Scenario analysis to identify a sustainable pond rehabilitation approach for flood mitigation: A case study in Jaffna, Sri Lanka

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Scenario analysis to identify a sustainable pond rehabilitation approach for flood mitigation: A case study in Jaffna, Sri Lanka

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Abstract

Jaffna peninsula which includes a land mass of 1026 km^2 with 9.3% of inland water bodies suffers from severe flooding during the second inter-monsoon (October ~ December) where it receives about 68% of its total annual rainfall. Its ancient pond system used to drain the accumulated runoff to the lagoon without much inundation. However, due to the dilapidating condition of the pond system, now the flood spreads out into the highly populated areas causing inconvenience to the public. This study seeks to identify the most sustainable pond rehabilitation approach for flood mitigation considering HEC-ResSim model results of the Paalkulam pond cascade in Jaffna Municipal Council. The analysis results show that in upstream ponds, bund level raising and pond bed dredging reduce the total inundation area by 27.5% and 19.7%, respectively. However, in downstream ponds, the results do not tally with the upstream ponds, where bund level raising reduces the total inundation area by only 21.4% while the pond bed dredging reduces the total inundation area by 34.3%. Therefore, results conclude that when the pond system is rehabilitated, the actual intervention at an individual pond should be based on its relative location in the cascade system in order to achieve sustainable results with positive impact on flood risk mitigation.

Keywords: Flood Mitigation; Inundation; Pond Cascades; Pond Rehabilitation; Water Sustainability

1. Introduction

Many urban areas are facing flood issues during high rainfall events due to the poor design and working condition of its drainage system [1]. The peak rainfall values in the dry zone are relatively higher compared to that in the wet zone [2]. The social and environmental damages from this disaster indicates the need of an immediate sustainable practice to overcome this crisis.

During October ~ November period, a higher rainfall is received in the Jaffna peninsula where it accounts for about three fourth of the total annual rainfall (Fig. 1) [3], [4]. The most recent flood in the Jaffna peninsula occurred in the year 2017 where a a considerably large extent of the peninsula was inundated. During the course of finding remedies for this long lasted flood crisis, authorities have suggested several alternative solutions. However, none of the solutions were proven successful including the rehabilitation/restoring of individual ponds [5]. Among the fifteen divisional secretariat divisions in the Jaffna district, the Jaffna

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Municipal Council (JMC) holds the highest population density of 2986 per km^2 [6]. Considering its significance for the living community, JMC area was selected for this study (Fig. 2). The municipal council area had had more than 100 of ponds where they were acting as the central water retaining mechanisms of the city stormwater management [7]. However, with the lack of proper maintenance, only 47 ponds are remaining at present. The primary reason for the physical damages to the pond system are the unawareness of the importance of the pond system for flood mitigation and pond encroachments [7].

