A CASE STUDY ON SUSTAINABLE RESTORATION APPROACH FOR CASCADE POND SYSTEMS IN JAFFNA MUNICIPAL COUNCIL AREA FOR EFFECTIVE FLOOD MANAGEMENT

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Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

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Thesis submitted in partial fulfilment of the requirements for the degree of

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DECLARATION OF THE CANDIDATE AND SUPERVISOR

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DEDICATION

I dedicate this thesis to my parents whose love, unselfish support and example over many years laid the foundation for the discipline and perseverance essentially required for me to complete this work successfully.

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I would like to express my sincere gratitude to my research supervisors Dr. R.L.H.L. Rajapakse and Dr. T.M.N. Wijayaratna for their guidance, suggestions and encouragement throughout this research for me to overcome the obstacles which I had to face in the completion of the case study and also for the knowledge that I gained by working under their guidance.

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Thilakarathne J.A.S.I.
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ABSTRACT

A Case Study on Sustainable Restoration Approach for Cascade Reservoir Systems in Jaffna Municipal Area for Effective Flood Management

A unique characteristic of dry zone rainfall is its higher peak rainfall, even though the annual rainfall is relatively low. Jaffna peninsula is located in the northernmost part of Sri Lanka and faces these critical storm events during the second inter-monsoon. The pond system in the area was acting as the major water retention body, however due to the lack of awareness and proper rehabilitation, their retention efficiencies have severely been reduced.

Research methodology was developed to check the effect of reservoir connectivity for flood mitigation. HEC-ResSim computer simulation application was used to model Paalkulam and Nayanmarkaddu kulam pond cascades in the Jaffna Municipal Council region. Model results were used to quantify the flood affected area and the results were validated based on a water balance model. Daily rainfall data of year 2017, pond survey (contour) maps, canal network and natural stream network were used. Two scenario analyses were followed to identify the reduction in inundation area after the inclusion of reservoir cascade behaviour and the two rehabilitation approaches for sustainable pond restoration.

HEC-ResSim modeling was continued for scenario analyses, considering the insignificant deviations (6~8%) with the water balance model results. During the 2017 flood hazard, 27.5% of Paalkulam cascade catchment area out of total 156.7 ha was flooded and it was found that the affected area could have been reduced to 13.2% saving 21.73 ha area (14.3% of the Cascade land area), had the cascade connectivity been restored. The bund raising and bed dredging approaches showed a flood area reduction of 4.5 ha (20.2%) and 7.2 ha (33.3%) for downstream reservoirs and 5.8 ha (26.4%) and 3.9 ha (17.2%) for upstream reservoirs.

Furthermore, the second scenario analysis for rehabilitation approaches confirmed that the most suited rehabilitation approach for upstream and downstream reservoirs are reservoir bund raising and reservoir bed dredging, respectively.

Therefore, for a sustainable pond rehabilitation approach, proper accounting of the cascade connectivity is vital. Moreover, the best pond rehabilitation approach highly depends on the corresponding pond location in the cascade.

Key words: *Flood Mitigation; Water Balance Approach; HEC-ResSim; Reservoir Prioritization*

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List of Abbreviations

Abbreviation	Description
JMC	Jaffna Municipal Council
HFL	High Flood Level
BTL	Bund Top Level
ASI	Average Storage Index
SR	Storage Ratio
DD	Dredging Depth
CS	Cascade System

1 INTRODUCTION

1.1 Background

During heavy rainfall events, many poorly designed urban areas are facing flood issues (Kuller, Dolman, Vreeburg, & Spiller, 2017). They need a proper methodology to overcome this crisis which otherwise brings many social and environmental issues. In many dry zone areas where a low average annual rainfall is being experienced, it has been observed that the peak rainfall during the rainy season is considerably higher than those in wet zone (Alam, bin Toriman, Siwar, & Talib, 2011). Flooding in the urban areas always affect the economy in a negative way (Berry, Yassin, Belcher, & Lindenschmidt, 2017). When the average monthly rainfall in Jaffna peninsula is considered, it is observed that during October- November period, the precipitation is relatively high. The Jaffna peninsula, spanning through a 1025 km^2 land area, has faced many flood disasters in recent times and the 2017 flood can be identified as one of the most damaging in the recent past. During the post disaster phase, many authorities tried to find a better solution and has addressed various key points targeting flood mitigation such as increasing the retention and detention time periods in the catchment. Due to the existence of ponds which have initially been used for water retention purposes (Shanmugarajah, n.d.) in the urban area, this can be considered as a feasible option to test. The upstream ponds in the catchment area can detain a considerable amount of stormwater which will cause a retardation in the flood wave (Madduma Bandara, 2009).

A 14.06% of the Jaffna peninsula's population lives in the Jaffna Municipal Council (JMC) area and JMC has the highest population density (Rajeswaran, 2005) of 2986/ km^2. This value is 66.72% higher than the next highly populated area, Nallur. Therefore, Jaffna municipal council area was selected for this case study since a larger number of people are getting affected by the flood issues especially during the inter monsoon period. In the first chapters of the 20^{th} century, there had been more than hundred ponds in JMC area in full working condition (Thushyanthy & De Silva, 2012). However, today only about half of them are remaining and out of that a limited number of ponds are in proper working conditions. Since the urbanization has hit the Jaffna city area in both positive and negative ways, many encroachments near to these ponds can be seen. It has been observed that the capacities and efficiencies of the ponds are getting decreased rapidly due to this (Rajeswaran, 2005; Thushyanthy and De Silva, 2012; IWMI, 2013).

Furthermore, apart from the flood hazards in the second inter monsoon, Jaffna community faces severe droughts during the rest of the year. In this case study on sustainable restoration approach for cascade pond systems in Jaffna municipal area for effective flood management, a consideration is given for the water scarcity in the dry season as well. The inability to fulfil the total water demand from the existing quantity of water available is called as the water scarcity (Janen & Sivakumar, 2014; Sivakumar, 2015). Water scarcity in the peninsula is threatening the environment and the social life and it is not second to the damage done by monsoon flooding. Due to the absence of a perennial rivers in the peninsula, the existing pond system acts as the main source of groundwater recharge. A striking feature of the groundwater source in the peninsula is, its limestone aquifer system which is known for its higher water retention capacity (Hidayathulla & Karunaratna, 2013; Mikunthan et al., 2013a). These pond systems are generating a considerable interest in terms of flood mitigation and sustaining water security in the region.

For an effective flood management in the peninsula, the water holding capacity of ponds has to be increased and the increased water retention can be expected to enhance the groundwater recharge. The fundamental characteristic of the pond cascade system is the interconnected water sharing network. Therefore, a failure of one pond will negatively affect the downstream ponds and in turn the total cascade system efficiency will reduce (Panabokke, Tennakoon, & Ariyabandu, n.d.; Tennakoon, 1999). However, the present condition of these ponds are not satisfactory and many ponds are seeking an immediate rehabilitation actions (Itakura, 1995). If the pond connectivity is restored, it is expected that both the flood issue and water scarcity can be reduced by storing a higher water quantity in the system which will help to reduce the flood volume and increase the water recharge to the aquifer system.

From a longer period of time, numerous water management projects have been proposed to increase the water availability in Jaffna peninsula. However, previous work could not address this issue considering the pond system as a holistic unit. Due to many circumstances, some were stopped at the initial stage and many were limited to a project proposal. In the later 1970s, a project proposal was brought to convert the Jaffna lagoon to a freshwater lake (Kuganesan & Sivakumar, 2016). However, the response of fishery societies towards this was not positive as the lagoon is the major prawn cultivation location in their fishery industry. If the proposal was carried into action, it would have damaged the ecological relationship of the peninsula and this was raised by many environmentalists (Kuganesan & Sivakumar, 2016). Water supplying from the Iranamadu reservoir in Kilinochchi was proposed as another solution for this water crisis and it as well was unsuccessful, after Kilinochchi community raised the concerns about their own water problems. A crucial issue of these previous water management proposals is their complexity. Rather than using the existing sources, they have looked into ideas which are ill-defined and thus failing at the end.

This present study predominantly outlines a new approach to increase the quality and quantity of the groundwater recharge in the peninsula. Freshwater availability will be increased and many water related issues can be overcome by this. Recent findings regarding the water extraction from Jaffna limestone aquifer says that the extraction exceeds the recharge. Therefore, it results saltwater intrusion to the freshwater lenses and reduce the water quality. Also the available fresh water quantity will be reduced to a critical level during the dry season. There still exists some controversy surrounding this hypothesis, and once it is adequately proven, it can be used as a sustainable water management approach.

In the beginning of the 21st century, authorities understood the importance of the existing pond network in Jaffna peninsula and individual pond rehabilitation projects have been implemented. However, the pond connectivity had been totally neglected and it had resulted a devastating failure of the ponds in the immediately next flood season.

Moreover, other approaches have failed to provide a better water availability to the Jaffna community. With the recent developments in the region, existing water retention structures are getting damaged due to the unawareness of the local residents.

Followings are observed as the major issues on the failure of the cascade system and individual ponds.

- Sediment accumulation in ponds and channel network
- Barriers to the connectivity of ponds (debris, garbage, etc.)
- Damages to the substructures
- Plant invasion on the surface of the pond and other components
- Disturbances to the pond catchments
- Encroachments

Among the several hundreds of ponds present in the peninsula, forty-seven functional ponds are present in the JMC area and considered for the present study. This approach can be identified as a preliminary attempt to examine the effect of pond cascade systems for sustainable water retention and flood mitigation agenda in the region. The study results would be useful to reduce the water scarcity issue in the Jaffna peninsula area which has distinct dry zone weather conditions.

The whole study is based on the water balance approach and manual calculations and real-time data are used to verify the simulation application results. Many simulation applications are proposed and considering their individual performance, the most suitable application is to be chosen. The stream network in JMC area, catchment characteristics, weather and climate data and pond physical characteristics are considered for the hydrological analysis. Individual and holistic behaviour of pond storages are simulated using the water balance equation (Eq. 01).

$$\text{Storage} = \left\{\begin{matrix}\text{Inflow}\\ \text{from}\\ \text{upstream}\end{matrix}\right\} + \text{precipitation} + \left\{\begin{matrix}\text{Outflow}\\ \text{to the}\\ \text{downstream}\end{matrix}\right\} - \text{Evaporation} - \text{Seepage} \qquad (1)$$

Monthly end storage values for different conditions and scenarios were manually calculated using the Eq. 1 (Ponrajah, 1984). Considering the limitations of the manual calculations, a computer simulation application was chosen and hydrological model was tested considering the individual ponds and pond cascade systems.

1.2 Study Area

The Jaffna Municipal Council area lies in the Southern part of Jaffna Peninsula between the latitudes 9° 38' North and 9° 42' North and between the longitudes 79° 59' East and 80° 03' East (Figure 1.1). The Municipal Council consists of Jaffna and part of Nallur Divisional Secretariat Divisions and it is the local authority for the Jaffna city in northern Sri Lanka which is responsible for providing a variety of local public services including roads, sanitation, drains, housing, libraries, public parks and recreational facilities. The area of the JMC is about 18.62 km^2 and the council is longer in the East – West direction measuring a maximum of 6.8 km in length and its width varies from 1.0 to 4.0 km.

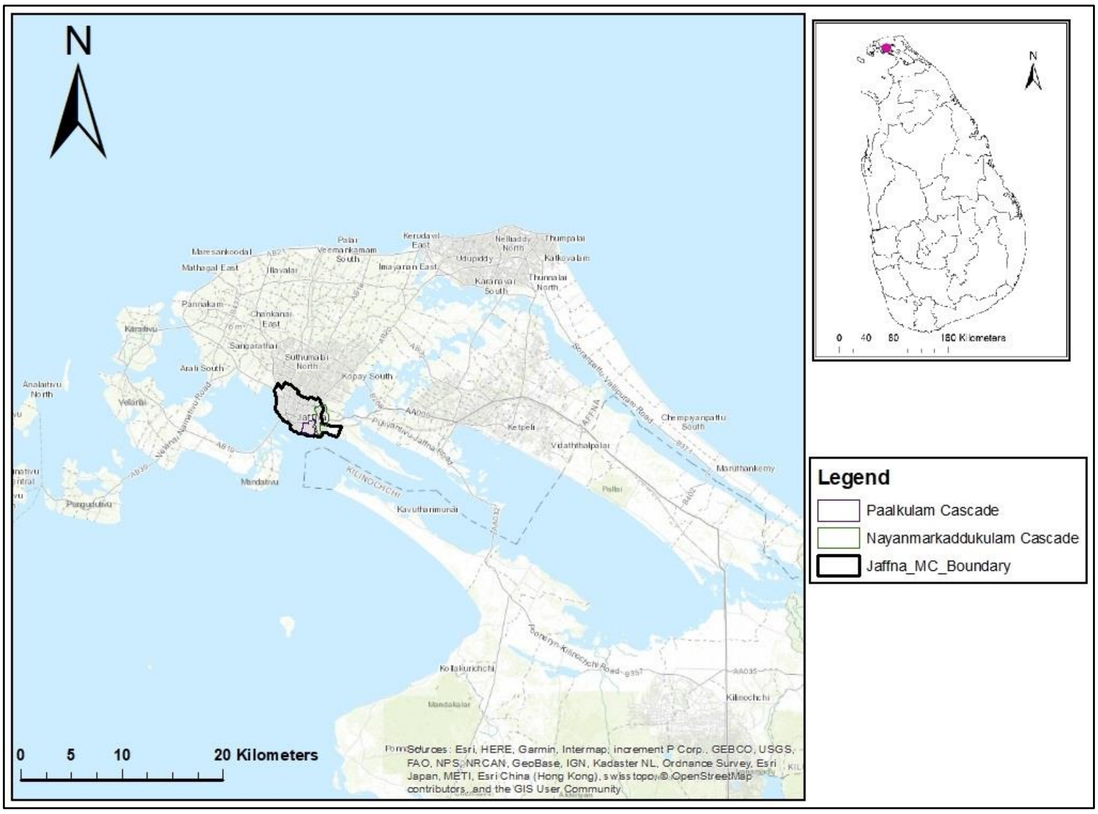

Figure 1.1: Jaffna Municipal Council Area

The Jaffna lagoon forms the Southern boundary of the municipality. This area is characterized by the karstic coastal plains of the island. The area is highly sensitive both in hydrological and environmental terms, where the terrain is mostly flat and undulating towards the Lagoon with land elevations ranging from +0.3~+10.0 m AMSL in the region.

1.2.1 Ponds in the Jaffna Municipal Council Area

Forty-seven ponds were identified in the Jaffna Municipal Council area and their connectivity was identified using the existing stream network, canal network, DEMs of the JMC area and identified eight pond cascades are tabulated as in Table 1.1.

Table 1.1: Ponds in the Jaffna Municipal Council area

Cascade 01	**Cascade 02**	**Cascade 03**	**Cascade 04**
Sinnakulam Uppukulam Vannankulam Nedunkulam	Ilanthaikulam Nayanmarkaddu kulam Pirapankulam Purakulam Neernochchithalvu kulam	Vannankulam Maravakulam Makkiyakulam Mudalikulam Paalkulam Pasaiyoorkulam Vilaththikulam	Moondukulam Thevarikulam Pillaiyarkovil kulam
Cascade 05	**Cascade 06**	**Cascade 07**	**Cascade 08**
Nedunkulam Katkulam Thamaraikulam	Kannathiddykulam Vannankulam Vattakkulam Pullukulam Kallu kulam Neeraviyadi kulam Nedunkulam Thamaraikulam Vannankulam	Rjalikulam Nachchimarkovil kulam Anjuthankulam Nariyankundu Kulam Kompayan Kulam Sinnapalli Sinnakulam Sinnapalli Periyakulam Thurumpan Kulam	Pandarakkulam Yamuna Eri Cheddiyarthodda Kulam Poothavarayar Kulam

Considering the modifications to connectivity to the canal systems, slight changes to the identified cascades were introduced and two scenario analyses were carried out only for the Paalkulam cascade. Moreover, the water balance approach was applied for both Paalkulam and Nayanmarkaddu kulam cascades.

1.2.2 Topography and Drainage

The topography in the Jaffna Municipal Council area can be recognized as a flat terrain with very mildly sloping towards the Jaffna Lagoon. There already exists a drainage network which connects the ponds to the stormwater drainage network. However, this stormwater drains are not currently in a proper working condition. Considering the relative elevation distribution in the area, some of the canals are driven to the lagoon and others are driven to inland. Due to the heavy rainfall during second inter monsoon period, the water level of the Municipal Council area close to the lagoon can unexpectedly increase leading to flooding mainly due to pond overflowing. This is adversely affecting the residents and various economic activities are also affected during the flood time periods.

The natural drainage connectivity in the peninsula is formed mainly along the valleys and due to the relatively flat terrain in the area, stormwater is expected to flow very slowly. Therefore, during the flood season, stormwater stagnates leading to floods. Along the drainage linkage, sub-catchments are located contributing the accumulated stormwater to the corresponding ponds. When the rehabilitation process of the pond system is considered, it is envisaged that a holistic overview reflecting natural set up of the present drainage arrangements will produce a better and sustainable water retention system.

The existing ponds in the peninsula act as the stormwater retention and detention mechanism while providing storage capacities for considerable rainfall events. They also function as a sustainable groundwater recharging zoning structure and contribute to balance the natural ecosystem in the region. The attenuated stormwater is then driven to the linked canal system before releasing into the Jaffna lagoon or into the peninsula. The existing drainage system in the JMC area is shown in the Figure 1.2.

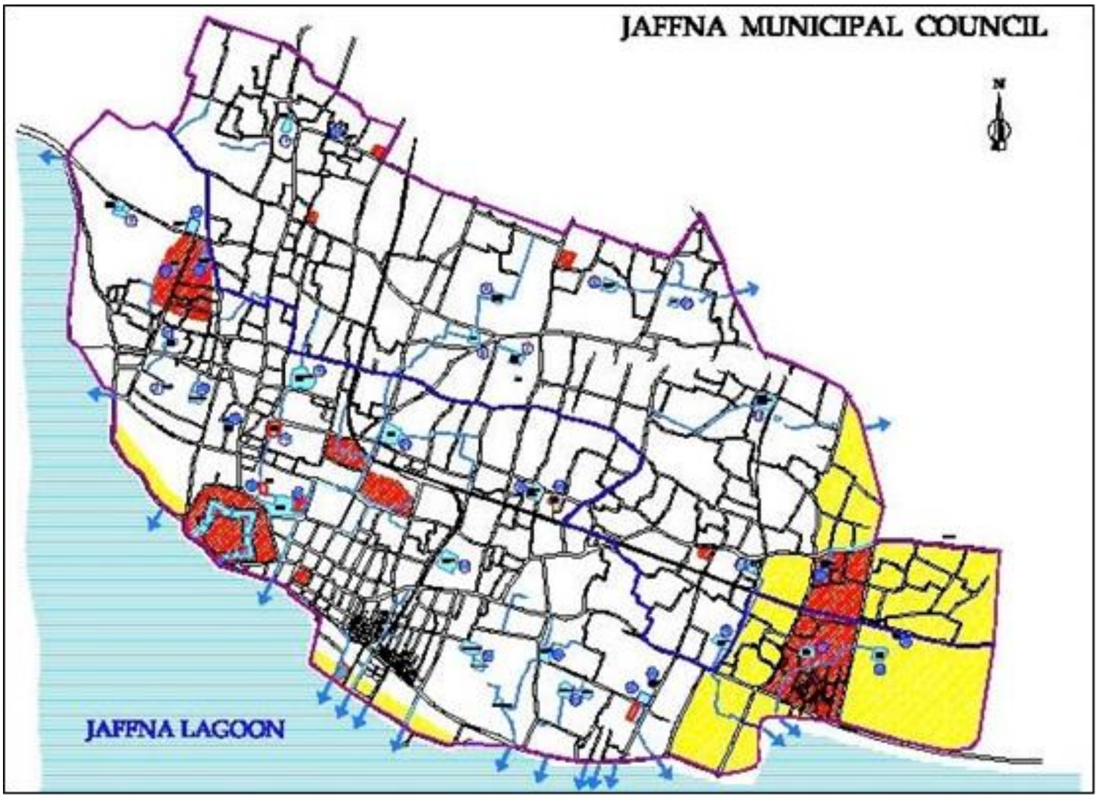

Figure 1.2: JMC Drainage Network
Source: Rajeswaran (2005)

1.2.3 Pond Characteristics

Pond clusters in the JMC area are very useful for stormwater management and therefore many flood hazards can be prevented while acting as groundwater recharging sources (Punthakey & Gamage, 2006). Since no perennial river is present in the peninsula, only source of water is the precipitation and accumulated stormwater is directed to the ponds by the existing stormwater drainage system. It has been observed that during the dry period, some of the ponds are retaining considerable amount of water quantity (Joshua, Thushyanthy, & Nanthagoban, 2013). However, the water quality of these ponds is poor and therefore water usage is limited and at resent, they are hardly being used for domestic purposes.

Among the identified 47 ponds in the Jaffna Municipal Council area, many of the ponds are lacking satisfactory storage capacities mainly due to the siltation over the time and encroachments by the nearby people. Therefore, enhancing their capacities is a much needed remedy and a comprehensive study on the pond system and related ecosystem and natural habitat is recommended prior to the pond rehabilitation process. When the pond rehabilitation is considered, it can be pond bed dredging, increasing the bund heights or strengthening the pond structures for critical storm conditions. The rehabilitation process should also focus on strengthening the pond spillway, embankment or regulatory structures as well.

The corresponding catchment of each pond should be well surveyed for encroachments which may be obstructing the natural drainage system. Especially, the nearby land area of the pond should be assessed for horizontal expansion of pond capacity.

Since the pond system retains the stormwater generated in the upstream catchment area, it prevents the flash flooding. Many ponds in the region are acting as the key groundwater recharging mean and therefore it can be clearly stated that their contribution does not limit to a mere flood mitigation. The main water uses of these ponds are irrigation, usage for nearby temples, washing clothes, water source for animals, etc. Further, the pond contribution to the Jaffna fauna and flora cannot be neglected and to sustain the natural ecosystem, their active contribution is highly desired. Subsequently, when the pond water retention is increased, it increases the groundwater water availability as well. It will lead to have a higher water flow into the dug wells located near to the ponds. However, the residents are not aware of this correlation and they believe the pond system cannot be used for any domestic or industrial purposes. Therefore, they do not pay a much attention on the well-being of these pond systems. That can be identified as a major reason for pond encroachments and their continuous deterioration.

