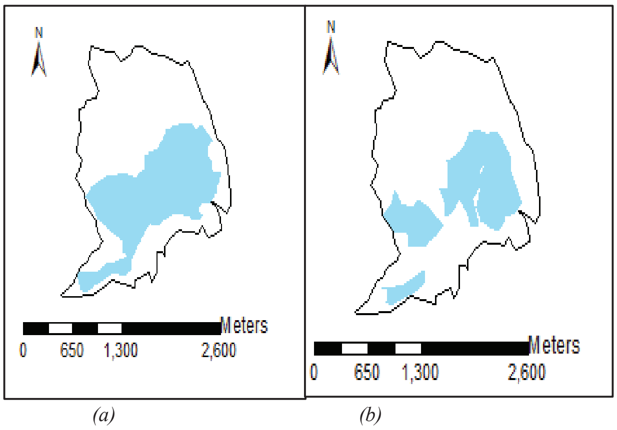

Fig. 6. Flood inundation map with catchment area

V. Conclusion

It was concluded that the flood inundation area was reduced by the holistic behavior of the pond cascade while some amount of excess water was restored. It is possible to increase the reduction of flood inundation area to improve the ponds capacities, especially in the downstream ponds, while considering the land availability. Here, the result showed that 0.1308 km^2 area was saved from the flood hazard.

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