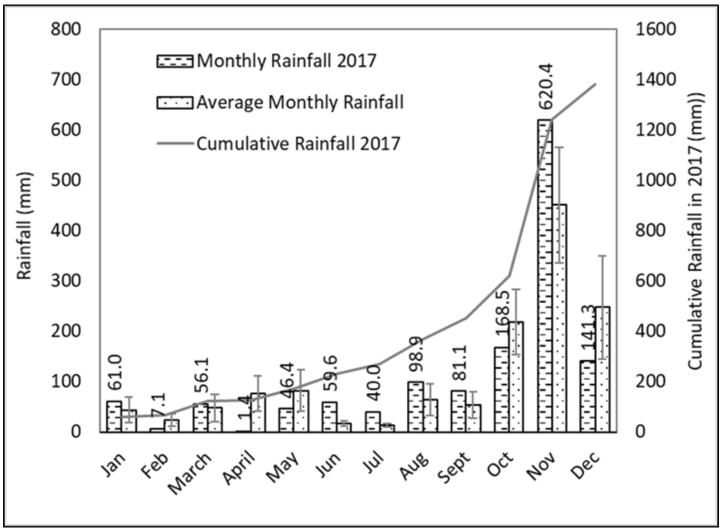

Fig. 1. The monthly rainfall pattern in Jaffna peninsula

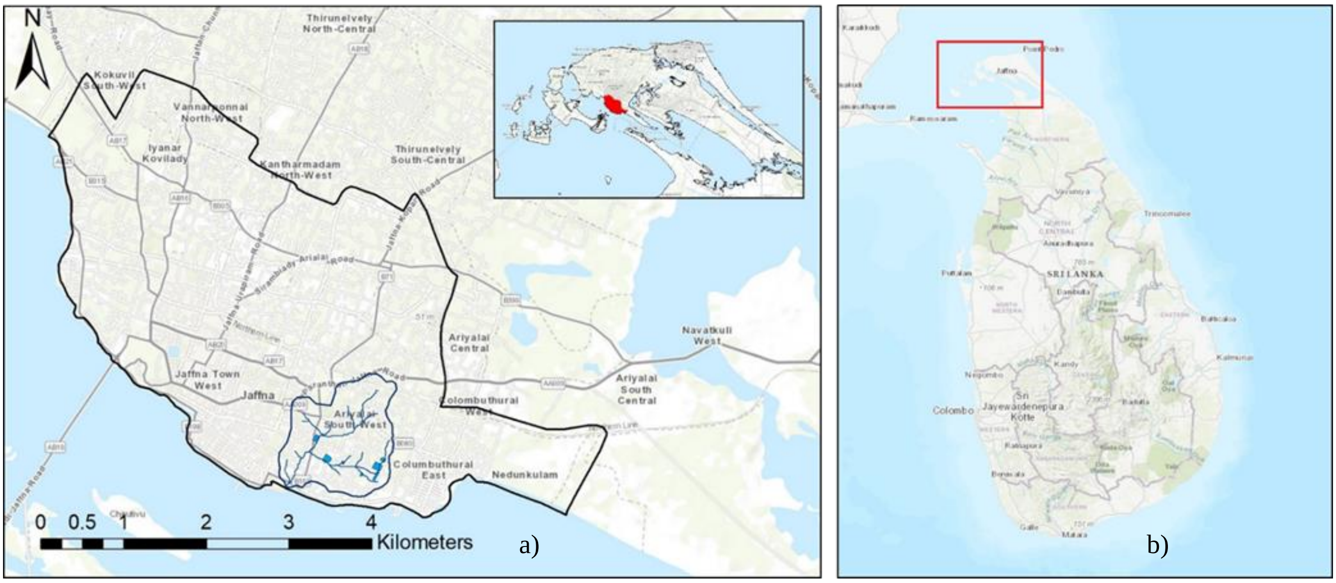

Fig. 2. a) Study area: Jaffna Municipal Council, b) Jaffna Peninsula in Sri Lanka map

Strategic development of the pond system rehabilitation approaches increases the water retention capacity [8] as well as sustainability of the system. The existing pond system acts as an interconnected water sharing network where it speedily distributes the nearby floods to the downstream. This holistic behaviour of water retention bodies is highly beneficial in flood mitigation until the connectivity is broken by the failure of one or more of ponds [9], [10]. When the 47 ponds in the Jaffna Municipal Council area are considered, many of them are not in proper working conditions, seeking immediate restoration [11]. If the pond cascade system is restored by identifying a proper methodology, flood issue is expected to be minimized. Further, it increases the total water retention and the net groundwater recharge. Since the peninsula is suffering from a severe water scarcity during the dry season, this approach can be identified as a viable solution. The holistic view of pond rehabilitation enables the maximum water sustainability in the cascade system. Several early studies have tried to identify the best methodology leading to the identification of the best rehabilitation approach for water retention bodies [8], [12], [13] focusing on different individual objectives . The present study engulfs an approach based on wholistic perspectives to achieve pond rehabilitation goals while recognizing sustainable aspects.