In the recent times, it is very common that people are using pumps to use water for irrigation and industrial purposes. Excessive pumping of groundwater can cause saltwater intrusion into the Jaffna aquifer system and freshwater availability can be highly affected. Moreover, the groundwater pollution is also a major issue which should be addressed in an engineered way and due to various types of pollutants, the available freshwater quantity is rapidly decreasing. Therefore, a proper rehabilitation of ponds in Jaffna Municipality area will increase the living standards by increasing the freshwater availability and reducing the flood hazards. Community awareness programs will also be required to educate the local citizens about the direct and indirect benefits of pond systems to their livelihoods, thus changing their attitudes.

1.3 Research Problem

The rainfall pattern in Jaffna peninsula is creating a high flood situation in the second inter monsoon and during the rest of the year, community is suffering from severe droughts. Many social and environmental issues have arisen due to this challenging climate pattern in the region (Kandiah & Miyamoto, 2016) and proposed solutions to this so far are ill-defined and not well grounded.

The core problems for the severe floods in the rainy season and crucial water scarcity during the dry period is sought to be unveiled from this study. Furthermore, this study examines the applicability of cascade behaviour of pond systems for an efficient stormwater management approach. The results are expected to resolve the described community issues in the peninsula. During the dry season, the local community in Jaffna peninsula is totally dependent on the groundwater storage in the aquifer system and surface water availability is none or the available water is polluted. Therefore, it is clear that water scarcity problem has not been dealt with in depth. However, previous studies suggest that only 33% of the precipitation penetrates into the aquifer system (Institute International Water Management, 2013; Panabokke & Perera, 2005).

During the second inter-monsoon period (October to December), a very intensive rainfall is expected in the peninsula where in the year 2017, it was more than 65% of the total annual average rainfall in the region. For the past decades, the existing stormwater drainage system in the peninsula is continuing to fail, resulting a massive flooding in the area. This has been identified as another problem which the Jaffna community faces.

The residents in the Jaffna peninsula are not exactly aware of the importance of the existing pond system in recharging the groundwater aquifer. For many years, these pond systems in the peninsula have been used for all the domestic, irrigation and industrial needs. However, the recent developments in the JMC area have led to abandon some of the ponds and the rest is only used for castles and Hindu temple purposes. During the last two decades, a considerable reduction of available water quantity has been recorded (Thushyanthy & De Silva, 2012). The domestic and irrigation well water levels have decreased but still people are not aware of the simple connectivity of surface water and groundwater. Within the next few years, groundwater levels will be further reduced and then it will be too late to find solutions. Exclusive groundwater extraction has resulted saltwater penetration into the aquifer system by in equilibrium of pressure forces (Panabokke & Perera, 2005; Thushyanthy & De Silva, 2012).

The existing stormwater management system in the Jaffna peninsula is not much effective where retained water quantity is relatively very low and it results a lower groundwater recharge and higher flood levels. Moreover, the surface water retention is less than 35% of the total precipitation and it has become a vital aspect in water sustainability in the region (Kuganesan & Sivakumar, 2016; Punthakey & Gamage, 2006). The water retaining structures and substructures are deteriorated and that as well is a major problem in the peninsula. Among the forty-seven ponds in the JMC area, only a few has a higher water storage during the year. However, as a whole, the cascade water distribution has failed in all the identified cascades.

A better stormwater management approach should be restored in the peninsula as soon as possible and immediate actions should be taken in rehabilitating and conserving the existing pond systems. An approach which will be suited for the study area is to be analyzed and its feasibility to be further discussed under this present study.

1.4 Overall and Specific Objectives

The long lasted water crisis in the Jaffna peninsula can be well addressed if the research objectives are well achieved. The overall objective of this study is to propose a sustainable rehabilitation approach for Jaffna pond system and the specific objectives of the study are,

- Identification of cascade systems in the JMC area
- Carrying out the manual water balance calculation and checking the applicability of a proper computer simulation application.
- Pond prioritization for rehabilitation.
- Identifying the effect of pond cascade behavior on flood mitigation.

- Identifying the best rehabilitation approach for upstream ponds.
- Identifying the best rehabilitation approach for downstream ponds.
- Considering the future works on this case study.

If all the specific objectives are achieved, then the overall objective will inevitably be achieved where the Jaffna peninsula communities will have a reliable water source and the flood hazards will properly be addressed. Furthermore, the study methodology can be tested for different geographical locations while evaluating its adaptability for various scenarios.

2 LITERATURE REVIEW

2.1 Introduction

Literature survey is carried out considering five main aspects related to the study, namely pond restoration and rehabilitation approaches, cascade connectivity behaviour of ponds, water balance approach, Jaffna groundwater system, stormwater management and flood mitigation. Many of the studies were on irrigation tanks/reservoirs and this was a major shortcoming since the proposed study is eyeing on small scale water retaining structures (ponds) which are currently not being used for irrigation purposes.

Water scarcity problem in the Jaffna region is negatively affecting the community life. Relatively very low rainfall, throughout the many part of the year results this water scarcity in the area (during months of January-September) (Rajeswaran, 2005). However, an effective storm management approach with any other solution to reduce the perilous water scarcity is still sought for the living community and ecosystem of the region. In order to understand the classical water balance approach, literature review was structured integrating all possible types of scenarios. This directs to identify the weaknesses and strengths of past water balance approaches and helps to build an improved approach.

Since the study is looking into the rehabilitation and restoration of forty-seven ponds in the Jaffna Municipal Council area, past literature on tank/reservoir rehabilitation or restoration approaches are identified considering the extent of the study. Number of studies have been carried out on many village tanks in the central part of the country. In the classical approach of reservoir rehabilitation, it considers about the correlated behavior of the reservoir with the ecosystem as well. Today, many of the existing reservoirs/tanks have been gaining much attention with the intention of increasing the retention capacity due to regional change of climate pattern.

In the recent times, it has been observed that the flood risk is increasing and many urban areas are facing frequent flood hazards. This common concern has adversely affected community life leading to numerous social, environmental and economic damages. When a better stormwater management approach is developed for Jaffna city area, it is expected that the living standards of the community will improve and it will lead to a rapid development in the area as well.

2.2 Comprehensive Review

2.2.1 Pond Restoration and Rehabilitation Approaches

The systematic behaviour of minor tanks as a unit is identified for rehabilitation process and following six components should be considered for an inclusive rehabilitation (Panabokke, Wijayaratna, Sakthivadivel, & Fernando, 1996). The proposed framework for reservoir cascade rehabilitation focuses on six major fragments of holistic cascade unit and can be categorized as follows.

- Water Shed Boundary of the Meso-catchment
- Individual Micro-Catchment Boundaries of Small Tanks
- Main Central Valley
- Side Valleys
- Axis of the Main Valley
- Small Tanks and Irrigated Lands

In their study, small reservoirs in the North Central Province have been considered and two cascades named as Toruwewa and Kadiragama cascades have been identified. Furthermore, authors identify the criticality of identifying these six key aspects for cascade behaviour while missing the discussions on rehabilitation approaches. Itakura (1995) as well uses the connectivity of minor reservoir systems and has been gaining much attention due its practicability in irrigation purposes. However, the connectivity of many watercourses are not considered here and only one water path is assumed to be present.

When the average annual rainfall in Sri Lanka is considered, the land area is divided into three major climatic zones (two basic climate zones, termed as dry zone and wet zone and an intermediate zone) and many studies underline this fact of cascade location in cascade inflow generation (Dharmasena, 2000; Natural resources energy and science authority of Sri Lanka, 1991; Tennakoon, 1999; “Time and Space Characteristics of runoff,” 1976; Wijesekera, 2018). It has been questioned

(Panabokke, 2009a; Panabokke et al., n.d.) on the present reservoir rehabilitation planning process in many occasions. They claim that the process adopted by the local agencies does not properly discuss the sustainability of these rehabilitation approaches and the issues arising following the rehabilitation work.

Importance of proper assessment of groundwater potential, recharge and the possibility of harnessing groundwater to complement rain water and tank water to increase overall cropping intensity is suggested prior to a comprehensive rehabilitation and restoration analysis (Nagarajan, 2013; Punthakey & Gamage, 2006; Rutherfurd, Jerie, & Marsh, 2000; Subramanya, 2008; Vincenzo & Molino, 2013).

A study conducted on stormwater wet pond and wetland management has identified possible causes for reservoir deterioration due to following reasons (Environmental Protection Agency, 2009).

- Sediment accumulation (leading to storage volume reduction)
- Debris blocking the outlet structure
- Damages to pipes/ risers
- Invasive plant growth on reservoir surface
- Losing the slope stabilizing vegetation
- Compromising the structural integrity of embankment, weir or riser

The main pitfall of this study is that the authors do not elaborate possible causes for these failures. Instead, this pond water management study tries to find critical failures in the pond system rather than attempting to identify the likely pond rehabilitation approaches.

During the process of pond/small reservoir system rehabilitation, priority should be given to increase the water sustainability in the system rather than merely increasing the individual pond capacities. (Abdullah, 2013; Chang et al., 2008b; Choo, Huh, Yoon, Yun, & Son, 2016; Rathnayaka et al., 2011). Also many studies focus on individual reservoir rehabilitation rather than considering their inter-connectivity (Abdullah, 2013; Choo et al., 2016; Rathnayaka et al., 2011). Their framework is limited to its own catchment characteristics and therefore its applicability to other areas would give dubious results. Several studies, for example Chang et al. (2008a) has been conducted in developed urban areas where a better conveyance system and advanced engineered knowledge is applied. A key problem with almost all the studies on pond rehabilitation is that their results merely recommend a rehabilitation approach considering the geographical location of the system.

The water development mechanism proposed by Sakthivadivel, Fernando, Panabokke, & Wijayaratna (1994) highlights all the reservoir components (reservoir, reservoir catchment, neighboring highlands, reservoir command area and drainage area of the tank) as small geographically and socially integrated units of micro watersheds. This approach seems to be trustworthy and the authors have investigated on integrated rural development planning and implementation as well. Furthermore, it is highly recommended to have the farmer community's collaboration on the reservoir/pond rehabilitation process (Alam et al., 2011; Berry et al., 2017). However, when the urban pond systems are considered, the involvement of farming organizations is not vital. Following rehabilitation approach is employed by Sakthivadivel et al. (1994) and it is based on the reservoir cascade behavior.

- Framework for Characterizing TCS
- Guidelines including Indicators and Criteria
    - Characterizing and Evaluating Their Potential
    - Identifying the Surface Water Extraction
    - Tank Selection for a Sustainable Design for Rehabilitation
- Criteria Selection for Agro Well Development in Upland and Lowland Area
- Design Parameter Selection for Water Resource Development
- Guidelines for Technical, Management and Socio-Economics Analysis
- Improved Implementation Strategy for Water Resources Development Component

Their findings on catchment identification are only valid in areas where ridges and valleys are present. In an attempt to identify the catchment boundary in a low-lying flat terrain, modern technology such as satellite images should be followed.

2.2.2 Tank/Reservoir/Pond Cascade Systems

The importance of tank cascade systems for higher water efficiency is widely discussed considering the village tanks in the North-Central province of Sri Lanka.

(Bandara, n.d.; Itakura, 1995; Jayakody, Mowjood, & Gunawardena, 2004; Kruijne, van Bakel, Adriaanse, & Boesten, 2008; MaddumaBandara, 2009; Somaratne, Jayakody, Molle, & Jinapala, 2005; Tennakoon, 1999). Though the terminology 'Reservoir Cascade System' is widely being used in surface water systems, the idea was not frequently addressed during studies up until the mid-twentieth century. There are many occasions where the reservoir cascade systems were being used for irrigation planning and village tank restoration projects (Ariyabandu, Panabokke, & Tennakoon, n.d.; Bandara, n.d.; Itakura, 1995; Panabokke, 2009a; Panabokke et al., 1996).

Two types of reservoir cascade systems are identified as *"linear cascades"* and *'branched cascades'* (Ariyabandu et al., n.d.). Though the branched cascades have been gaining much attention due to its common availability, very little is known about the linear cascades where all the reservoirs are connected along a one single watercourse. Various approaches have been put forward to identify reservoir cascades and in one case cropping intensity of minor tanks has been taken as a reliable and readily parameter (Panabokke et al., 1996).

When the upstream reservoirs' bunds are raised with the intention of having a higher water retention, it leads to have severe water shortages (especially for irrigation purposes) in the downstream command areas (Sakthivadivel et al., 1994). Another study on reservoir cascade behaviour for sustainable water management which was conducted in Anuradhapura, Sri Lanka concludes that reservoir connectivity optimizes the usage of the limited water resources in tank cascade systems for improved agricultural production (Jayatilaka, Sakthivadivel, Shinogi, Makin, & Witharana, 2001). Moreover, the reservoir location in a particular cascade has been considered on a scientific base where it would lead to optimize the cascade water retention (Tennakoon, 1999). The number of reservoirs in a particular cascade does not only depend on its geographical conditions, but on socio-cultural and economic systems as well (Somaratne et al., 2005).

Depending on the reservoir location on the cascade, reservoirs can be identified as start reservoir, confluence reservoir and normal reservoir (Jayatilaka et al., 2001) (Figure

2.1). When studying on the reservoir interconnectivity, identifying the reservoirs as nodes and connecting paths as links is frequently used.

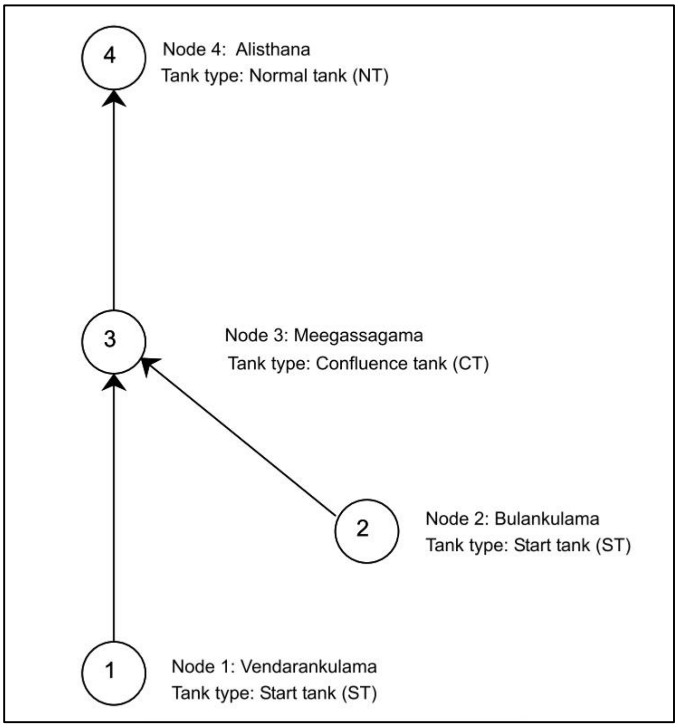

Figure 2.1: Thirappane Cascade System in Node-Link Model
Source: Jayatilaka et al. (2001)

When prioritizing reservoirs in a cascade system for rehabilitation purposes, there are many characteristics to be considered. In various analyses, parameter selection has been done considering the command area, individual catchment area, reservoir working condition, cascade efficiency, etc. (Jayatilaka et al., 2001; Kruijne et al., 2008; Madduma Bandara, 2009; Yoshiyuki Shinogi, Makin, & Witharana, n.d.). Several studies, for example Somasiri (1991) have been carried out considering cropping intensity as a parameter. However, its adoption is limited to cases where the reservoirs are being used for irrigation purposes.

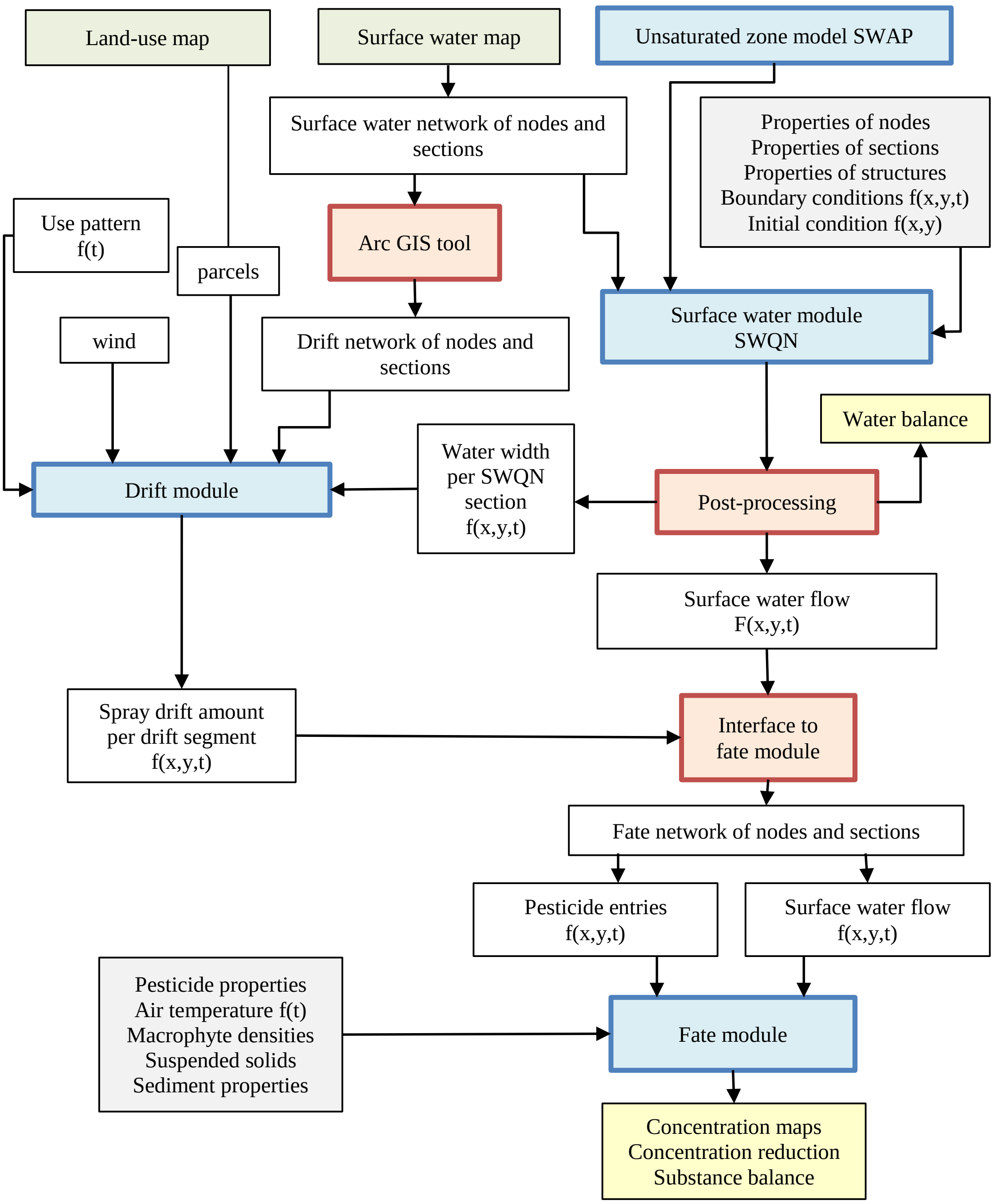

Figure 2.2: Model Components of Model Instrument Cascade
Source: Kruijne et al. (2008)

Another study carried out to check the surface water hydrology of a cascade system has used ArcGIS and SWQN for cascade modeling (Kruijne et al., 2008). In their analysis cascade behaviour is considered to predict the pesticide exposure concentrations at regional scale. Model components are shown in Figure 2.2.

When the cascade behaviour of reservoirs are being used for rehabilitation purposes, it integrates the hydrological, technical and socio-economic components of a reservoir system (Itakura, 1995). A serious criticism of many literatures followed on cascade reservoir systems are their limitation into irrigation reservoirs. However, the key parameters used for intra cascade system analysis are their Maha cropping intensity, ratio between reservoir catchment area and reservoir water spread area, and ratio between command area and water spread area (Bandara, Yatigammana, & Paranavithana, 2010; Janen & Sivakumar, 2014; Jayatilaka et al., 2001). These key points are vital in reservoir identification and prioritization for rehabilitation and many experts believe the cascade behaviour should be restored to increase the water sustainability.

Though many studies were there on reservoir cascade systems, their analysis has not received general acceptance on using it for rehabilitation purposes. However, the literature survey outlines that the reservoir connectivity increases the total water sustainability in the study area. Hence, for reservoir rehabilitation process, it is highly recommended to apply the reservoir connectivity.

2.2.3 Water Balance Approach

Capacity and monthly storage variations are the major characteristics of a reservoir and these should be considered prior to the rehabilitation (Güntner, Krol, Araújo, & Bronstert, 2004a). The most common tactic to study the reservoir storage variation is the water balance approach. However, it does not limit to determine the corresponding reservoir storage. For many scientific studies, this mass conservation approach is being used for studying the residual water quantity and change of water quantity approximations.

Though a vast amount of literature has been published on its applicability and accuracy, only a few studies have used the direct water balance approach for flood analysis (Berry et al., 2017; Choo et al., 2016; Gupta, 2016). Though a simple mass conservation equation is used here, currently it is developed to higher complex simulation applications which gives more accurate results than earlier. Many researchers have focused on the behavior of reservoir water usages with the aid of different types of water balance simulation applications (Government of Western Australia & Department of Water, 2011; Güntner et al., 2004a; Jayatilaka et al., 2001; Yoshiyuki Shinogi et al., n.d.; Lu Zhang, Walker, & Dawes, 2002). For the study on sustainable restoration approach for cascade pond systems in Jaffna municipal area for effective flood management as well this water balance approach is used. Therefore, a thorough review of past literature on this matter is highly needed.

Jayakody et al. (2004) developed a model using an already tested cascade water balance on the Maduragama and Karambewewa reservoirs in the Kala Oya river basin. Daily rainfall, pan evaporation, reservoir and its catchment characteristics, water demand and many other user-defined parameters are used for this model. For their analysis, modified equations of reservoir evaporation and seepage have been used and therefore many experts believe that this would produce optimum results. The main weakness in their study is that they make no attempt to discuss the cascade connectivity for the water balance. However, few studies have been published on this and their evidence highlights the importance of reservoir connectivity for overall water balance in each reservoir (Güntner et al., 2004a; Itakura, 1995; Jayakody et al., 2004).

Catchment runoff is quantified using antecedent precipitation index in many other instants (Jayakody et al., 2004). Moreover, the runoff estimation is outlined as Equation 2.

$$\text{Runoff yield} = \frac{C}{API} \times RF \times CA \tag{2}$$

where,

C	=	Runoff Coefficient
API	=	Antecedent precipitation index
CA	=	Catchment Area

Antecedent precipitation index (API) is a time dependent parameter which depends on the catchment wetness (Jayatilaka et al., 2001). (Equation 3).

$$API = \sum_{k=0}^{n} 1/(k+1) \tag{3}$$

Where n is the number of days since the last day with rainfall.

In many instants, evaporation quantity estimations are calculated using pan coefficients as shown in Equation 4.

$$\text{Evaporation from tank } (m^3/day) = f_p \times E_p \times RWS \quad (4)$$

where,

f_p = Pan Coefficient

E_p = Pan Evaporation (m/day)

RWS = Reservoir Water Surface

However, the impact of aquatic plants on the evaporation cannot be neglected and the above mentioned equation can be modified as shown in Equation 5 (Jayakody et al., 2004).

$$\text{Evaporation from tank } (m^3/day) = f_p \times f_p \times E_p \times RWS \quad (5)$$

where,

F_c = Plant Coefficient

The water losses due to evaporation is higher when the aquatic plants are present when compared to the free water surface (Kuganesan & Sivakumar, 2016). Therefore, its inclusion is vital for a much accurate study.

Apart from the surface evaporation, the reservoir seepage quantity as well contributes to the change of reservoir storage. When the reservoir water balance approach is considered, there are various techniques proposed to determine the seepage losses. However, these seepages losses increase the groundwater availability and hence the total water sustainability of the catchment will be increased as well (Jayakody et al., 2004; Kuganesan & Sivakumar, 2016; Mikunthan et al., 2013b). In some cases, a multiplier of the downstream water delivery and upstream spillage is taken as the seepage quantity (Jayatilaka et al., 2001). For many reservoir operation studies conducted in Sri Lanka, the seepage is frequently taken as 0.5% of the reservoir water storage (Ponrajah, 1984). A number of studies reveals that field seepage data gives more accurate results than considering it as a percentage value (Kuganesan & Sivakumar, 2016; Subramanya, 2008).

When the field data is being used for seepage calculations, depth of groundwater table has to be measured and in many cases piezometers are being used for these measurement purposes (Punthakey & Gamage, 2006; Subramanya, 2008; Tubau, Vázquez-Suñé, Carrera, Valhondo, & Criollo, 2017). In more recent studies, it is proposed to use electronic devices for higher accurate measurements (Qi & Lixin, 2018). In order to carry out a simple and valid quantification for reservoir seepage rates, Darcy's equation (Equation 6) can be applied. Observations should be made during low rainfall periods and seepage from upstream reservoir to downstream reservoir is calculated (Jayakody et al., 2004; Lu Zhang et al., 2002).

$$\text{Seepage} = \text{K} \times \text{A} \times \text{I} \tag{6}$$

where,

K	=	Hydraulic Conductivity
A	=	Cross Section Area
I	=	Hydraulic Gradient

The hydraulic gradient is the ratio of pressure difference to the distance where two measuring points are located. Product of the average water elevation of reservoir beds and the width of the valley is taken as the average cross section area for seepage rate calculations (Jayakody et al., 2004). To investigate its applicability, hypothesis should only be applied to larger catchment areas and therefore it will not suit for the Jaffna peninsula area.

Importance of the catchment soil characteristics in seepage rate during a dry period is addressed by Jayatilaka et al. (2001) and the runoff generation after a prolonged dry period is addressed as well. Moreover, this method points out that the large head differences of reservoir water levels and groundwater levels as an indication of an increased seepage rate. A modified equation is proposed for reservoir bed seepage (Eq. 7) (Jayatilaka et al., 2001),

$$\text{Tank Seepage} = \{\text{A} \ln(\text{Tank Water Height}) + \text{B}\} \times \text{Tank Volume} \times 0.01 \tag{7}$$

Where,

A, B	=	Parameters of Seepage Function
Tank Volume	=	f (Tank Water Height)

Moreover, the return flow from seepage and water issue is estimated by Equation 8 (Jayatilaka et al., 2001),

$$\text{Return Flow} = \sum_{i=a}^{b}[K\{WQ_i + SP_i\}] \tag{8}$$

where,

b	=	Number of Contributing Upstream Nodes
K	=	User Defined Coefficient (in between 0 - 1)
WQ	=	Water Issue at Upstream Node *i*
SP	=	Seepage at Upstream Node *i*

The return flow calculation of the above equation considers all the upstream tanks/reservoirs.

Jayakody et al. (2004) have further emphasized the seepage component of the Eq. 8 using a water balance approach. Their model results of the seepage values tally with the field measurements. Furthermore, they claim that the relationship between reservoir storage and seepage rate (Ponrajah, 1984) is plausible for general practices. For reservoirs in dry zone, monthly end water storage is being used for water management decision making process (Rathnayaka et al., 2011; Lu Zhang et al., 2002). Therefore, for an accurate water balance approach, seepage calculations are very important.

In order to understand the reservoir storage alteration throughout a particular water year, all the water balance components should be thoroughly examined. When calculating the reservoir storage change, its outflow values should be measured or a corresponding demand curve should be followed (Jayakody et al., 2004; Mioduszewski, Querner, & Kowalewski, 2014; Verstraeten & Poesen, 2000). Moreover, in the absence of a sluice in a reservoir, its spillway characteristics are being used for reservoir discharge calculations (Jayakody et al., 2004).

When the reservoir spills, the spillway is assumed to be working as a broad crested weir and Equation 9 is used for discharge calculations.

$$\text{Spillway Discharge} = L \times f_d \times H^{1.5} \tag{9}$$

where,

L	=	Length of Spill
f_d	=	Discharge Coefficient
H	=	Spill Height (Afflux)

The return flow from the upstream reservoir is taken as a percentage of the upstream tank spillway discharge and in dry zone cascade systems this coefficient varies between 0.57 - 0.67 (Y Shinogi, Makin, & Witharana, 1998). Moreover, in this approach, the irrigation demands of the upstream reservoirs are not considered. This water flow analysis evidently shows that the spill form upstream does not fully return. Part of the upstream spill water quantity returns as an underground water flow. However, the nearby water sources contribute to this seepage component as well and it has not been addressed in this study.

The key to successful water balance modelling is to have a clearly defined objective and to select an appropriate model. Not understanding the functions of the system as a whole, is leading to rise many environmental problems (Güntner, Krol, Araújo, & Bronstert, 2004b; Kuganesan & Sivakumar, 2016; Lu Zhang et al., 2002). The surface water balance is highly affected by the massive clearing of native vegetation and the distorted rainfall pattern in the dry area makes it more challenging to simulate. Precipitation, evapotranspiration, surface runoff and groundwater recharge are the four major phases of interest in the hydrological system which should be considered in water balance in the catchment area.

Surface runoff can be generated by infiltration excess runoff (Hortonian overland flow) and saturation excess runoff (Dune and Black overland flow) (Freeze, 1974). In an attempt to identify the change in root zone soil water storage, L Zhang, Dawes, & Walker (2001) have used a water balance model. However, in their analysis, only a part of the catchment is considered as the control volume and their root zone water balance is expressed as (Eq. 10),

$$\Delta S = P - I - E - T - RO - DD \tag{10}$$

where,

ΔS	=	Change in Root Zone Soil Water Storage
P	=	Precipitation
I	=	Interception Loss
E	=	Evaporation from Surface
T	=	Transpiration by Plants
RO	=	Surface Runoff
DD	=	Deep Drainage

Though surface runoff is negligible in agricultural fields, it cannot be neglected when the whole catchment is considered. Another simple model is frequently used for analytical purpose which is being called as simple bucket model (Lu Zhang et al., 2002). The main alterations of these two can be clearly identified as follows.

Water balance model - As a system of equation designed to represent some aspects of the hydrological cycle Depending on the objectives and data availability modelling level may change.

Simple bucket model - The control volume is considered as a bucket which is filled up by rainfall and emptied by evapotranspiration. Extra water is assumed to become groundwater recharge.

Many computer simulation applications are developed to apply the water balance concept to different hydrological scenarios and their accuracy and adaptability are emerging as more acceptable. Moreover, in many simulation applications, reservoir systems are represented using nodes and links, where a node represents a reservoir or any other water retaining structure and a link is a water path or a canal (Güntner et al., 2004b, 2004a; Jayatilaka et al., 2001; Perera, Wijayaratna, Manatunge, & Priyadarshana, n.d.). Watershed modeling can be performed for an individual reservoir, reservoir cascade system or basin (collection of cascades). All the components of a cascades should be added to the simulation application for an optimum model water balance results. The return flow from spillage is computed using the Equation 11.

$$\text{Return flow} = \sum_{i=a}^{b} \{ \text{B} \times \text{SO}_i \} \tag{11}$$

where,

b	=	Number of Contributing Upstream Nodes
B	=	User Defined Coefficient (in-between 0 and 1)
SO	=	Spill Discharge at Upstream Node

A series of steps is suggested to model the catchment for hydrological analysis. Since this method excludes the diversion weirs and feeder canals in the system, it is better to modify this hydrological model considering these features to have better results The step by step model procedure proposed by Jayatilaka et al. (2001) can be summarized as Figure 2.3.

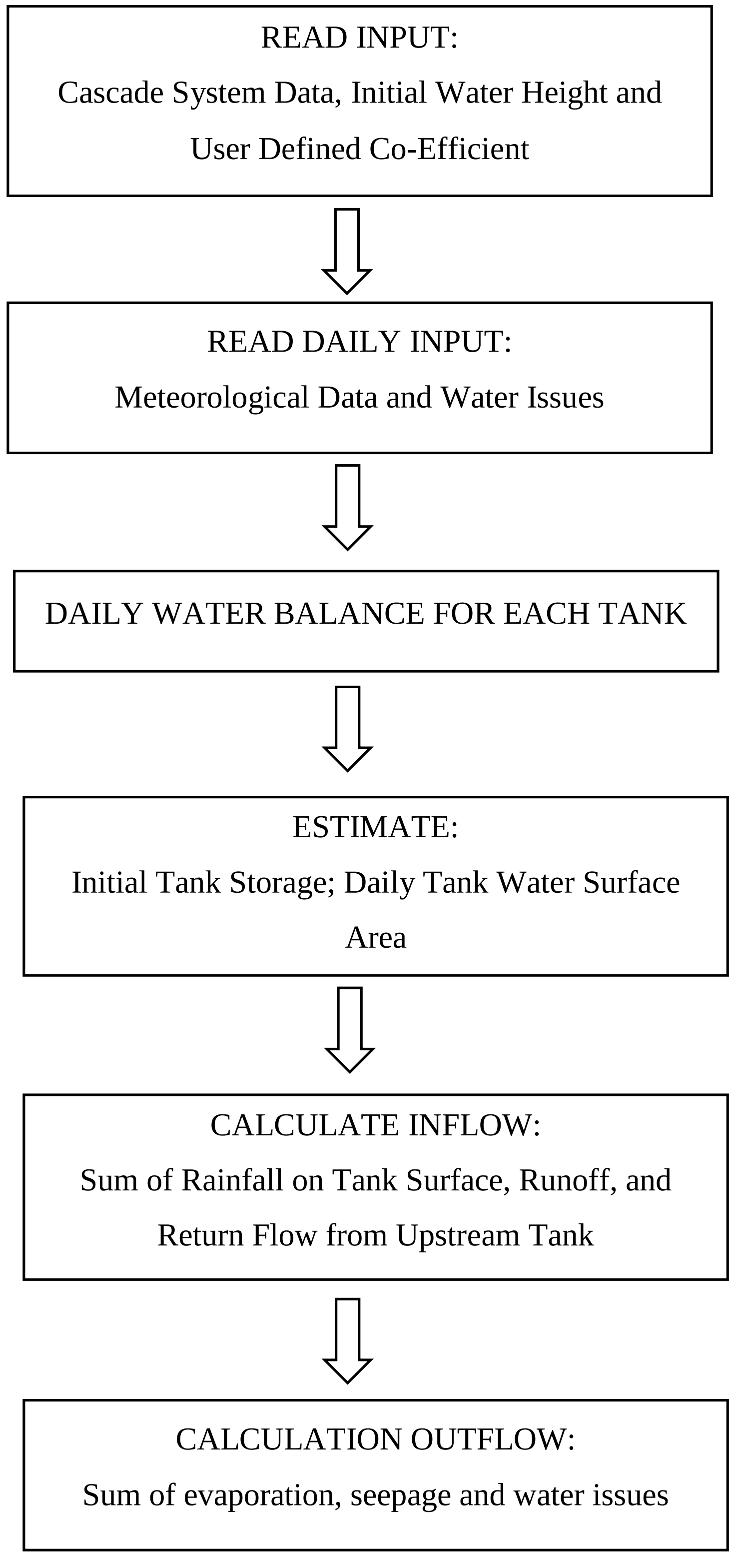

Figure 2.3: Step by Step Model Procedure as a Flow Chart
Source: Jayatilaka et al., (2001)

The flaws of their method have been clearly recognized as not concerning about the ground soil type. This shortcoming is addressed in another study where the authors have considered the geological characteristics of the study area (Y Shinogi et al., 1998). Since a higher number of parameters are considered, the model is more complicated. Many of the studies on reservoir water balance which have been carried out in Sri Lanka are limited to the North Central area. Therefore, geological characteristics of these study areas have a similarity (Panabokke, 2009a; Tennakoon, 1999; Tubau et al., 2017). However, during their study on effect of ground soil type for reservoir water balance, Y Shinogi et al., (1998) have investigated the relationship of minor reservoirs and the corresponding geological conditions of watersheds. They suggest that the cascade measurements should be taken two times a day and daily groundwater levels should be measured. Furthermore, daily rainfall, evaporation and temperature values have to be recorded to increase the model accuracy. Since this study is developed with the consideration of catchment geological qualities, soil physical parameters are measured by conducting soil surveys (e.g.: Infiltration Tests, Soil Hardness by Penetrometer test, Tests on Soil Moisture Characteristics and Saturated Hydraulic Conductivity).

Y. Shinogi et al. (1998) has used Equation 12 for their water balance model.

$$dS = \left\{ \sum_{i=1}^{n} \left(Qa_{i,t} \right) + \sum_{j=1}^{m} \left(Sp'_{j,t} + Rf_{j,t} \right) \right\} - \left\{ \sum_{k=1}^{l} \left(W_{k,t} \right) + Sp_t + S\&P_t \right\} \tag{12}$$

where,

dS_t	=	Change in Tank Storage
$Qa_{i,t}$	=	Rainfall Inputs to Tank
$Sp'_{j,t}$	=	Spill Discharge from Upstream Tanks
$Rf_{j,t}$	=	Return Flow from Upstream Irrigation Release
$W_{k,t}$	=	Water Issue from Tank for Issue
Sp_t	=	Spill Discharge
$S\&P_t$	=	Seepage and Percolation

n	=	Number of Soil Classes Considered
m	=	Number of Upstream Tanks
l	=	Number Irrigation Sluices
t	=	Time Step (days)

Kandiah & Miyamoto (2016) have modeled the storage variation of shallow well systems in Jaffna using a typical water balance model. The typical water balance parameters of precipitation, evaporation, surface water flow and groundwater flow are introduced to the model considering three shallow wells. The storage change is directly measured from the temporal variation of well water level. The structure of typical shallow well in the study area is shown in Figure 2.4. Though the structural components of a well do not tally with a reservoir, the water storage change pattern from a water balance analysis is compatible (Kandiah & Miyamoto, 2016).

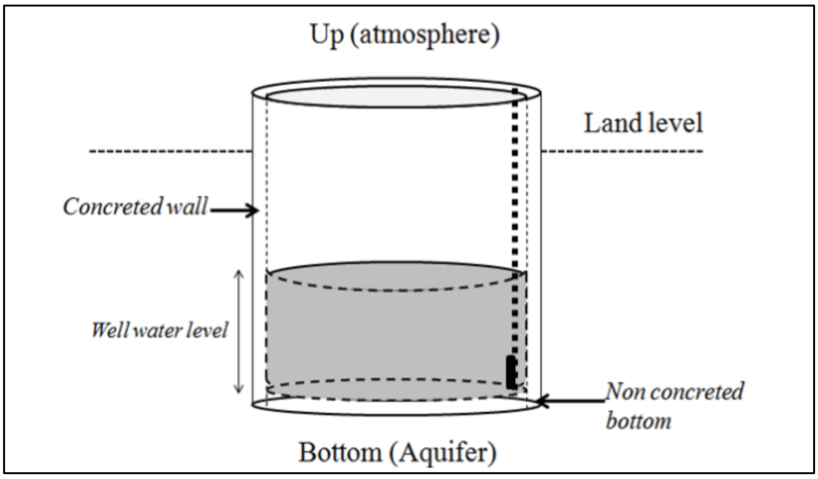

Figure 2.4: Structure of Typical Shallow Well
Source: Kandiah & Miyamoto, (2016)

In their study, Kandiah and Miyamoto (2016) have used pressure gauges for well water height estimations. The major focus of their research is the water budget in the Jaffna region during the dry season. The study was carried out from August to December and water balance analysis has shown that the inflow to the well is increasing. This is due to the typical monthly rainfall pattern in the Jaffna region where a higher rainfall is expected in October and November months (Sutharsiny, Manthrithilake, Pathmarajah, Thushyanthy, & Vithanage, 2014). In their analysis (Kandiah & Miyamoto, 2016), the connectivity of well water sources have been neglected and this is a major drawback of the work. However, the method proposed for groundwater recharge is well-founded and its applicability in JMC area would be realistic.

Large reservoirs which are connected via a river network, mutually affect their inflow and outflow water quantities and results in considerable changes in catchment areas as well (Güntner et al., 2004a). However, when small scale reservoir (pond) systems are considered, drainage canals are more frequent due to the connecting paths to establish the cascade connectivity.

2.2.4 Jaffna Groundwater System

Jaffna peninsula region only receives a considerable rainfall during the second inter monsoon time period (Joshua et al., 2013; Sutharsiny et al., 2014). This near 3-month rainfall to the region is the only freshwater recharge which should sustain during the whole water year to fulfill the total water demand of the peninsula.

The existing groundwater system in the Jaffna peninsula is the major water source during the dry period (January to August) to living community. Retained storm during the second inter monsoon gradually recharges the aquifer system (Thushyanthy & De Silva, 2012). Most importantly, community and ecological water needs are highly depended on the existing aquifer system, especially with the absence of a perennial river nor a major water supply system (Mikunthan et al., 2013a).

A formation, or group of formations which yields water in sufficient quantity to be of consequences as a source of supply is called as an aquifer (Balendran, Sirimanne, & Arumugam, 1968). The indistinguishable Jaffna Miocene Limestone aquifer system reflects its higher water retention qualities which are highly beneficial to the community and the eco-system (National Water Supply and Drainage Board, 1989). Improved development practices should be implemented on the existing water systems in the Jaffna to increase the water security.

The groundwater quality in Jaffna peninsula is decreasing due to various human activities such as excessive extraction of groundwater, intensive agricultural practices involving very high inputs of artificial and natural fertilizers and the improper construction of latrine soakaway pits (Rajasooriyar, Mathavan, Dharmagunawardhane, & Nandakumar, 2002). Concentrations of mineral constituents in the groundwater are increasing due the saltwater intrusion (National Water Supply and Drainage Board, 1989). During the rainy season, groundwater level increases and the contaminants which are very close to the ground surface mixes into the groundwater (Senthuran, 2016).

Limestone hydrological studies conducted in Jaffna peninsula show a thin mantle of soil above the limestone (Panabokke & Perera, 2005). There are four aquifers present in the Jaffna peninsula region namely Chunnakam (Valikamam area), Thenmaratchi, Vadamaratchi and Kayts (Figure 2.5). The Chunnakam Limestone aquifer which overlays the Jaffna Municipal Council is well recognized for its higher water holding capacity (Sutharsiny, Pathmarajah, Thushyanthy, & Meththika, 2012).

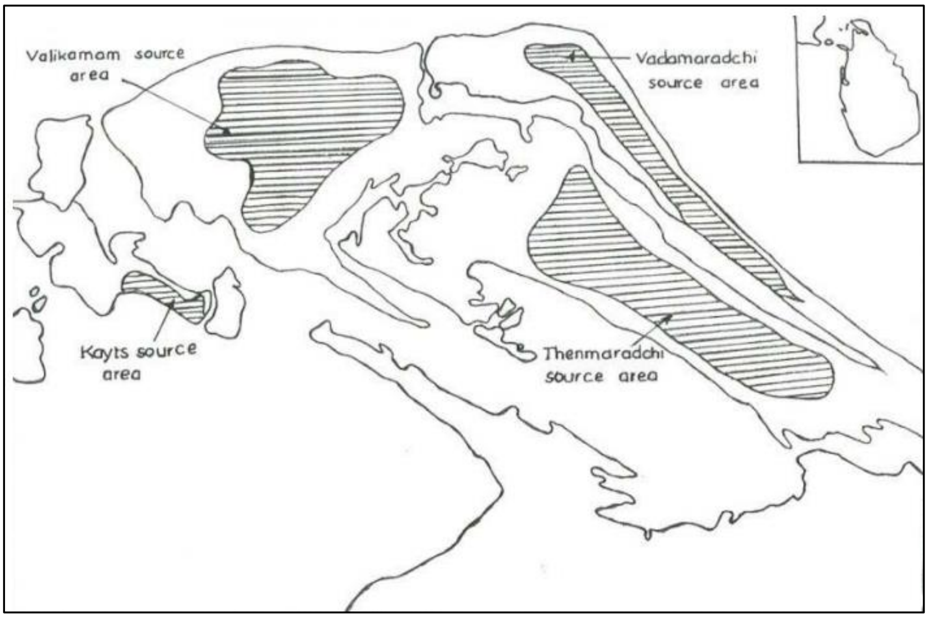

Figure 2.5: Groundwater Resources in Jaffna Peninsula
Source: Balendran et al., (1968)

Groundwater is trapped in the limestone cavities and they are opened to sea and when an improper well construction is taken place, there is a higher risk of saltwater intrusion to inland. In the western and northern coastal area of the peninsula where a karstic formation of limestone is present, cavities have been damaged and therefore the salinity has increased due to the saltwater intrusion (Janen & Sivakumar, 2014;

Sivakumar, 2013). Raw wastewater of Chunnakam power station is dumped to the neighboring area and it results in higher oil contamination (Figure 2.6) in the underground aquifer (Senthuran, 2016).