2. Materials and study objectives

The study focuses on finding the most reliable rehabilitation approach for flood mitigation and methodology was developed accordingly. Methodology compares two pond capacity increment tactics for higher stormwater retention. Forty-seven ponds in the Jaffna Municipal Council area were selected for this study and they fall into eight pond cascade systems according to the basin separation of the catchment. Out of these eight cascades, Paalkulam cascade which mothers to seven ponds was selected for this study (Table 1). This study uses a computer simulation application termed HEC-ResSim (Hydraulic Engineering Center, U.S. Army Corps of Engineers, USA) which is based on the water balance. A geographical information system was used to generate the flood contour maps to identify the inundation areas for different scenarios.

Table 1. Paalkulam cascade ponds

Pond	Total capacity (m^3)	Max. depth (m)	Pond	Total capacity (m^3)	Max. depth (m)
Vannankulam	5,525	2.5	Paalkulam	11,800	2.0
Maravakulam	7,175	1.5	Pasaiyoorkulam	4,975	2.0
Makkiyakulam	10,300	1.5	Vilaththikulam	4,200	2.0
Mudalikulam	1,575	2.0			

2.1. Study area

The Paalkulam cascade has a basin area of 156.7 ha and the land use pattern of the area is identical to the typical characteristics in majority of catchments in Jaffna where they are mostly residential and paddy cultivated area [14]. The topography of the area is relatively flat, and land elevation holds a maximum of 14 m AMSL (above mean sea level) and drops when reaching the shoreline. The climate of the region is tropical monsoonal with a seasonal rainfall pattern where the highest monthly rainfall is received during the month of November [6]. The temperature ranges from 26 ˚C to 33 ˚C and annual precipitation ranges from 847.7 mm to 1909.3 mm [6]. The second inter-monsoon (October to December) to the peninsula brings about 68%

of the total annual rainfall. The study area falls within two Divisional Secretariat (D.S.) administrative divisions, namely Jaffna Municipal Council and Nallur Pradeshiya Sabha [7].

One of the significant contributions of these pond systems in the study area is their groundwater recharge capabilities. The peninsula is receiving relatively much lower rainfall during the first nine months of the year, and many of the water needs are satisfied by the freshwater available as groundwater. Therefore, the aquifer system in the area is vital to meet the domestic and industrial water demand. The aquifer system in the region is a highly karstic Miocene limestone and freshwater is present as mounds or lenses by floating over the saline water [10]–[12].

2.2. Research objectives

The parimary objective of this study is to propose a sustainable rehabilitation approach for Jaffna pond system. The specific objectives of the study are to identify the cascade systems in the JMC area, and to find best rehabilitation approaches for upstream/downstream ponds.

If all the specific objectives are achieved, then the overall objective will inevitably be achieved. Then, the Jaffna communities will have a reliable water source and the flood hazards will be mitigated. Furthermore, the study results can be tested for different geographical locations and evaluate its adaptability to similar pond cascades elsewhere with identical management issues.

2.3. Data processing

HEC-ResSim computer application is used for the modelling of Paalkulam cascade and this application uses a simple water balance approach to model the temporal behaviour of the pond storage. The water balance equation for the storage change is given as in the Eq. (1)

$$\Delta S\ (Storage\ change) = Q_i(Inflow) - Q_o(Outflow) - E(Evaporation) - S_e(Seepage) \quad (1)$$

Table 2. Monthly average evaporation values of Thondamanar gauge station

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evap. (mm)	115.5	113.1	133.5	139.3	171	164.6	151.8	153	156	135	107.6	111.6

Study uses monthly average evaporation values (Table 2) of Thondamanar gauge station for the HEC-ResSim modelling. The pond survey maps were referred to identify the elevation-area-storage relationship of each pond in the cascade. Also, physical characteristics of the spillway were fed into the model using the data collected based on the pond survey maps. The daily rainfall data from the Department of Meteorology were used for runoff generation, and the pond seepage rate was taken as 0.5% of the storage [15].

2.4. HEC-ResSim modelling

Individual pond basins in the Paalkulam cascade were identified prior to the HEC-ResSim modelling. Runoff generation in each sub-catchment was taken as a lump and fed to the model. Computer application simulates the pond storage behaviour considering the physical characteristics of the canal network which connects two ponds. Moreover, when the water spills through the spillway, a part of it flows to the downstream pond and the balance causes the flooding.