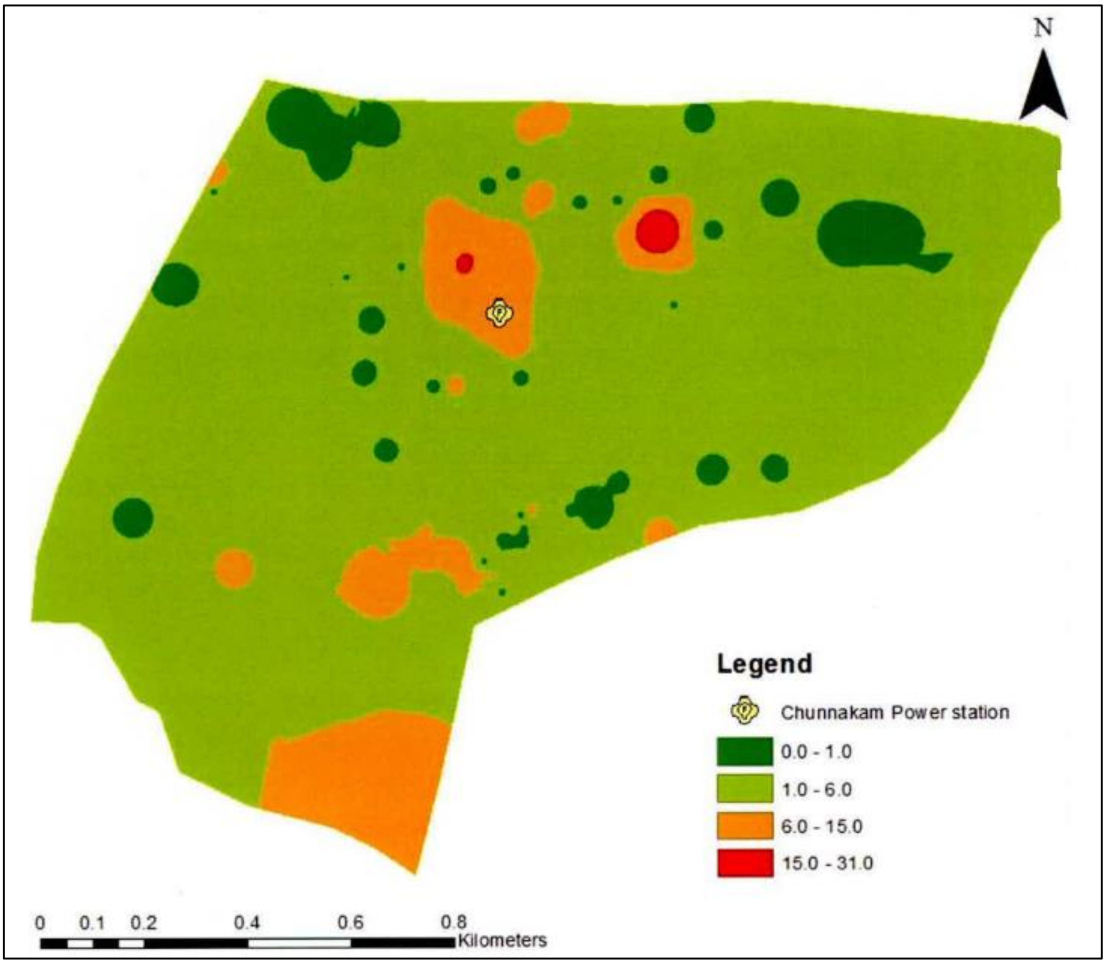

Figure 2.6: Spatial Distribution of Oil and Grease Concentrations
Source: Senthuran, (2016)

Jaffna groundwater is predominantly used for domestic and irrigation purposes (Mikunthan et al., 2013a). Moreover, especially in intensive cultivations in the Valikamam area (where the Chunnakam aquifer is overlain), a higher inorganic fertilizer usage can be seen. Similarly, the long term water availability is being questioned due to the continuous groundwater over extractions.

With the increased usages of more advanced machineries in the Jaffna peninsula area, monthly water extraction quantity from aquifers is increasing (Nanthini, Mikunthan, & Vijayaratnam, 2001). The limestone locations with a thin sand layers provide a better drinking water to the community and this easily soluble limestone layer has many underground solution caverns as well (Mikunthan et al., 2013a). Groundwater salinity increases with the short of rainfall and therefore groundwater sources should be frequently recharged to increase the water sustainability in the peninsula. Only around 30% of the total precipitation penetrates into the aquifer system and the rest is lost from transpiration and surface runoff (Thushyanthy & De Silva, 2012).

The intensive rainfall to the peninsula during the second inter-monsoon (October to December) aids to continuously recharge the limestone aquifer system which goes up to a 70 m thickness during and after the rainy season (Senthuran, 2016). However, from January to September, the mean evaporation exceeds the rainfall (Thushyanthy & De Silva, 2012). During this extreme dry period, mean groundwater extraction is higher than the recharge. Dug wells and tube wells are the most common methods of groundwater extraction and they are being used to satisfy all the water needs in the area. However, while tube wells are used only for domestic purposes, dug wells are being used for industrial, irrigation and many other purposes (Thushyanthy & De Silva, 2012).

Among the seven aquifer types in Sri Lanka, Jaffna limestone aquifer is the most studied one (Panabokke & Perera, 2005) and this highly karstic Miocene limestone aquifer qualities should be carefully examined prior to any rehabilitation project which may destruct the existing ecology. A quantitative estimation of groundwater resources in Jaffna peninsula shows that the total average annual withdrawal (0.66 MCM) exceeded the total average annual recharge (0.57 MCM), implying the system is in deficiency (Thushyanthy & De Silva, 2012). Therefore, when the reservoir water budget is considered, considerable seepage must be allowed. Moreover, if a better pond rehabilitation approach is followed, groundwater extractions for agricultural purposes can be reduced.

2.2.5 Stormwater Management and Flood Mitigation Approaches

A dry climate is expected in Jaffna peninsula during the most part of the year. However, during the second inter-monsoon (October - December), a higher rainfall is expected and it frequently causes recurrent flash flood situations in the area (Asian

Development Bank, 2010). The mean annual rainfall to Jaffna peninsula is 1340 mm and during the October – December period an average rainfall of 920 mm is received (Joshua et al., 2013). When about 70% of the annual rainfall is received during a 3-month time period, existing water retaining structures may not be able to sustain the stormwater generation. More recent evidence suggests that the rainfall intensities are comparatively larger in dry zone and it is creating disastrous situations (Herath & Ratnayake, 2004).

In many urban areas, rapid development projects are going on and therefore its natural ecosystems are continuously getting disturbed (Roy et al., 2008). These sudden changes to the natural ecosystem are resulting blocked watercourses and many flood situations are raised due to damages to the drainage system. However, the major reason for inundations in the urban areas is the disorganized constructions. The existing canals and natural watercourses are being damaged and a continuous rainfall to the area will create a flood situation (Aronica & Lanza, 2005).

In their investigation onto conversion of ex-mining ponds to stormwater retention ponds, (Chang et al., 2008a) show that pond rehabilitation and restoration as stormwater facilities is possible. Furthermore, the existing hydraulic and hydrologic characteristics of existing ponds and the surrounding drainage systems should be thoroughly studied before signifying a suitable stormwater management method (Villarreal, Semadeni-Davies, & Bengtsson, 2004). They propose to design integrated stormwater facilities and its major components are shown in Figure 2.7. In addition, the urban pond systems are not only providing water retention capacities to the urban stormwater management, they also bring an esthetically pleasing appearance while increasing the water sustainability by reusing (Niemczynowicz, 1999).

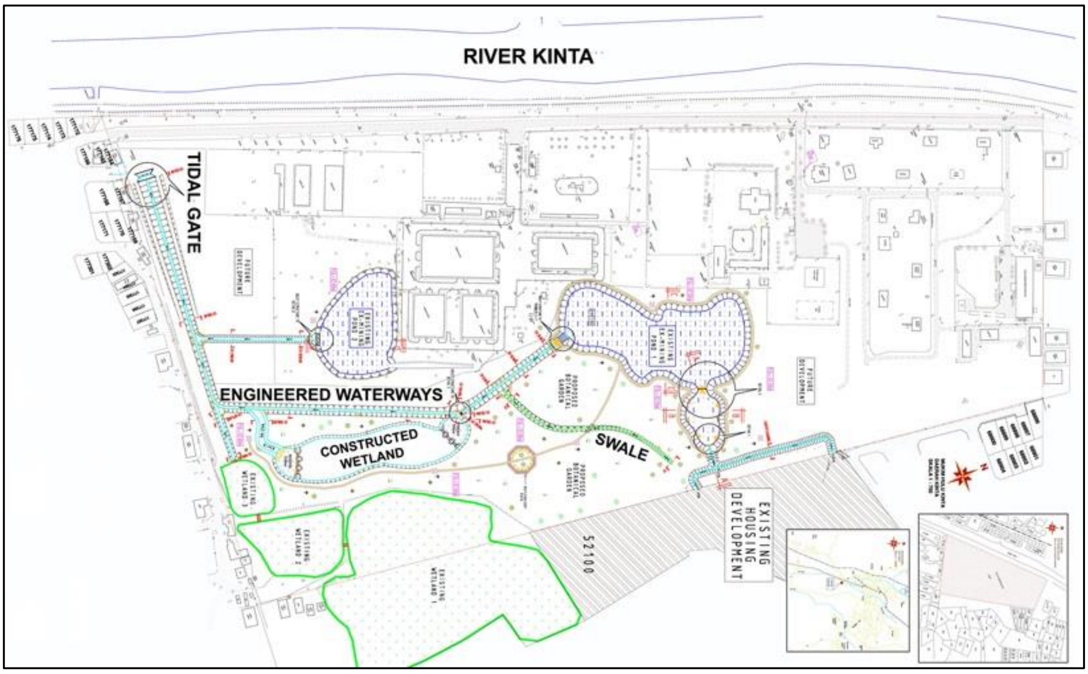

Figure 2.7: Layout of the Stormwater Facilities
Source: Chang et al., (2008a)

Prabhu & Venkateswaran (2015) draw attention to artificial recharge zones which will increase the groundwater recharge and in the meantime the downstream stormwater generation will be retarded. This is highly promoted as an efficient stormwater management system and this methodology can be adopted along any river basin. However, when an artificial recharge method is considered, both spatial and temporal analysis of the study area should be completed out in order to validate the study area.

Where a higher stormwater generations are present, a well-engineered flood mitigation methods are required to follow. The use of a flood mitigation approach is frequently sought in this situations. When the stormwater generation is relatively larger than the stormwater draining rate, flood situation begins to propagate (Aronica & Lanza, 2005; Villarreal et al., 2004). The flood mitigation practices are immensely dependent on the study area characteristics and management practices should be developed accordingly.

Before following any kind of a flood mitigation approach, it is obligatory to understand the roots for these flood situations (Gupta, 2016). He claims that direct and indirect factors which are causing the urban floods should be extensively studied and his major causes are shown in Figure 2.8.

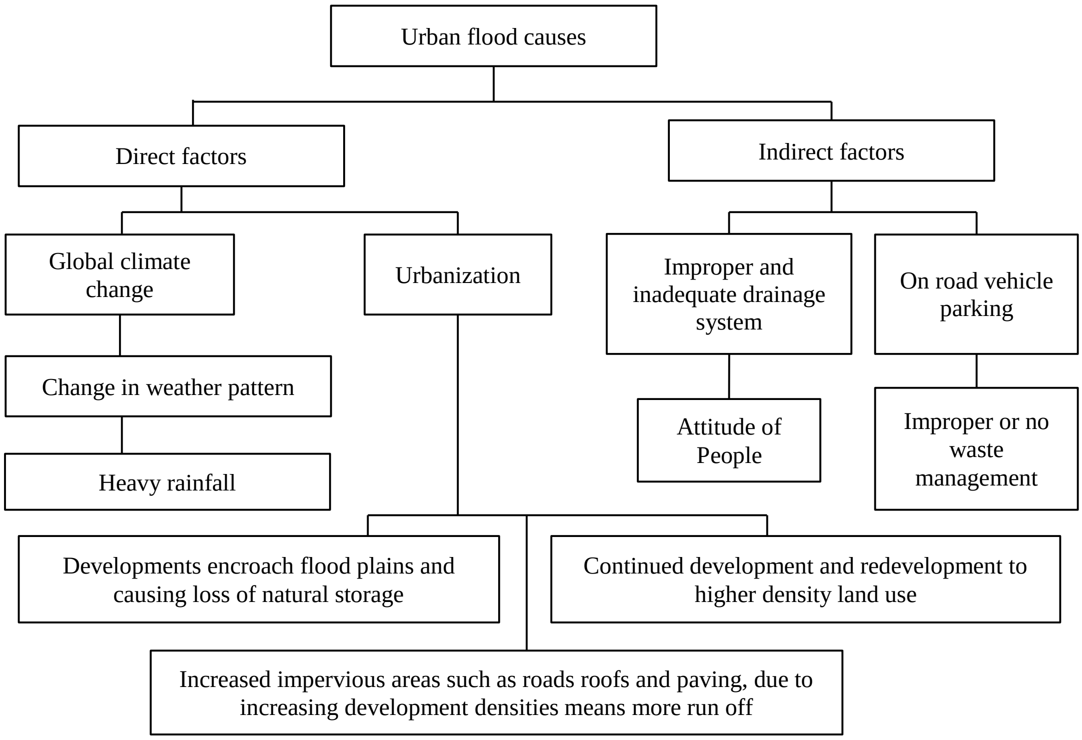

Figure 2.8: Causes for Urban Floods
Source: Gupta, (2016)

The use of small scale water retention bodies on flood mitigation will act as a better stormwater management approach (Niemczynowicz, 1999). However, the applicability of these methodologies varies depending on many factors such as land use and land cover pattern, future development plans, etc. (Roy et al., 2008). Fluvial, coastal, estuarial and pluvial are the most common types of floods and it is expected that with the rise of many awareness programs on global warming this can be omitted (Minh, Chi, & Toulouse, 2017). The need of seeking crowdsourced data for flood mitigation is investigated and the implemented prototype has given positive results. The overall architecture of a mobile crowdsourcing based urban flood mitigation system is shown in Figure 2.9.

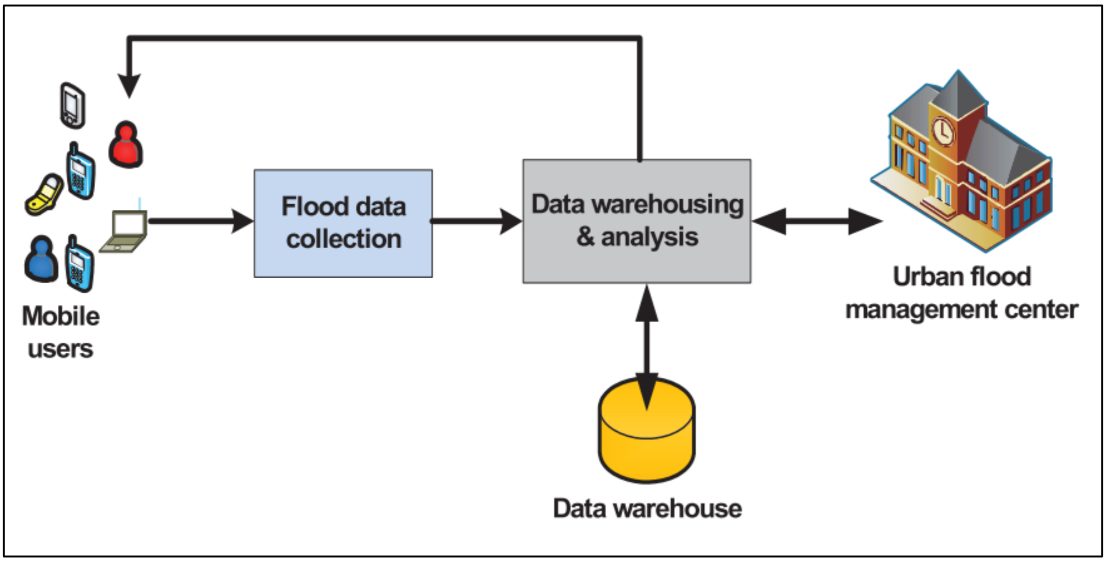

Figure 2.9: A Mobile Crowdsourcing based Urban Flood Mitigation Approach
Source: Minh et al., (2017)

2.3 Research Gap

Many researches have tended to focus on the individual reservoir/tank/pond behaviour rather than considering holistic behavior of reservoir system. A larger number of studies have used water balance approach for their analysis, however all of these literature are on irrigation reservoirs (Panabokke, 2009b; Panabokke et al., 1996). In the recent times, various computer applications have been developed based on the reservoir water balance approach and due to its versatility with ability to adapt to any study area, they are currently commonly used in practice (Government of Western Australia & Department of Water, 2011; Güntner et al., 2004a).

Individual rehabilitation and restoration approaches for reservoirs, considering their unique geographical location and structural components is vital and all the previous studies have neglected these criteria. A water balance approach which can be used for any location cannot be practically developed and nevertheless the HEC-ResSim modeling application give more freedom to adapt the simulations according to the corresponding characteristics. These recently developed stormwater management practices are very rarely adopted in Sri Lanka and this can be a major drawback in decision making process.

The crucial shortfall of the reviewed literature is their lack of adaptability to different geographical area. Proposed study is to be conducted on the ponds in JMC area and none of them are being used for irrigation purposes, therefore when a previously used water balance model is applied to this system, many alterations should be incorporated. Most of the water balance applications use nodes and links approach to model the cascade components (Jayatilaka et al., 2001; Nagarajan, 2013). However, HEC-ResSim model simulations focus on all the key parameters expected in this study (Klipsch & Hurst, 2013). The simulation application has the ability to include any number of reservoirs (water retaining structures) to the model, and the reservoirs and all other structures present in the cascades are treated separately. One of the major drawbacks of all the previous applications had is, their disability to consider the holistic behavior of reservoir system and HEC-ResSim application can simply satisfies all of them.

3 MATERIALS AND METHOD

3.1 Background

Research methodology is developed aiming at identifying the applicability of the proposed methodology based on cascade system to the chosen area and its adaptability to the given conditions. Moreover, its methodology flow is introduced in such a way where it compares the adaptability of the research hypothesis and further inclusions of two scenario analyses. Methodology begins with the comprehensive literature review which is aimed at examining the study area characteristics and to cover previous instances where the used hypotheses are more or less similar to the one which is being used in this study. The review is carried out in a broad way to investigate on results of the previous studies where the proposals were made on flood mitigation and other objectives of this study.

Prior to the main analysis of this study, the methodology is developed to identify the primary and secondary data needed. Data validation and its usability is also included in this methodology. A detailed methodology flow chart which begins with the literature survey is presented at the end of this chapter (Fig.3-9).

3.2 Study Area: Paalkulam Cascade and Nayanmarkaddu Kulam Cascade

Among the eight cascades present in the study area, two cascades were selected for the study considering the availability of the pond contour maps and other required data for modelling (Figure 3.1). In order to apply the water balance method/HEC-ResSim model, the elevation-area-capacity relationship is crucial. Furthermore, one selected cascade discharges catchment runoff to the Jaffna southern sea and the other brings the runoff to the inland storage areas in the peninsula producing diverse conditions for modelling.

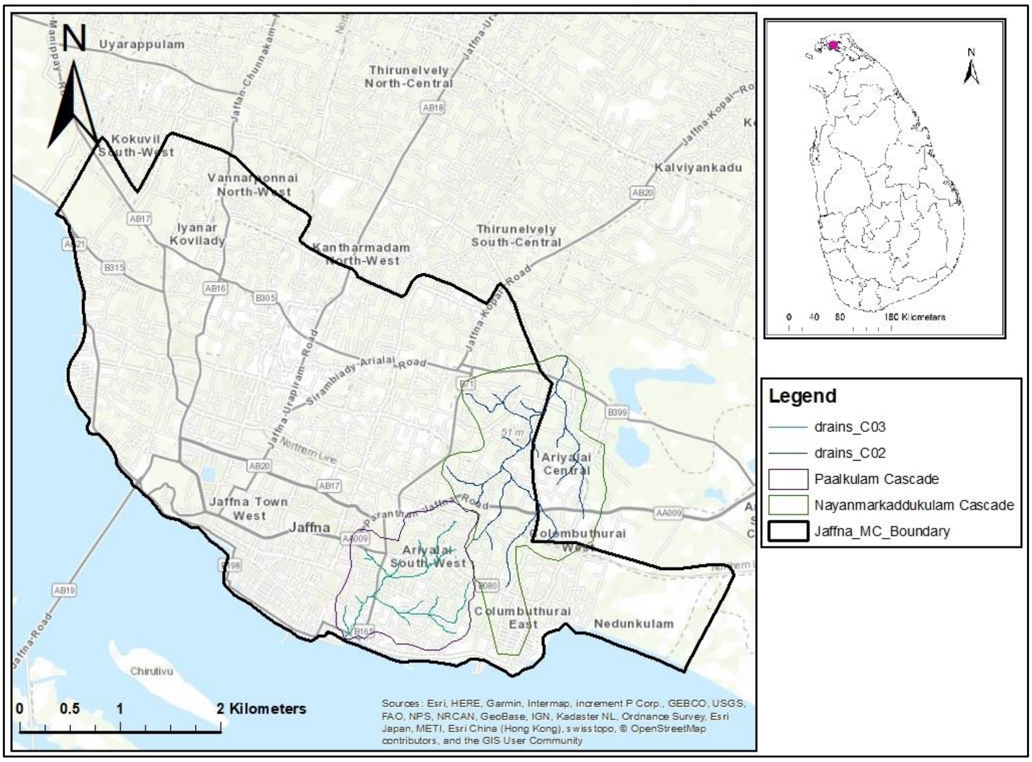

Figure 3.1: Paalkulam Cascade and Nayanmarkaddu Kulam Cascade

3.2.1 Paalkulam Cascade

The seven pond-cascade which is located to the south-east region of the Jaffna municipal council area is the Paalkulam cascade (Figure 3.2). Among the seven ponds in the cascade, Paalkulam and Vannankulam are the largest and the highest contributors to the catchment runoff generation. A major part of the land belongs to the Nallur north, Jaffna part of the peninsula and ponds belong to either the Jaffna municipal council or the nearby Hindu temples. Total catchment area of the cascade is 156.7 ha and the area falls to DL3 Agro Ecological zone (Ponrajah, 1984) and the corresponding monthly 75% probable rainfall in that zone was used for water balance analysis. Jaffna peninsula falls into the Hydrological Zone II (Ponrajah, 1984) and that was used to determine the corresponding Rainfall-Intensity-Frequency relation in the study area. Evaporation data in the study area was taken considering the nearest evaporation gauge station as the Thondamanar station (Ponrajah, 1984). Moreover, the longest water course in the cascade is 1.769 km and average stream gradient is 0.0075 (m/m). Average catchment slope is 0.005 (m/m) and in all the seven ponds present in the cascade, all the spillways are natural spillways.

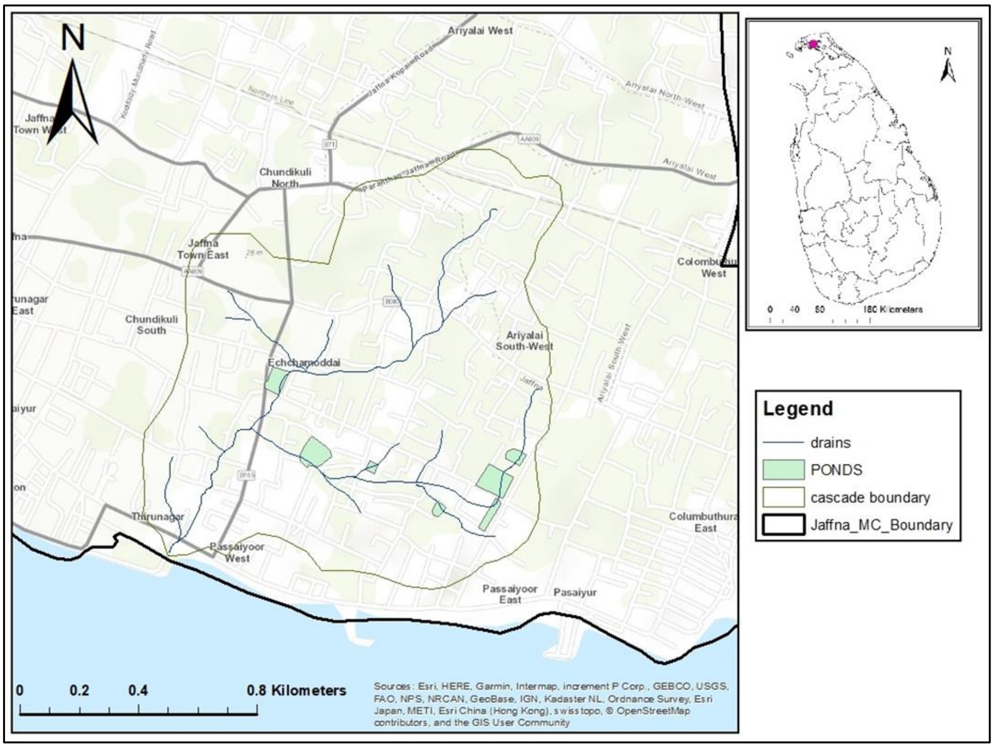

Figure 3.2: Paalkulam Cascade

Moreover, locations of the seven ponds in the cascade are given in the Table 3.1.

Table 3.1: Paalkulam Cascade Ponds

JMC Pond No.	Pond Name	Location in the Cascade
03	Vannankulam	Upstream
31	Makkiyakulam	Upstream
39	Pasaiyoorkulam	Upstream
63	Vilaththikulam	Middle
33	Mudalikulam	Middle
37	Paalkulam	Downstream
09	Maravakulam	Downstream

3.2.2 Nayanmarkaddu Kulam Cascade

Unlike the Paalkulam cascade which drains into the Jaffna lagoon, Nayanmarkaddu Kulam cascade directs the catchment runoff into the peninsula. However, the catchment characteristics are more or less same as those of the Paalkulam cascade. This cascade is also situated in the same agro ecological zone of DL3, as Paalkulam cascade which is used to find the 75% probable monthly rainfall in the region. Five ponds are present in the cascade and the Nayanmarkaddu kulam pond is the largest among them. Cascade is located in Nallur Sankiliyanthoppu, Kandarmadam and all the five ponds belong to Jaffna Municipal Council or to the nearby temples. The total catchment area is 290 ha and the longest water course in the catchment is 3.176 km long. Average stream gradient is 0.0075 (m/m) and the catchment slope is approximately about 0.005 (m/m). Nearest pan-evaporation gauge station is Thondamanar and this cascade also belongs to the Hydrological Zone II. All the ponds in the cascade has natural spillways where simple engineering considerations are present mainly due to the minor scale ponds and their very low capacity.

The cascade, with its five ponds and their locations in the cascade are shown in Figure 3.3 and their locations are tabulated in Table 3.2.

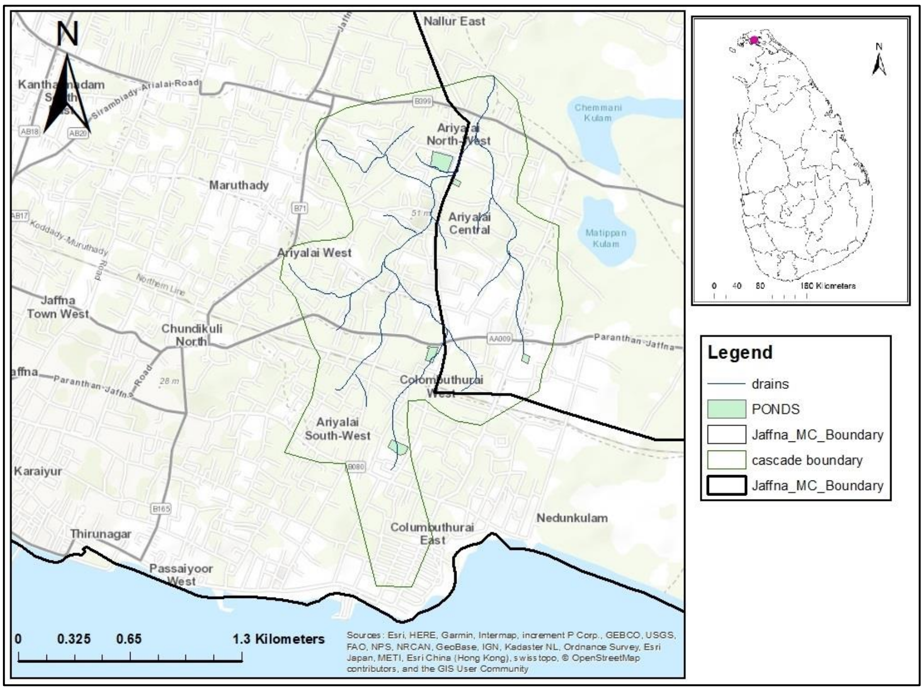

Figure 3.3: Nayanmarkaddu Kulam Cascade

Table 3.2: Nayanmarkaddu Kulam Cascade Ponds

JMC Pond No.	Pond Name	Location in the cascade
05	Ilanthaikulam	Upstream
50	Neernochchithalvu kulam	Upstream
27	Pirapankulam	Middle
28	Purakulam	Downstream
26	Nayanmarkaddu kulam	Downstream

3.3 Data and Data Checking

3.3.1 Pond and Catchment Data Collection

The data collection was carried out in many stages of the study and both primary data and secondary data were used for the study. The study was carried out using a simple water balance method and HEC-ResSim computer application simulation (typical components in a water balance approach were present in this application). Accordingly, the base of the used water balance approach and HEC-ResSim application is that the difference of net inflow and net outflow would be the storage increase (or decrease), with following data requirements.

- Rainfall Data
- Evaporation Data
- Survey maps for Ponds
- Existing Canal Network
- Contour Maps of Jaffna
- Elevation and Contour Data in Jaffna as ESRI Shape Files

Table 3.3: Data Collected for the Analysis

Data	Source
Survey data of cascade Ponds	World Bank funded Strategic Cities Development Project (SCDP), Jaffna
Existing canal network	
Natural Stream network	
DEM maps of the JMC	
Iso yield maps	Irrigation Department guideline (Ponrajah, 1984)
IDF curves	Irrigation Department guideline (Ponrajah, 1984)
Evaporation values	Irrigation Department guideline (Ponrajah, 1984)
Rainfall data (Daily data)	Department of Meteorology

3.3.1.1 Rainfall Data

Daily rainfall data of Jaffna main metrological station were collected from Department of Meteorology, Colombo 07.

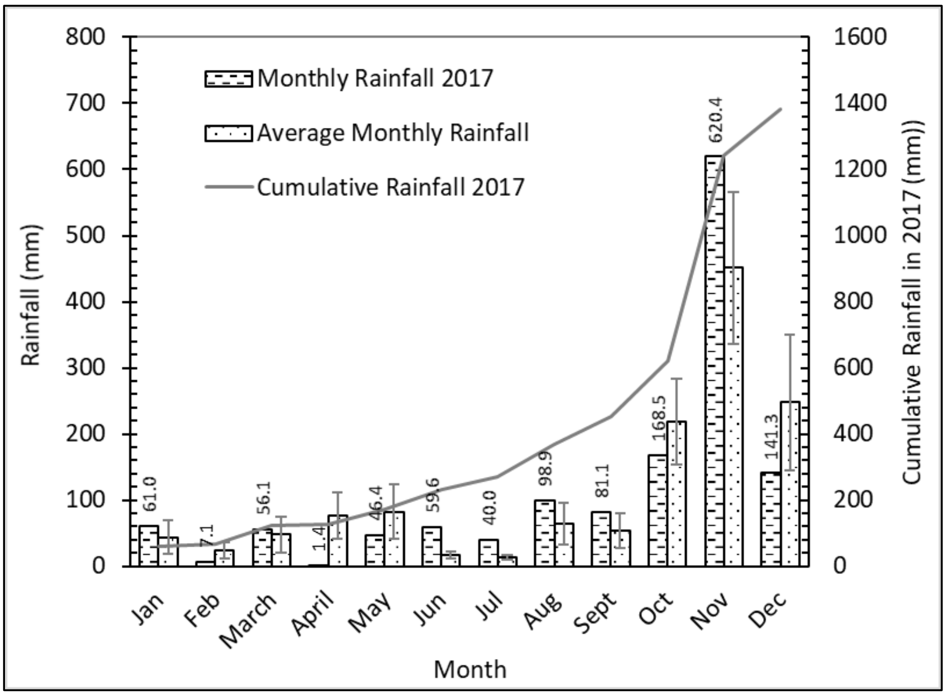

Figure 3.4: Monthly Rainfall Pattern of Jaffna Peninsula

The Jaffna city rainfall gauge station records for the year 2017 were collected from Department of Meteorology, Colombo 07 for this flood study. The rainfall variation is shown in Figure 3.4. To calculate the net runoff inflow due to precipitation, several methodologies were considered, however, the applicability of many of those were doubtful due to the unique catchment characteristics. Moreover, iso-yield maps for the Jaffna peninsula were used for the runoff generation. Daily Annual maximum rainfall in Jaffna and return period of extreme events are shown in Table 3.4 and further illustrated in Figures 3.5,3.6 and 3.7.

Table 3.4: Daily Annual Max. Rainfall in Jaffna and Return Period of Extreme events

No	Annual Max. RF (mm)	Date of Occurrence	Rank	Frequency	Return Period T (Years)
1	389.8	2008-11-25	1	6.7%	15.00
2	187.9	2005-12-10	2	13.3%	7.50
3	179.2	2002-11-19	3	20.0%	5.00
4	178.9	2016-05-15	4	26.7%	3.75
5	166.3	2015-11-14	5	33.3%	3.00
6	152.5	2004-12-13	6	40.0%	2.50
7	121.2	2009-04-11	7	46.7%	2.14
8	120.3	2014-11-27	8	53.3%	1.88
9	118.2	2010-11-26	9	60.0%	1.67
10	102.4	2007-12-18	10	66.7%	1.50
11	97.1	2011-11-24	11	73.3%	1.36
12	96.0	2012-12-26	12	80.0%	1.25
13	79.3	2013-01-07	13	86.7%	1.15
14	73.0	2006-01-05	14	93.3%	1.07
15	71.4	2003-06-07	15	100.0%	1.00

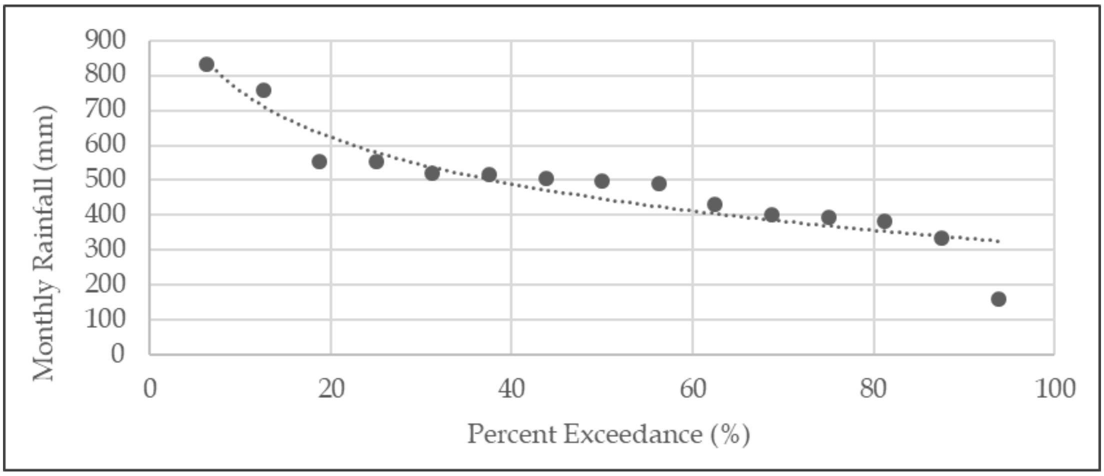

Figure 3.5: Percentage Exceedance for Monthly Rainfall (Data Period 2002~2016)

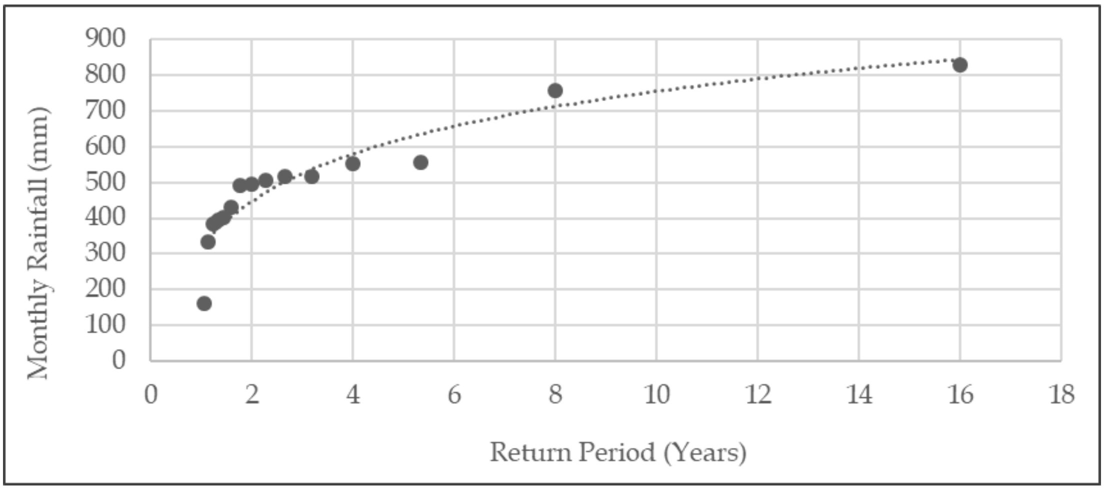

Figure 3.6: Return Period (Years) for Monthly Rainfall (Data Period 2002~2016)

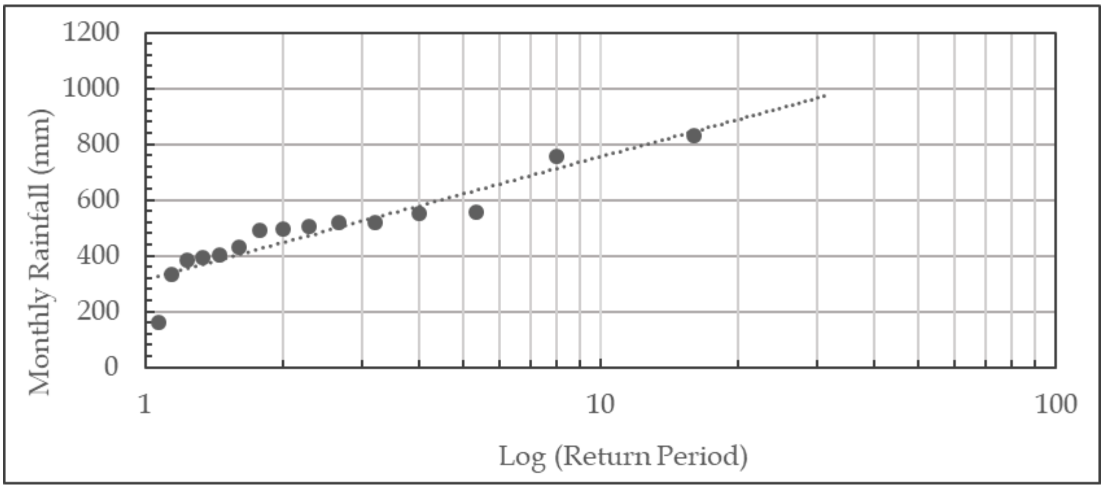

Figure 3.7: Log (Return Period) for Monthly Rainfall (Data Period 2002~2016)

3.3.1.2 Evaporation Data

The monthly evaporation data of the Thondamanar gauge station (Figure 3.8) was used for the analyses and the data is tabulated in Table 3.5.

Table 3.5: Monthly Evaporation Values (mm)

Jan	***Feb***	***March***	***April***	***May***	***Jun***
115.5	113.1	133.5	139.3	171	164.6
Jul	***Aug***	***Sept***	***Oct***	***Nov***	***Dec***
151.8	153	156	135	107.6	111.6

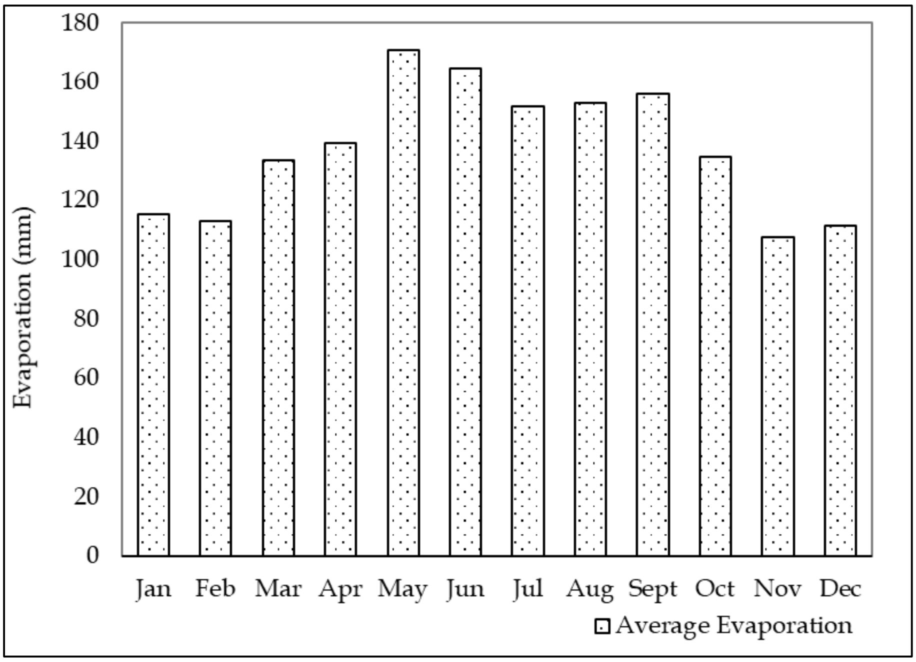

Figure 3.8: Monthly Evaporation Variation of Thondamanar Gauge Station

3.3.1.3 GIS Data

The ESRI shape files of the Jaffna Municipal Council area geographical data were collected from the Strategic Cities Development Project (SCDP) and data were checked with the google earth application.

The GIS maps were used to generate terrain maps with existing drainage patterns (using SRTM/GTOPO30 Satellite Terrain DEM).

3.3.2 Data Checking

The pond survey data were collected from the Strategic Cities Development Project (SCDP). Hence, data checking for these secondary data was required. The survey maps for all twelve ponds were checked with the DEM of the Jaffna Municipal Council area and verified from the field visits to the ponds during the dry period where a low water storage is present. Since all the ponds were surveyed in the year of 2017, the field inspections showed same elevation characteristics as the maps collected from the SCDP. The details of the existing structures, their functionality and drainage flow path connectivity were verified based on field observations.

3.4 Methodology Development

Methodology development is carried out considering the catchment analysis, water balance approach, HEC-ResSim simulation and the two scenario analyses to achieve the research objectives.

3.4.1 Methodology Flow Chart

The Figure 3.9 illustrates the methodology approach followed in this study. The analysis is comprised three major sub sections, named Pond storage analysis, Scenario analysis on cascade behaviour and Scenario analysis on pond rehabilitation.

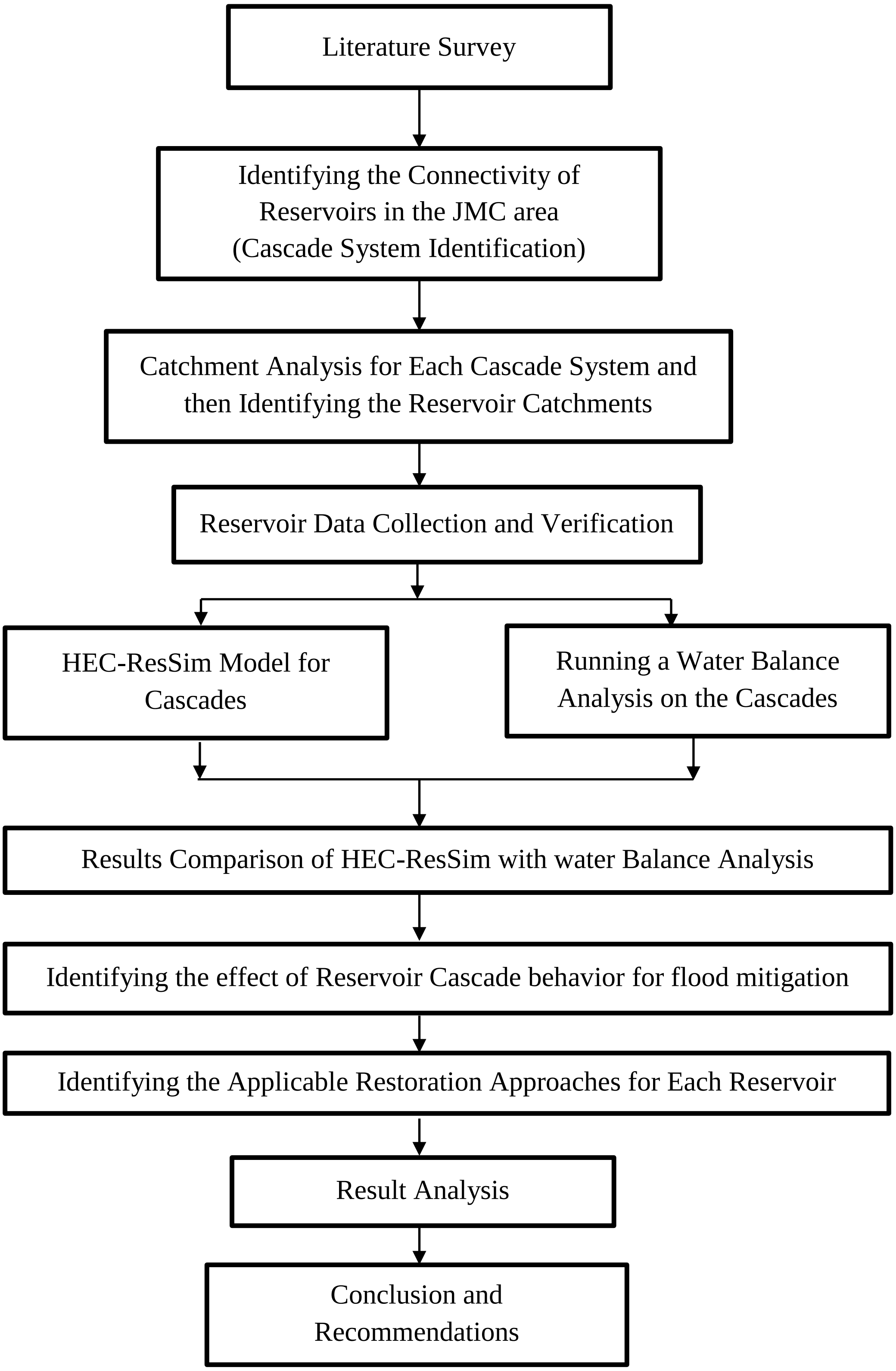

Figure 3.9: Methodology Flow Chart of the Research

3.4.2 Catchment Analysis

3.4.2.1 Runoff Calculation

The Jaffna city rainfall gauge station records for the year 2017 were used for this flood study. To calculate the net runoff inflow due to precipitation, several methodologies were considered, however, the applicability of many of those were doubtful due to the unique catchment characteristics.