There are three modules in the computer program which is being used for pond cascade modelling where each contains different sets of functions and data directories. First, modelling begins with the Watershed Setup module and it seeks the stream network and all the ponds in the system. Next, the Reservoir Network module is prepared using the pond physical characteristics and hydrological characteristics of the catchment. Finally, the simulation module carries out the model simulations and it shows the individual pond and canal behaviour [16]. The simulations were carried out using the daily rainfall data of the year 2017 to check the probable inundation area. The spill discharge rates during the second inter-monsoon were observed to be much higher and it results in hazardous flood situation in the sub-catchment levels. The 2017 flood did severe damages to the peninsula where it has been identified as one of the most hazardous events occurred in the last fifty years.

2.5. GIS flood analysis

Jaffna Municipal Council area was modelled using a geographical information system. From the spot height values and contour data of Paalkulam cascade, Triangular Irregular Network (TIN) and Digital Elevation Model (DEM) were generated. The results were validated by checking the elevation data extraction using the Google Earth software and ground truthing. Spatial analyst supplemental tool was used to generate the storage capacity relationship of each sub-catchment and in entire Paalkulam catchment, accordingly.

Cascade catchment area is divided into the miniature scale (sub-catchment), and for the quantified spill amount, the inundation area was identified. The exact procedure was followed, when the whole cascade was considered too. Those results can be directly used to test and prove the initial hypothesis. ArcGIS results play a significant role, to achieve the specific objective of this study and the cascade connectivity was totally ignored when the ponds were modelled individually.

3. Methodology

Prior to the methodology development, upstream (Vannankulam, Makkiyakulam and Pasaiyoorkulam) and downstream (Paalkulam and Maravakulam) ponds of the Paalkulam cascade were identified. The flood situations when the upstream bund level is raised, and the pond bed was dredged, were modelled using the HEC-ResSim application and ArcGIS toolkit.

The Paalkulam cascade is divided into seven sub-catchments considering the runoff contribution to individual ponds. During the rainy seasons, the generated runoff in each sub-catchment drains to the corresponding individual pond and pond spills when the Full Supply Level is reached. The HEC-ResSim computer simulation application identifies the net spill water quantity in the rainy period which causes the floods in the downstream.

3.1. Increasing the bund height levels

The first approach of the pond rehabilitation was bund height raising and this was followed for upstream and downstream ponds, separately. Each upstream/downstream pond bund height was raised by 0.5 m, and HEC-ResSim simulations were used to find the storage behaviour. Pond elevation-area-capacity input values were changed accordingly while all the other parameters were kept constant. The modelling procedure was same for both upstream and downstream ponds. HEC-ResSim model simulation dates on 1st of January, 2017 to 31st of December, 2017 for the simulations. Evaporation values and runoff generations from rainfall were fed to the model as described in the HEC-ResSim modelling.

Later, the total inundation area was established using the DEM generated for the cascade catchment area. The GIS flood analysis shows an inundation area of 21 ha was there before any rehabilitation approaches are taken place.

3.2. Pond bed dredging

The next approach was the pond bed dredging, and dredging quantity was calculated as it would be the same as the capacity increment by bund height raising. Dredging quantity is calculated using the Eq. 2.

$$\text{D}redging\ Quntity = \sum Reservoir\ capcity\ increment\ by\ bund\ height\ raising \tag{2}$$

The dredging quantity was distributed among them considering its individual capacity values. Eq. 3 illustrates the dredging quantity calculation for upstream ponds of the Paalkulam cascade.

$$\begin{Bmatrix} \text{Dredging} \\ \text{quanitty of} \\ \text{pond}_\text{i} \end{Bmatrix} = \begin{Bmatrix} Total \\ dredging \\ quantity \end{Bmatrix} \times \frac{Capacity\ of\ pond_i}{\sum_{j=1}^{n} Capacity\ of\ pond_j} \tag{3}$$

The pond Elevation-Area-Storage relationship was accordingly changed, keeping the pond bund heights constant, and depth value was changed in the range of 0.5 – 2.0 m. The dredging depth was identified following an iteration method (Fig. 3). When the storage ratio (Eq. 4) is higher than 4, dredging starts from a higher contour.