Initially, several runoff generation methodologies were followed such as Binnie's approach where the runoff was taken as a function (percentage) of total annual precipitation (Abdullah, 2013; Subramanya, 2008), Strange's approach where the rainfall runoff relation depends on the nature of catchment and as well as soil condition (Strange, 1928; Subramanya, 2008) and Barlaw's method where runoff coefficients depend on the nature of precipitation and catchment (Subramanya, 2008). However, due to its own unique soil type, climate pattern and geographical conditions in JMC area, the model produced somewhat dubious results. Consequently, iso-yield maps from Ponrajah (1984) were used for runoff generation and it was found that its applicability is justified due to more accurate results obtained in tandem with the actual flood data. Therefore, yield maps were continued to be used for runoff generation calculations during subsequent modelling.

During the four monsoon seasons, (North East monsoon, South West monsoon and two inter monsoons), the precipitation to Jaffna peninsula does not show a significant trend in the period 2002~2017. During the second inter monsoon (October/November), the highest rainfall is expected and during the time period considered for this study (2017) that has led to a disastrous flood situation due the continuous high intensity rainfall. Moreover, when total rainy days in each month is considered, during the flood effected period of October/November, the rainfall expectancy is around 75%.

3.4.2.2 ArcGIS Flood Analysis

ArcGIS 10.3.1 tool kit was used to model the terrain in the Jaffna Municipal Council area. 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 Arc-Google Extension and ground trothing. Spatial analyst supplemental tool was used to generate the storage capacity relationship of each sub-catchment and in entire Paalkulam catchment, accordingly. The 156.7 ha catchment area of the cascade is again divided into 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. To achieve the specific objective of this study, the ArcGIS results play a major role and the cascade connectivity was totally ignored when the ponds were modelled individually. Generated DEM in the Paalkulam cascade is shown in the Figure 3.10.

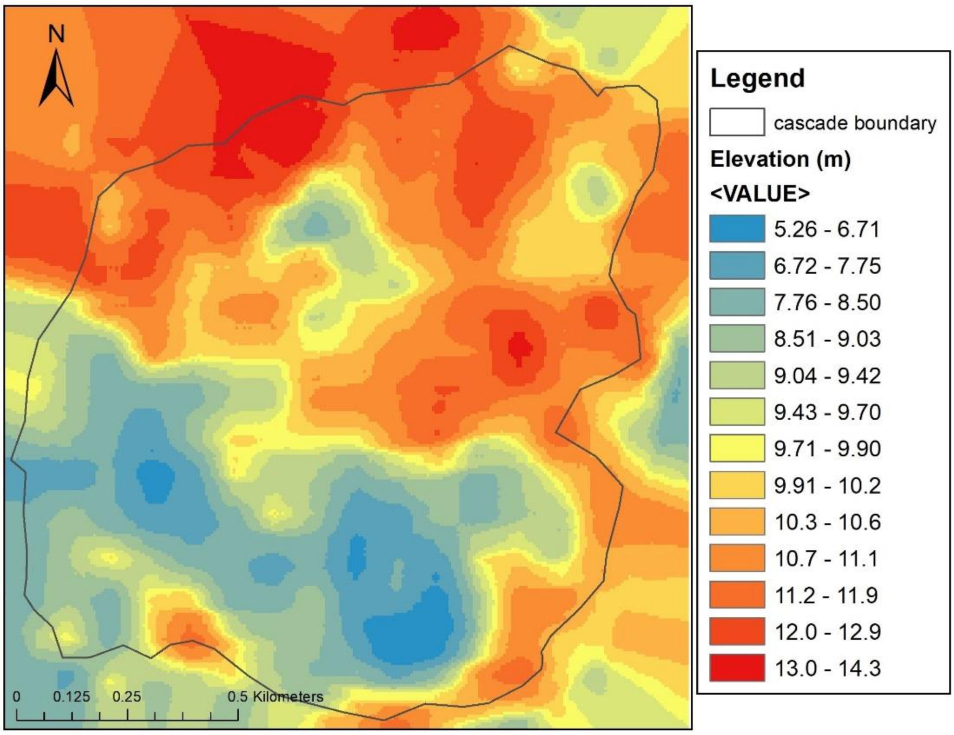

Figure 3.10: Generated DEM and Demarcated Catchment of the Study Area

3.4.2.3 Cascade System Identification

The identified problem in JMC area was the water scarcity in dry period and flood occurrence in the rainy season. Moreover, it was expected that if the cascade behaviour is restored, then that particular holistic behaviour would act as an improved water retention technique during the dry period and water detention in flood season will help mitigate flood damages in the nearby areas. Among the thousands of ponds present in Jaffna peninsula, there were about hundred small ponds in the Jaffna municipal area which were in better working conditions. However, due to vast amount of encroachments, many ponds have disappeared. It was identified as a serious issue that many ponds are becoming totally dry or fully filled due to the encroachments. Many environmentalists have warned about the major environmental issues that have arisen and how it is going to result in low water availability in the groundwater and surface water storages.

Due to the flat terrain in the Jaffna peninsula, cascade identification could not be carried out using the geographical conditions (existing ridges and valleys) alone. The main problem identified here is that the existing ponds are treated individually rather than considering them as a well-connected cascade system. The main criteria used during the identification is that the stream network indication of how the cascades are differentiated. Among the forty-seven water storage ponds present in the Jaffna municipal council area, from the basic identification it was found that there has to be about eight cascade systems present in the area. However, further studies have to be conducted to validate the initial identification. When the cascades were identified, the main data used are the existing channel flow connectivity and the natural flow connectivity.

Table 3.6: Number of Ponds in each Cascade

Cascade No	**Cascade name**	**Number of Ponds**
01	Nedunkulam Cascade	04
02	Nayanmarkaddu kulam Cascade	05
03	Paalkulam Cascade	07
04	Thevarikulam Cascade	03
05	Vannankulam Cascade	11
06	Katkulam Cascade	03
07	Rajalikulam Cascade	10
08	Pandarukulam Cascade	04

Catchment analysis for cascades and individual ponds were conducted following the traditional approach focusing on ridges and valleys. Later the GIS toolkit was used to identify the catchment boundaries, since the flat terrain in the Jaffna peninsula hindered identifying ridges in the study area. Among the identified forty-seven ponds in the Jaffna municipal council area, eight cascades were identified, accordingly.

Pond locations in the identified eight cascades are in the appendix A and the pond capacity variation along the stream path is also shown there.

3.4.2.4 Area Capacity Curve Generation

Survey maps, Evaporation, Seepage and Monthly end spillage data are used to generate Elevation-Area-Capacity curves. The non-existence of pond survey maps was a huge drawback to this study. However, for the selected two cascades, all the pond survey contour maps were available and the survey map of Vannankulam pond is shown in Figure 3.11. The Area-Capacity relationship with respect to the pond elevation is shown in Figure 3.12.

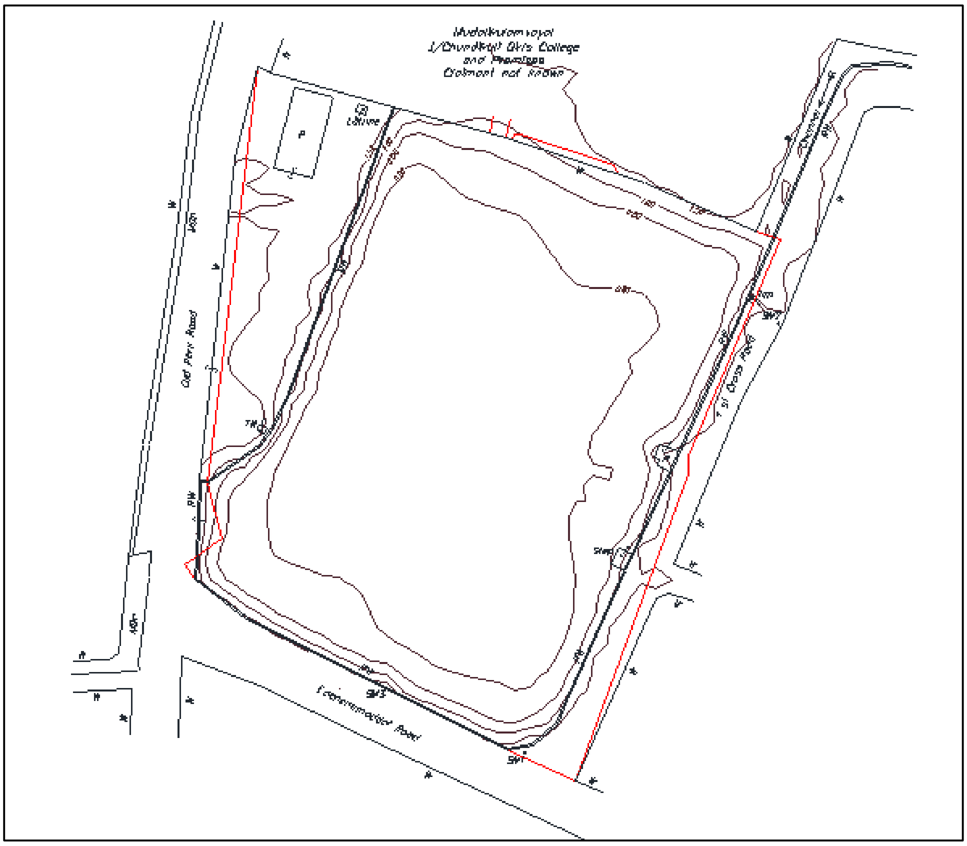

Figure 3.11: Vannankulam Pond Survey Contour Map

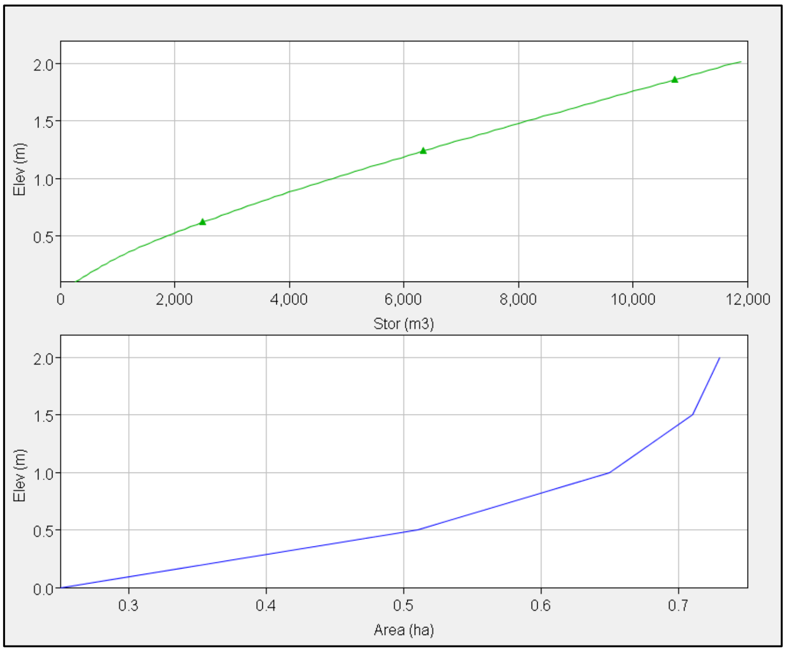

Figure 3.12: Area and Storage Variation with Elevation; Vannankulam Pond

3.4.3 Flood Analysis Using the Water Balance Approach

Irrigation guidelines (Ponrajah, 1984) are used for tabular preparation for water balance approach to find the end of the month storage of ponds in identified two cascades (Eq. 13).

$$\begin{Bmatrix} \text{Monthly} \\ \text{End} \\ \text{Storage} \end{Bmatrix} = \begin{Bmatrix} \text{Storage} \\ \text{at the} \\ \text{begining} \end{Bmatrix} + \text{Inflow} - \text{Evaporation} - \text{Seepage} - \text{Spillage} \qquad (13)$$

Inflow : Using ISO yields for study area and monthly rainfall data

Maha season yield : 400 Ac.ft./sq. miles

Yala season yield : 50 Ac.ft./sq. miles

Seepage : 0.5% of water volume

Spillage : {Monthly end net water inflow – Storage at the spillway}

Corresponding parameters were identified during the data collection stage and it is summarized in Tables 3.7 and 3.8. Since all the JMC ponds can be categorized as small scale water storage reservoirs, 50-year design period was used (Ponrajah, 1984). All the required parameters from the guidelines are taken considering as the pond locations fall to the second hydrological zone.

Table 3.7: Parameter Selection for Nayanmarkaddu Kulam Cascade

Parameter	**JMC 05**	**JMC 26**	**JMC 27**	**JMC 28**	**JMC 50**
Longest Water Course (miles)	0.450	0.472	0.317	0.867	0.240
Design Afflux (ft.)	1.5	2.0	2.0	2.5	1.5
Detention at HFL (Ac.ft.)	9.450	23.970	6.267	2.142	2.380
Catchment area (ha)	0.135	0.132	0.108	0.336	0.042
Catchment slope	0.5	0.5	0.5	0.5	0.5
Free board (ft.)	2	2	2	2	2
Detention at BTL (Ac.ft.)	13.400	29.650	8.491	2.834	3.269
Average gradient of stream	0.75	0.75	0.75	0.75	0.75

Table 3.8: Parameter Selection for Paalkulam Cascade

Parameter	**JMC 03**	**JMC 09**	**JMC 31**	**JMC 33**	**JMC 37**	**JMC 39**	**JMC 63**
Longest Water Course (miles)	0.150	0.680	0.050	0.141	0.410	0.050	0.125
Design Afflux (ft.)	2	2	1.5	2	2	1	2
Detention at HFL (Ac.ft.)	6.061	8.584	11.575	1.821	13.174	4.750	4.789
Catchment area (ha)	0.099	0.261	0.091	0.110	0.100	0.090	0.124

Catchment slope	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Free board (ft.)	2.0	2.0	1.5	2.0	2.0	1.5	2.0
Detention at BTL (Ac.ft.)	7.642	11.352	14.800	2.364	16.782	5.825	6.173
Avg. gradient of stream	0.75	0.75	0.75	0.75	0.75	0.75	0.75

3.4.4 Flood Analysis using HEC-ResSim Simulations

3.4.4.1 Introduction to the Application

The Paalkulam cascade is again divided into seven sub-catchments considering runoff contribution to individual ponds. During the rainy seasons, runoff in each sub-catchment accumulates to the associated individual pond and when the pond water level reaches the spill level, it starts to spill (Bandara, n.d.; Jayatilaka et al., 2001; Tennakoon, 1999). The HEC-ResSim computer simulation application was used to identify the net water quantity of spill during the rainy period which causes the floods in the downstream.

The computer program is divided into separate sets of functionalities called modules, and each module provides access to specific types and directories of data. There are three modules within the program, named Watershed Setup, Reservoir Network and Simulation (Klipsch & Hurst, 2013). Stream network and pond locations in the cascade are fed into the first module and all other data are fed to the application in the Reservoir Network module. During the simulations, the lookback data was taken as the 31st of December. The pond storage variation during the year was modelled for individual ponds. The water levels in the second inter monsoon were observed to be significantly higher than the spill crest levels in upstream ponds where it will lead to a flood disaster. From the water balance calculation, it can be calculated that the total spill water quantity and afflux over the weir release which help in turn to find the total inundation land area.

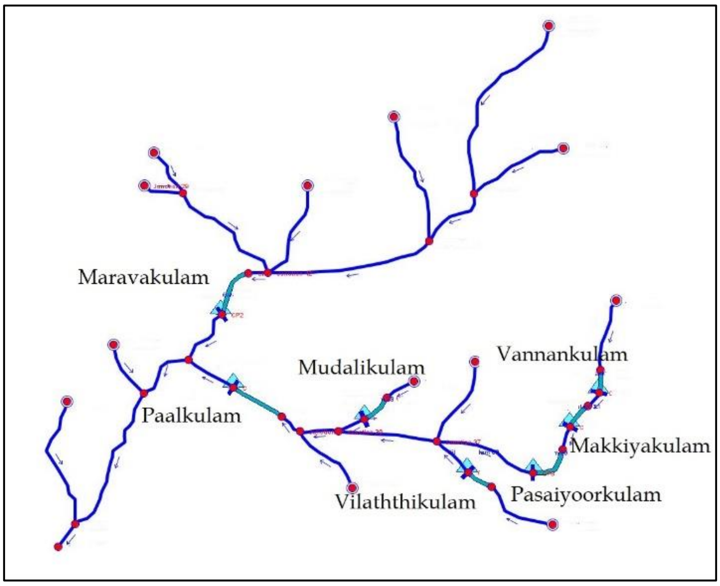

Figure 3.13: Paalkulam Cascade Pond Network in HEC-ResSim Modelling

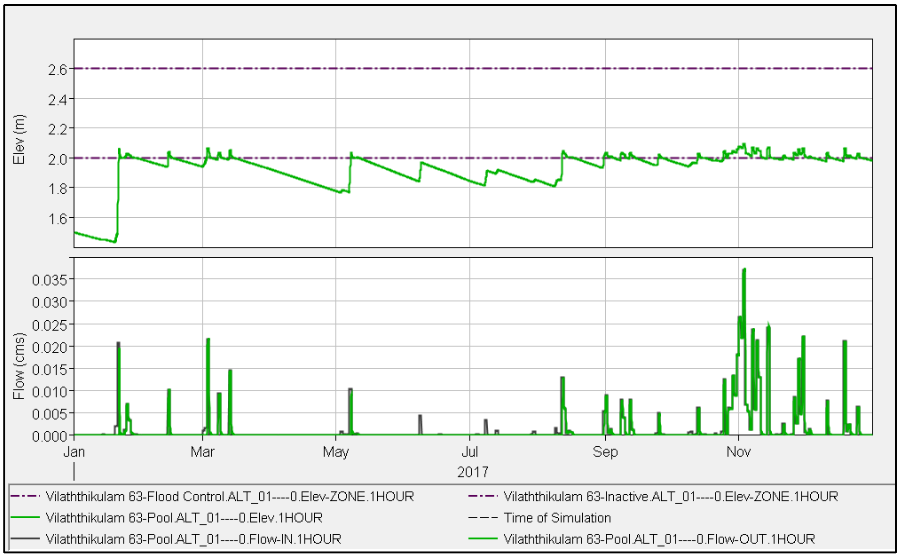

Figure 3.14: Elevation and Outflow Variation of Vilaththikulam

Program is divided into separate sets of functions called modules, each module provide access to specific type and directories of data. Three modules within the program,

- Watershed Setup
- Reservoir Network
- Simulation

3.4.4.1.1 Watershed Setup

The purpose of the Watershed Setup module is to provide a common framework for watershed creation and definition among different modelling applications. A watershed is associated with a geographic region for which multiple models and area coverages can be configured. A watershed may include all of the streams, project components (e.g., reservoirs, levees), gage locations, impact areas, time-series locations, and hydrologic and hydraulic data for a specific area. All of these details together, once configured, form a watershed framework. When a new watershed is created, HEC-ResSim generates a directory structure for all files associated with the watershed. In the Watershed Setup module, watershed's physical arrangement should be fed to the application. Once a new watershed is created, maps can be imported from external sources, layers containing additional information about the watershed can be added, a common stream alignment can be created, and furthermore elements can be configured.

3.4.4.1.2 Reservoir Network

The purpose of the Reservoir Network module is to isolate the development of the reservoir model from the output analysis. In the Reservoir Network module, network schematic can be built, by describing the physical and operational elements of the reservoir model, and alternatives can be developed that is sought to be analyzed. Using configurations that are created in the Watershed Setup module as a template, basis of a reservoir network can be created. Later, flow routing details of the reaches and possibly other network elements are added to complete the connectivity of network schematic. Once the schematic is complete, physical and operational data for each network element are defined. Also, alternatives are created that specify the reservoir network, operation set(s), initial conditions, and assignment of DSS pathnames (time-series mapping).

3.4.4.1.3 Simulation

The purpose of the Simulation module is to isolate output analysis from the model development process. Once the reservoir model is completed and the alternatives have been defined, the Simulation module is used to configure the simulation. The computations are performed and results are viewed within the Simulation module. When a particular simulation is created, a simulation time window, a computation interval, and the alternatives must be specified to be analyzed. Then, HEC-ResSim creates a directory structure within the watershed that represents the simulation. Within this simulation tree will be a copy of the watershed, including only those files needed by the selected alternatives. Additionally, elements can be edited and saved for subsequent simulations.

3.4.4.2 HEC-ResSim Simulation Application for Water Storage Calculations

Following the irrigation guidelines (Ponrajah, 1984), a simple water balance method is applied to each pond in the Jaffna city area and results are compared with the HEC-ResSim values. The future modelling fragments are completed only using the HEC-ResSim model application and the traditional water balance approach is performed as a result verification method to the computer application. Subsequently, the comparison of results and derived suggestions are to be used to check the suitability of the application when modelling small scale catchments. In the irrigation guidelines, the water demand is considered when the monthly end water storage is calculated. Nevertheless, the irrigation water demand or any other water use from ponds in Jaffna in the recent years can be neglected and therefore the total irrigation demand for each month can be taken as zero.