$$Storage\ Ratio\ (SR) = \frac{Dredging\ Quantity}{Maximum\ dredging\ upto\ 0\ m\ contour} \tag{4}$$

If the pond bed dredging was carried out assuming a conical variation of area-elevation, then the bottom area is calculated using Eq. 5.

$$Bottom\ contour\ area = \frac{2 \times Volume}{\Delta(contour\ height)} - Top\ contour\ area \quad (5)$$

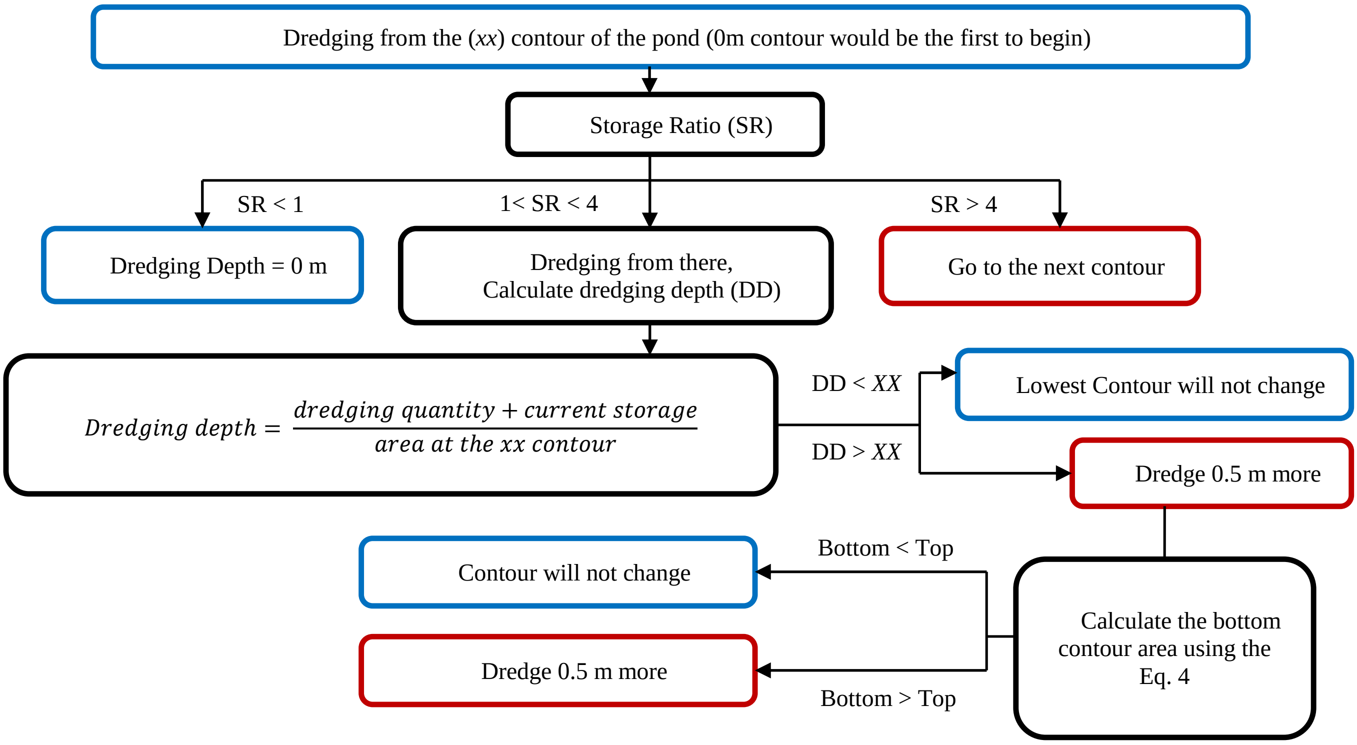

Fig. 3. Dredging Depth Calculation Method

3.3. Methodology development

Considering the cascade behaviour, two different rehabilitation approaches for flood mitigation were considered here and their model analysis results are to be used to identify the most suited approach considering the location of the pond in the cascade system.