Data are fed to the computer application as given in the previous paragraph and Figures 3.15 ~ 3.20 show different steps of data entry to the simulation application.

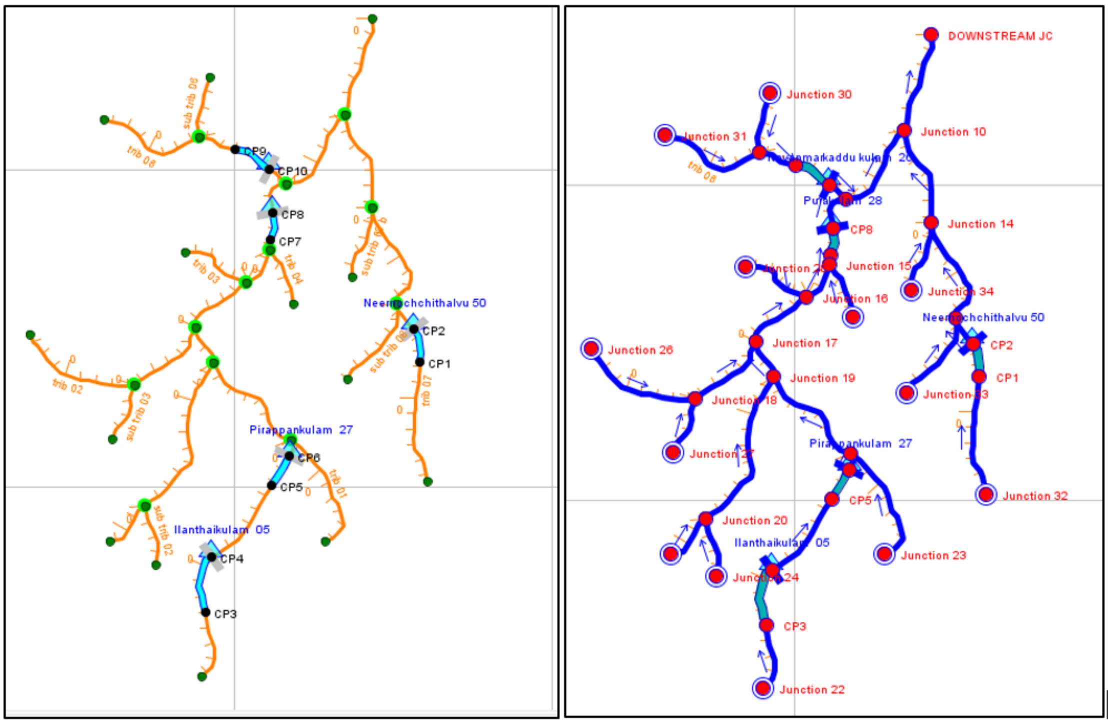

Figure 3.15: Watershed Setup and Network Setup of Nayanmarkaddu Kulam Cascade

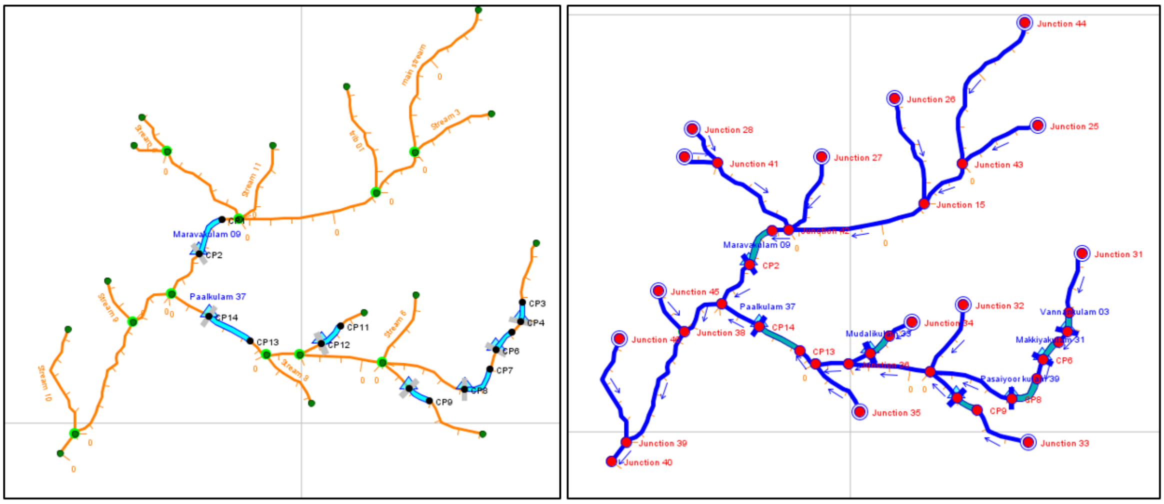

Figure 3.16: Watershed Setup and Network Setup of Paalkulam Cascade

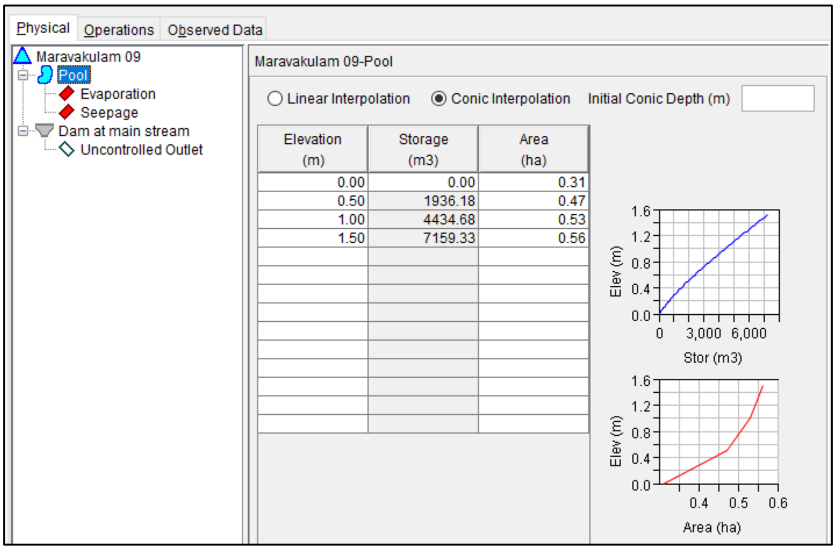

Figure 3.17: Elevation-Area Data to the Model; Maravakulam Pond

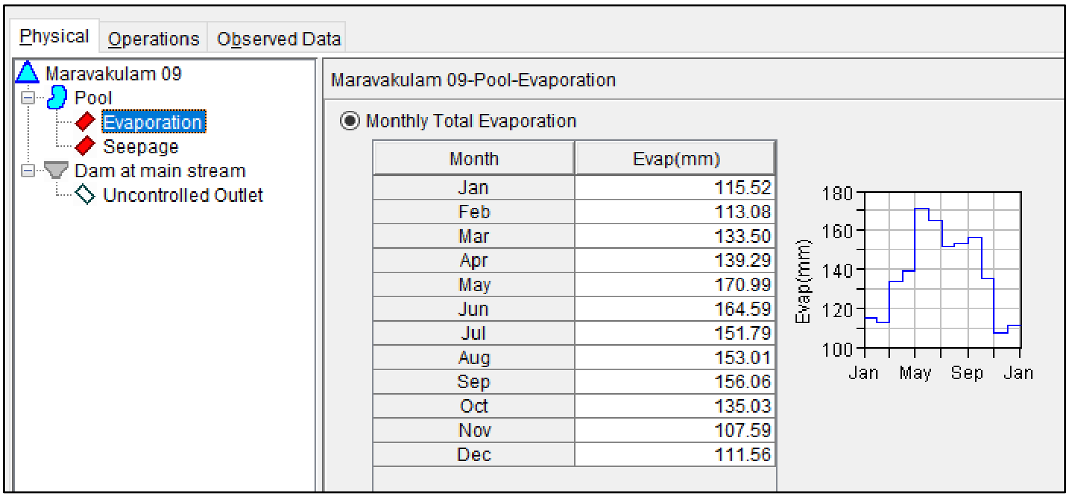

Figure 3.18: Monthly Total Evaporation; Maravakulam Pond

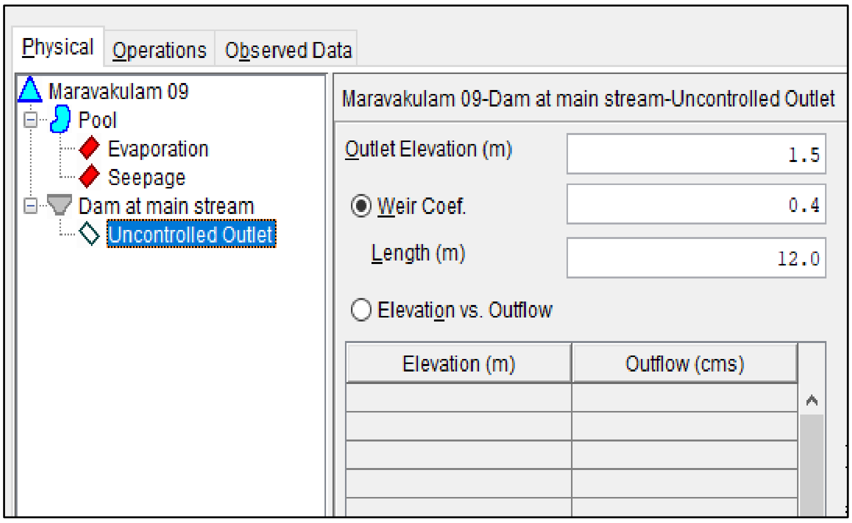

Figure 3.19: Uncontrolled Outlet Details; Maravakulam Pond

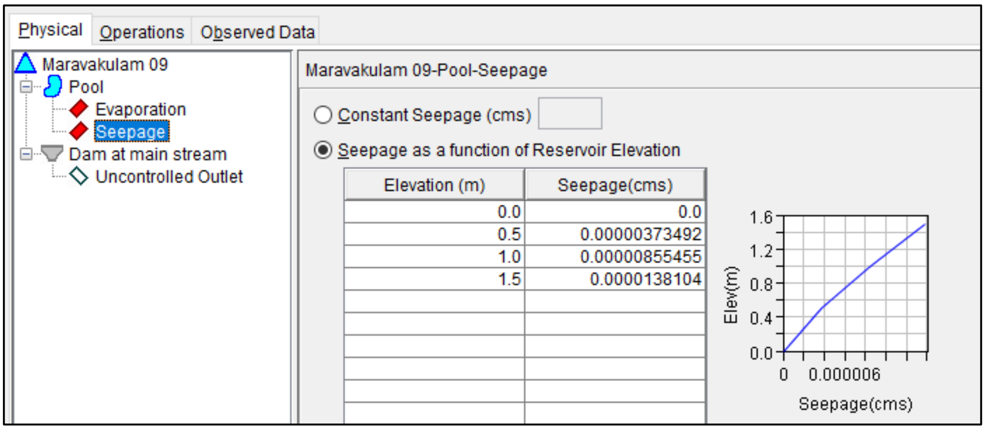

Figure 3.20: Seepage as a Function of Pond Elevation; Maravakulam Pond

3.4.5 Methodology for Scenario Analysis I

3.4.5.1 Introduction

For this scenario analysis, the holistic behaviour of pond systems was introduced, expecting that it will reduce the flood damages during second inter monsoon period (where the highest rainfall is expected in Jaffna peninsula). Total inundation area during the 2017 flood was compared with the simulated inundated area where the cascade connectivity was restored in Paalkulam cascade for the same climatic and geographical conditions. No detailed research has been undertaken to date to study the effect of pond cascade connectivity in an urban drainage system targeting flood mitigation and if this hypothesis is proven, the method will help to overcome similar flood crises occurring in similar urban areas around the world. Further to the provision of much required retention and detention for flood risk reduction, urban lakes and ponds are also known to promote passive recreational opportunities to the city dwellers while enriching landscape aesthetics, urban ecology and sound built-up environment.

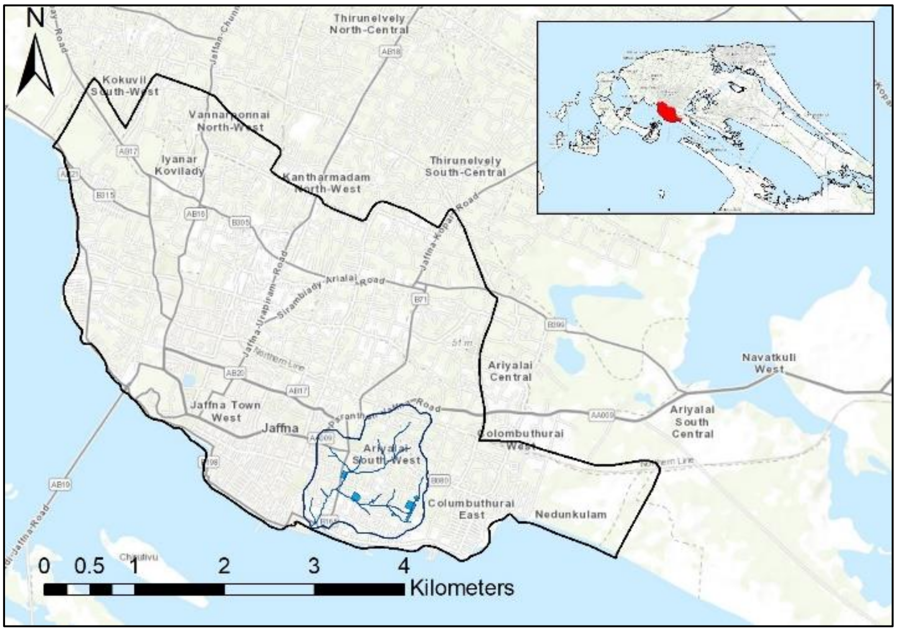

Figure 3.21: Paalkulam Cascade in Jaffna Municipal Council Area

The result comparison on the change of total inundation area after adding the cascade connectivity to the Paalkulam cascade is to be estimated using HEC-ResSim model simulations. Geographical and climatic data of the Paalkulam cascade, existing pond connectivity and stream paths were used in this study. Furthermore, the modelling approach was developed following the water balance approach and parameter selection was conducted following Ponrajah (1984).

3.4.5.2 HEC-ResSim Model Set up and Simulation

HEC-ResSim (HEC-US ACE, 2003), a reservoir simulation computer application (which is also based on water balance approach) has been used to model and simulate the behaviour of individual ponds and pond cascade system. The seven ponds in the Paalkulam cascade were first modelled individually and then modelling was introduced to the whole cascade. Equation 14 gives the net storage change, and the application should be fed with climatic and physical properties of ponds to find the net inflow and net outflow.

$$\text{Storage change} = \text{Inflow} - \text{Outflow} \tag{14}$$

The Paalkulam cascade is located in the South-eastern part of the Jaffna Municipal Council (Rajeswaran, 2005) and total catchment area of the cascade is 1.567 km^2. Land use pattern of the area is mostly residential and paddy area has been reduced by 26% from year 1995 to 2007 (Sutharsiny et al., 2012). Topography of the area is relatively flat and the catchments were demarcated based on SRTM 30 m resolution satellite DEM data and following the existing drainage network. The climate of the Jaffna peninsula region is considered as tropical monsoonal with a seasonal rhythm of rainfall where the highest rainfall is expected during the second inter monsoon period (Rajeswaran, 2005). The temperature ranges from 26 ˚C to 33 ˚C and annual precipitation ranges from 848 mm to 1909 mm (Rajeswaran, 2005). The North-East monsoon rain (October to January) accounts for more than 90% of the annual rainfall of the Jaffna peninsula. Due to the lack of surface water resources during the dry season, groundwater is being used for all the water needs such as drinking, agriculture and industry (Bandara, n.d.; Kandiah & Miyamoto, 2016). Paddy cultivation in Jaffna peninsula highly depends on the North East monsoon, but is limited for a three-month period in Maha season. However, it is hard to find any paddy cultivation in the Jaffna Municipal Council area during Yala season. The study area falls within two Divisional Secretariat (D.S.) administrative divisions, namely Jaffna Municipal Council and Nallur Pradeshiya Sabha (among the fifteen D.S. administrative divisions present in the peninsula) (Rajeswaran, 2005). The land elevation in study area holds a maximum of 14 m AMSL (above mean sea level) and drops when reaching south and southeast parts of the peninsula. Jaffna limestone aquifer is one of the most studied groundwater resources and it is a highly karstic Miocene limestone aquifer. Freshwater floats over the saline water and they are formed as mounds or lenses in the aquifer system and the water extraction is done by using those mounds or lenses (Joshua et al., 2013; Kumara, Rathnayaka, Mayadunne, & Rajapakse, 2013; Senthuran, 2016). During October to December, groundwater is getting recharged in the mounds of the karstic cavities.

However, soon after the rainfall stops, water table drops rapidly within less than three months.

Among the identified forty-seven ponds in the Jaffna Municipal Council area, seven ponds are in the Paalkulam cascade as shown in Figure 3.22 are used in this analysis. Capacity and maximum depth values of each pond are calculated using the survey maps (Survey map of Paalkulam pond is shown in Figure 3.23) of corresponding ponds.

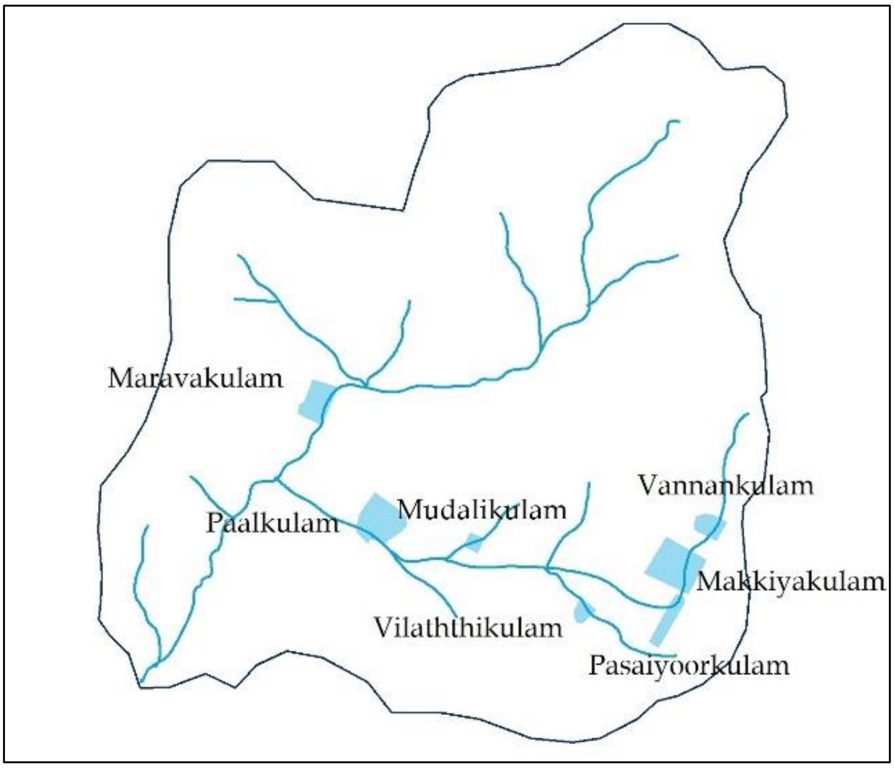

Figure 3.22: Paalkulam Cascade

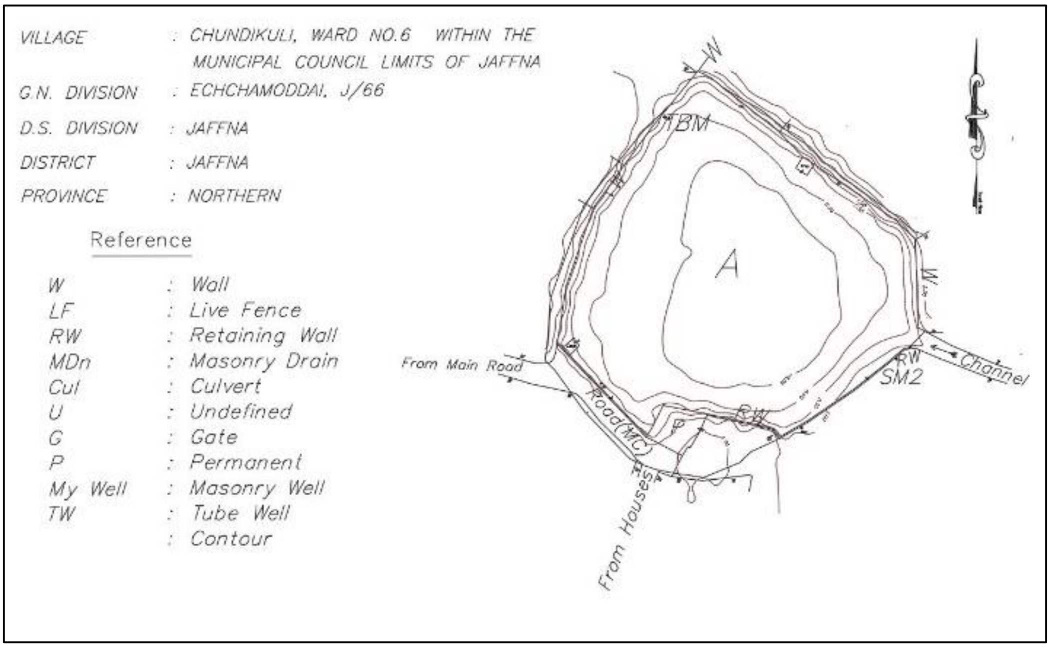

Figure 3.23: Contour Map of Paalkulam Pond

3.4.5.3 Data Processing

HEC-ResSim computer application is used for the analysis and it uses a simple water balance approach to model the pond storage changes as illustrated in Equation 15.

$$\Delta S = Q_i - Q_o - E - S_e \quad (15)$$

where,

ΔS	=	Storage Change
Q_i	=	Outflow from the Pond
Q_o	=	Inflow to the Pond
E	=	Evaporation
S_e	=	Seepage

Monthly average evaporation values of Thondamanar gauge station were fed into the application. Pond survey maps were used to generate the Elevation - Area curves and data was derived from the survey maps of recent Jaffna ponds rehabilitation project. The survey map of Paalkulam cascade ponds was used accordingly to identify the physical storage behaviour of each pond.