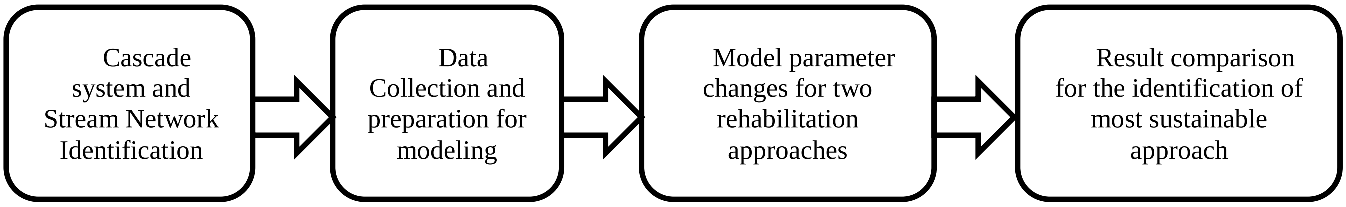

Fig. 4: Methodology Flow Chart

4. Results and Discussion

The scenario analysis results show that the upstream pond rehabilitation should be carried out by increasing the bund heights and downstream pond rehabilitation would be more optimised by dredging the pond bed. In this analysis, dredging quantity is determined by using the capacity increment by bund level raising and then it is distributed among the corresponding ponds. The dredging depth and contour lines are determined from an iteration method. The storage ration (SR) limit is taken as 4 from carrying out numerous sample calculations and checking for the best suited dredging option.

Subsequently, the total inundation area was established using the generated DEM of the cascade catchment area. The total catchment area of the Paalkulam cascade is 156.7 ha and before carrying out any rehabilitation approach, the inundation area was 21 ha. First, the upstream pond rehabilitation was carried out by considering the bund height level increasing and pond bed dredging. Later, the downstream pond rehabilitation was carried out for the same two rehabilitation approaches. The summary of the model simulation results is shown in Table 4. Further, the inundation areas of Paalkulam cascade for four scenarios (which were visualized using a GIS toolkit) are shown in Fig. 5.

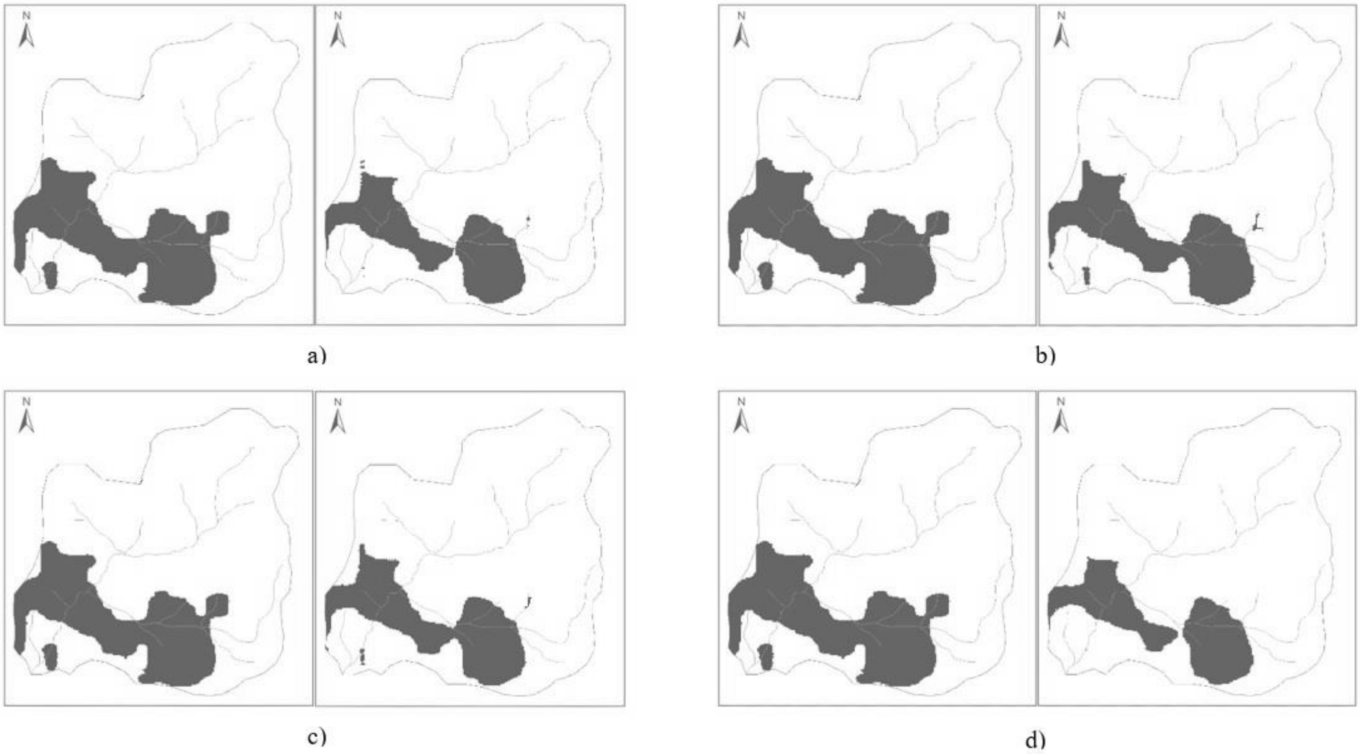

Fig. 5. a) Inundation Area Reduction after the Upstream Bund Raising, b) Inundation Area Reduction after the Upstream Bed Dredging, c) Inundation Area Reduction after the Downstream Bund Raising, d) Inundation Area Reduction after the Downstream Pond Bed Dredging

Table 3. Summary of different rehabilitation approaches

	Upstream pond rehabilitation		Downstream pond Rehabilitation	
	Increasing the bund levels	Pond bed dredging	Increasing the bund levels	Pond bed dredging
Inundation area (ha)	15.23	17.12	16.51	13.8
Reduction percentage (%)	27.5	18.5	21.4	34.3

When selecting the numerical value of 0.5 m for the step increment for bund raising, previous rehabilitation approaches were considered [8], [11], [12], [17]. Furthermore, the bund height increment of 0.5 m indicates a 0.5 m spill height increment. These two approaches (bund height raising/bed dredging) were not modelled simultaneously and only one parameter was changed in one simulation. The elevation-area-storage relationship of each pond was accordingly updated. The increased spill height and bund height upturn the stormwater retention in the pond and it results in a reduction in inundation area. However, further consideration should be given for the water balance in the system during the dry season where the downstream ponds highly depend on the upstream water sources.

When the upstream pond bed dredging was considered, the dredging quantity was decided by calculating the total capacity increment by spill height increment. Makkiyakulam has twice the capacity than the Vannankulam and Pasaiyoorkulam, and its dredging quantity (3664.42 m^3) was approximately twice than that of the other two (1965.63 m^3 and 1769.95 m^3). Though the dredging quantity if found, then there are two questions to follow. The dredging level is decided considering the ratio of dredging quantity and the maximum of dredging up to 0 m contour, (with/without changing the existing pond bed level). The pond capacity is increased and it changes the area elevation profile of the pond accordingly. This methodology may give fabricated outcomes if applied to larger water retention bodies. However, considering the extent of the pond capacities in the Paalkulam cascade, this dredging will not affect its boundary stability.

The scenario analysis was carried out to recognize the most sustainable rehabilitation approach for each pond. In this analysis, only pond bund height raising and pond bed dredging were considered, and for better results, various other rehabilitation approaches are recommended to follow.

5. Conclusion

As conclusions, it can be postulated that the upstream ponds/water retaining bodies in a cascade system should be rehabilitated by raising the bund and the downstream ponds/water retaining bodies should be rehabilitated by bed dredging. Further, when the pond connectivity for effective stormwater management is considered, the canal connectivity is vital as it helps directly distributing accumulated floods to the downstream ponds in the cascade system.

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