Table 3.9: Paalkulam Cascade Ponds

Pond	Total Capacity (m^3)	Max. depth (m)
Vannankulam	5,525	2.5
Maravakulam	7,175	1.5
Makkiyakulam	10,300	1.5
Mudalikulam	1,575	2.0
Paalkulam	11,800	2.0
Pasaiyoorkulam	4975	2.0
Vilaththikulam	4200	2.0

3.4.6 Methodology for Scenario Analysis II

3.4.6.1 Introduction

Even though the cascade connectivity for flood mitigation was addressed in Chapter 5, an additional analysis was carried out to identify the most sustainable restoration approach considering the pond location in the cascade. As there are two possible rehabilitation options available, each option was evaluated to find out the best preference for the maximum water sustainability in the cascade. Analysis was only carried out for the Paalkulam cascade and HEC-ResSim modelling was used to identify the total effect. Many discussions have been carried out to identify the best methodology which should be followed to the identification of the most feasible alternative option. First the Paalkulam cascade model results were examined and then its upstream pond bund levels were raised while the downstream capacity was kept unchanged. Later it was changed the other way around. The reason for following this method is, at the end what was expected to arrive at is a better water retention in the cascade rather than increasing the total capacities in all ponds This methodology was followed expecting that it may indicate that even though the cascade behaviour was considered initially, the rehabilitation method which should be followed will not be the same as that. The HEC-ResSim model simulation shows that during the dry period of the Jaffna peninsula, the pond water level is very low.

For this study, Paalkulam cascade was considered and its upstream ponds (Vannankulam, Makkiyakulam and Pasaiyoorkulam) and downstream ponds (Paalkulam and Maravakulam) are identified. The flood situations when the upstream bund level is raised and pond bed was dredged, were modelled using the HEC-ResSim application and ArcGIS toolkit.

The Paalkulam cascade is divided into seven sub-catchments considering 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 was used to identify the net spill water quantity in the rainy period which causes the floods in the downstream. Moreover, this spill water quantity was distributed to the downstream ponds for dredging and was prorated according to the pond capacities during the quantity distribution.

3.4.6.2 Upstream Pond Rehabilitation

The first part of this analysis was to model the upstream pond rehabilitation approaches and compare the simulation results with the 2017 flood hazard. The two rehabilitation approaches are considered, namely raising the bund levels and pond bed dredging. Identified three upstream pond bund levels were raised and model simulations were carried out to establish the spill water quantity. Then the upstream pond bed dredging was considered and its inundation area is calculated from ArcGIS toolkit.

3.4.6.2.1 Raising of the Bund Levels

The first approach of the upstream pond rehabilitation was bund level raising. Each pond bund level was raised by 0.5 m and HEC-ResSim simulations were conducted to find out the change in pond water balance. In the meantime, downstream ponds were retained as their existing condition. Upstream pond elevation-area-capacity input values were accordingly changed and all the other parameters were kept as used in the scenario analysis II. In this analysis as well, the data collection and feeding to the simulation application is conducted in the same manner. The spill water quantity was used to determine the inundation area and it was compared with the 2017 flood affected area.

Only the bund level of the ponds was changed and other physical parameters were kept unchanged. Moreover, the same modeling procedure was adopted here as well.

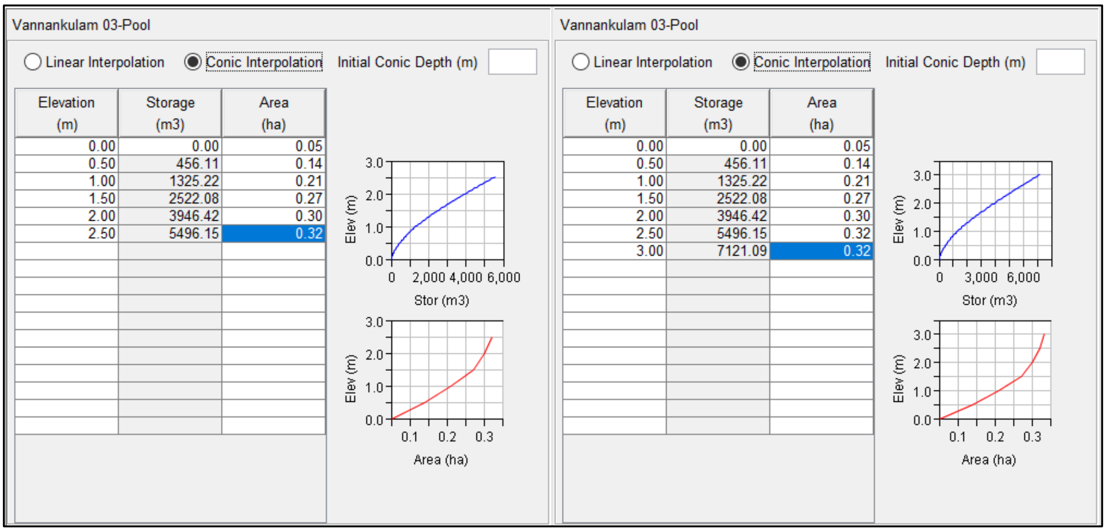

Figure 3.24: Change the Elevation Area Storage Relationship

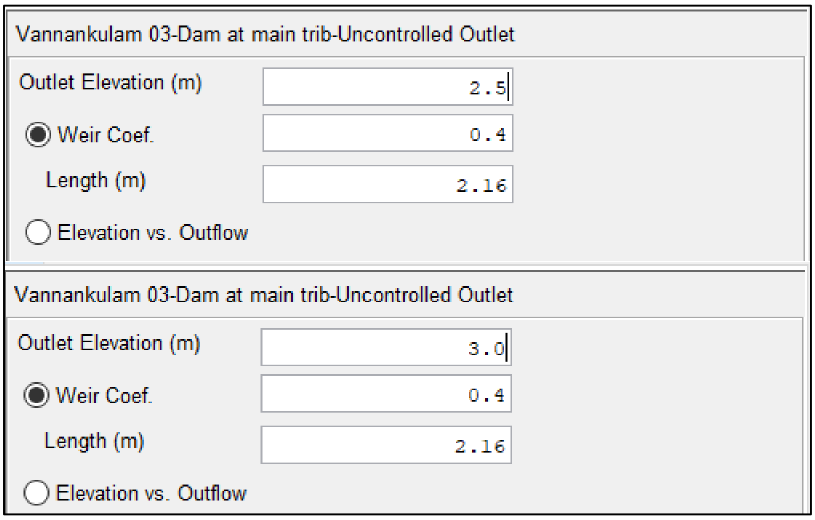

Figure 3.25: Change of the Uncontrolled Outlet Elevation (after the Bund Raising)

Then a model run was carried out for the period of 1st of January, 2017 to 31st of December, 2017. Evaporation values and runoff generations from rainfall were kept unchanged and they were similar to the water balance calculations and scenario analysis values.

3.4.6.2.2 Pond Bed Dredging

The next approach was the pond bed dredging and dredging quantity was calculated following the same method used in the pond capacity increment by bund raising. All three bunds of Paalkulam cascade ponds were raised by 0.5 m and the dredging quantity is calculated as shown in the Equation 16.

$$\text{Dredging quntity} = \sum \text{reservoir capcity increment by bund raising} \quad (16)$$

Therefore, required dredging quantity $= (0.5 \times 3200) + (0.5 \times 8700) + (0.5 \times 2900)$

$= 7{,}400\ m^3$

This quantity is distributed among the downstream ponds for dredging and the pond capacity values were used as the prorating parameter. For Paalkulam cascade, there are two downstream ponds (Maravakulam and Paalkulam) and considering their existing capacity values, the proposed dredging quantity was distributed (Table 3.10).

Table 3.10: Dredging Quantity Calculations

Pond	Capacity (m^3)	Dredging quantity (m^3)
Vannankulam	5525	$= 7400 \times \frac{5525}{(5525 + 10300 + 4975)}$ $= 1965.63\ m^3$
Makkiyakulam	10300	$= 7400 \times \frac{10300}{(5525 + 10300 + 4975)}$ $= 3664.42\ m^3$
Pasaiyoorkulam	4975	$= 7400 \times \frac{4975}{(5525 + 10300 + 4975)}$ $= 1769.95\ m^3$

The pond Elevation-Area-Storage relationship was accordingly changed, keeping the pond bund level constant and depth value was changed in range of 0.5 – 2.0 m. The dredging depth was identified following an iteration method (Table 3.11) and checking whether the expected capacity increment is received or not.

It is recommended that when the storage ratio is higher than 4, it is more appropriate to start dredging from a higher contour. The Storage Ratio (SR) margin of 4 is defined based on that.

Table 3.11: Dredging Depth Calculation Method

Dredging from contour	***Storage ratio***	***Depth to be dredged***
Beginning contour (xx) of the dredging	$\frac{Dredging\ quantity}{maximum\ dredging\ upto\ 0\ m\ contour}$	*If SR < 1;* *0 m* *If 1<SR<4* *Dredge from there* *Calculate, (DD) dredging depth* $DD = \frac{dredgin\ quantity + current\ storage}{area\ at\ xx\ contour}$ *If DD < xx;* *Lowest contour won't change* *If DD > xx;* *Dredge 0.5 m more* *Calculate the bottom contour area using the eq. 07.* *If Bottom < Top;* *Lowest contour won't change* *If Bottom > Top;* *Dredge 0.5 m more* *If SR> 4* *Go to the next contour*

If the pond bed dredging has to be carried out, a conical variation of area-elevation is assumed and bottom area is calculated using the Equation 17.

$$\text{Bottom contour area} = \frac{2\times\text{Volume}}{\Delta(\text{contour height})} - \text{Top contour area} \tag{17}$$

Table 3.12: Dredging Depth Calculation of Vannankulam Pond

Dredging from contour	Storage ratio	Depth to be dredged
0.5 m	$\frac{1965.65}{0.5\times 1400 - 475} = 8.73$	SR > 4 Go to the next contour
1.0 m	$\frac{1965.63}{1\times 2100 - 1350} = 2.62$	1 < SR < 4 Dredge from there $\text{DD} = \frac{1965.63 + 1350}{2100\times 1} = 1.579$ Dredge 0.5 m more 1 m contour area = 2100 Volume = 1965.63 + 1350 = 3315.63 Form eq. 07 Bottom area = 2320.84 Bottom area > Top area Dredge 0.5 m more From eq. 07 Bottom area = 1215.63 Bottom area < Top area Acceptable!

The iteration method was used for Makkiyakulam and Pasaiyoorkulam ponds as well and results are summarized in the Table 3.13.

Table 3.13: Dredging Notes of Upstream Ponds; Paalkulam

Pond	Dredging note
Vannankulam	Dredge 1 m where the –1 m contour area is 1215.63 m^2
Makkiyakulam	Dredge 0.5m where the -0.5 m contour area is 5029.24 m^2
Pasaiyoorkulam	Dredge 0.5m where the -0.5 m contour area is 1326.6 m^2

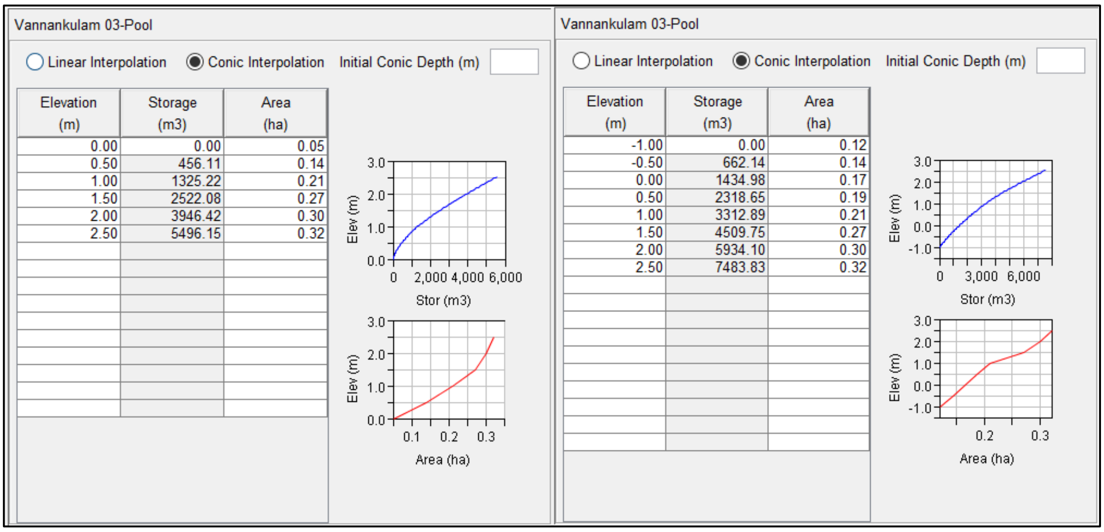

Figure 3.26: Adjusting the Elevation-Area-Storage Relationship of Vannankulam Pond

Vannankulam pond elevation-area-storage relationship is to be changed accordingly and is shown in Figure 3.26.

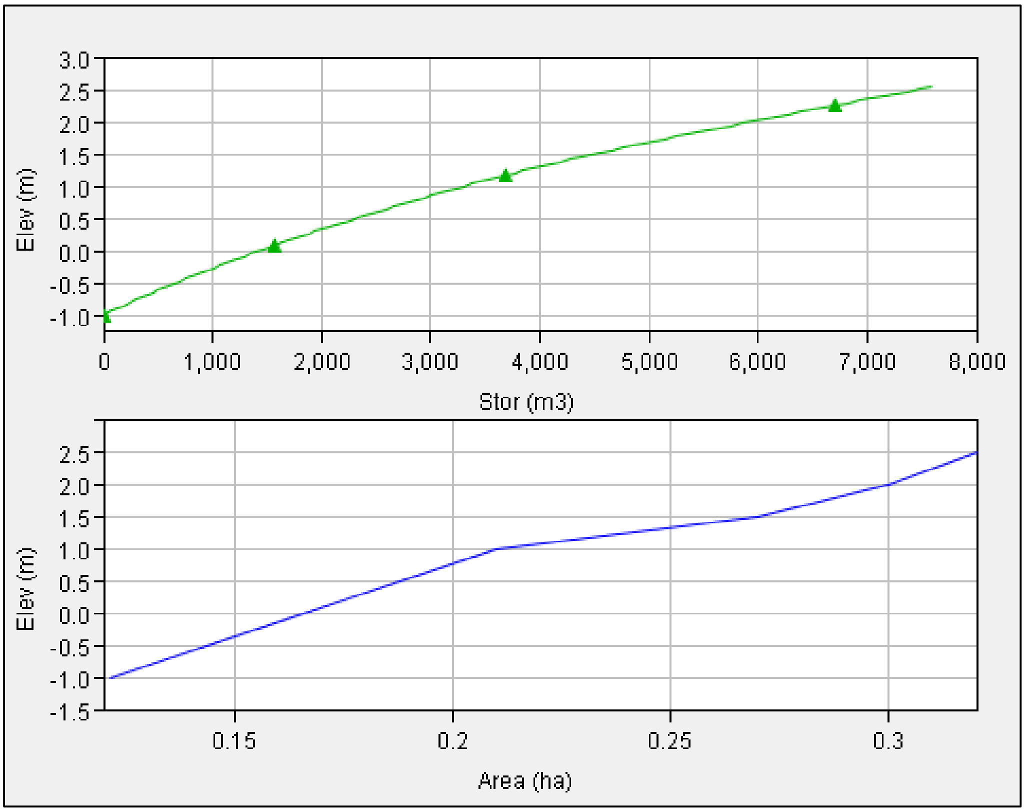

Figure 3.27: Elevation-Area-Storage Relationship of Dredged Vannankulam Pond

For the updated pond elevation contours, Elevation-Area-Storage relationships were developed. The HEC-ResSim simulations were carried to identify the spill water quantity and inundation areas were demarcated using the Digital Elevation Map (DEM) of the catchment. The 2017 flood data were compared with these results and inundation area reduction is calculated.

3.4.6.3 Downstream Pond Rehabilitation

The same procedure for the pond bund raising in the upstream is followed in this scenario analysis as well. The bund height was increased by 5% 10% and 15% and then HEC-ResSim application was used to determine the storage behaviour of particular ponds in two cascades (Paalkulam and Nayanmarkaddu kulam cascades).

In the identified two cascades which are used for modelling, the effect of changes in the total capacity by dredging was considered. Dredging can damage the pond bed and that may increase the average water seepage rate, nevertheless it was not considered and it has been assumed that the seepage rate will not be changed in this analysis. The possible 5% 10% and 15% total capacity increments were modelled.

3.4.6.3.1 Raising of the Bund Levels

In the same manner followed in the first approach of the downstream pond rehabilitation, its bund level raising was considered. Each pond bund level was raised by 0.5 m and HEC-ResSim simulations were carried out accordingly. However, the downstream ponds were kept as its current condition. Upstream pond Elevation-Area-Capacity input values were changed accordingly and other parameters were retained as used in the scenario analysis I. Data collection and feeding to the simulation application is carried out in the same manner for the previous analysis. Furthermore, the spill water quantity was used to find the inundation area and it was plaid with the 2017 flood affected area.

Only the bund level was changed while keeping other physical parameters of the Paalkulam cascade were unchanged. The bund level raising of downstream ponds was carried out for both Paalkulam and Maravakulam ponds (Figure 3.28). Inundation area reduction of Paalkulam pond is compared. The bund level of Maravakulam was raised by 0.5 m for the analysis. Along with that, Paalkulam pond uncontrolled outlet elevation also was changed by 0.5 m (Figure 3.29).

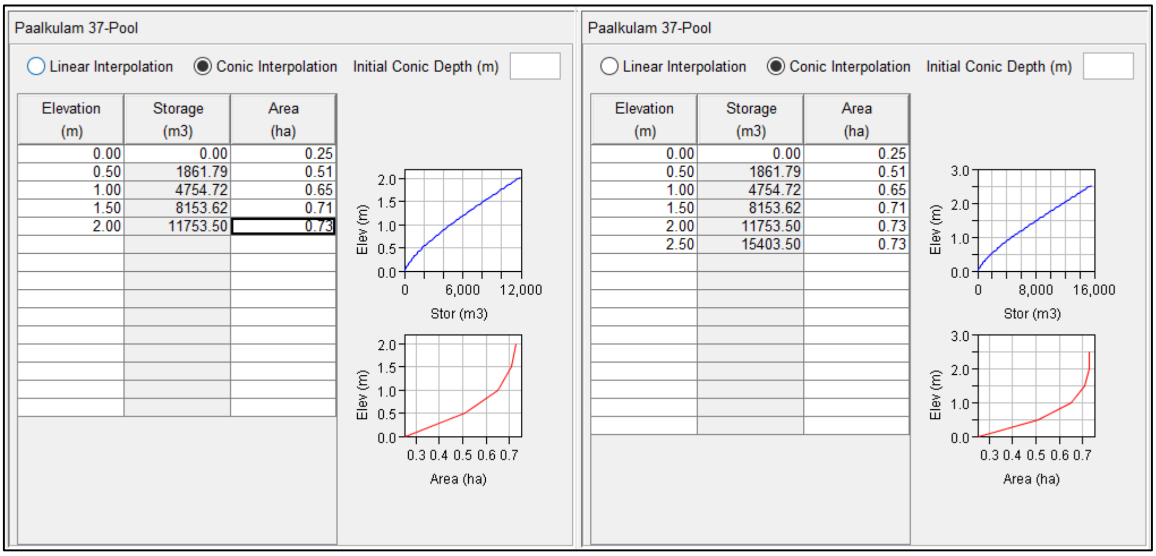

Figure 3.28: Change the Elevation Area Storage Relationship

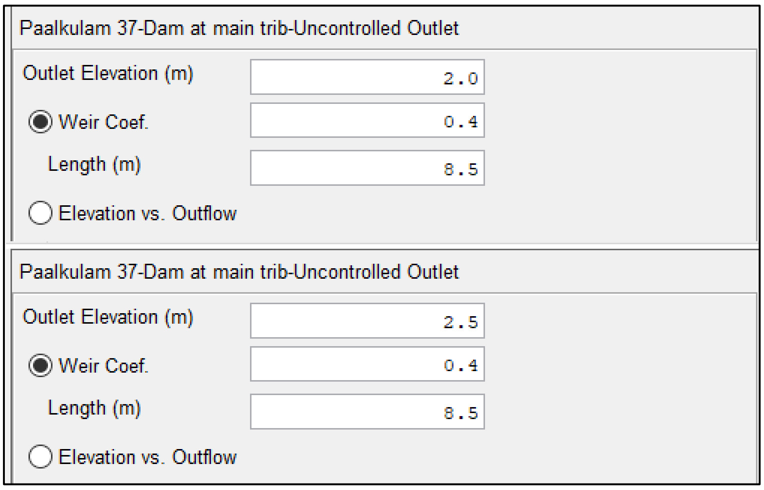

Figure 3.29: Change of the Uncontrolled Outlet Elevation (after the Bund Raising)

Then a model run was carried out for the period of 1st of January, 2017 to 31st of December, 2017. Evaporation values and runoff generations from rainfall were kept same as the initial water balance calculations and scenario analysis.

3.4.6.3.2 Pond Bed Dredging

The next rehabilitation approach was pond bed dredging and dredging quantity was calculated as same as the pond capacity increment by bund raising (Table 3.14). All three bund levels of Paalkulam cascade ponds were increased by 0.5 m and the dredging quantity is calculated as shown.

Required dredging quantity $= (0.5 \times 7300) + (0.5 \times 5600)$

$= 6450\ m^3$

This quantity is distributed for dredging in the downstream ponds and the pond capacity was taken as the prorating parameter.

Table 3.14: Dredging Quantity Calculations; Downstream

Pond	**Capacity**	**Dredging quantity**
Paalkulam	11800	$= 6450 \times \frac{11800}{(11800 + 7175)}$ $= 4011.07$ m3
Maravakulam	7175	$= 6450 \times \frac{7175}{(11800 + 7175)}$ $= 2438.93$ m3

Pond Elevation-Area-Storage relationship was changed accordingly such that the pond bund level does not change but the depth was changed in the range of 0.5 – 2.0 m. The dredging depth was identified following the same iteration method and continuation with checking whether the expected capacity increment is achieved or not.

Dredging depth calculation method was used for the upstream ponds as well. The dredging depth calculations for Maravakulam pond are shown in Table 3.15 and summarized in Table 3.16

Table 3.15: Dredging Depth Calculation of Maravakulam Pond

Dredging from contour	**Storage ratio**	**Depth to be dredged**
0.5 m	$\frac{2438.93\ m^3}{0.5\ m \times 4700\ m^2 - 1950\ m^2} = 6.20$	SR > 4 Go to the next contour
1.0 m	$\frac{2438.93\ m^3}{1\ m \times 5300\ m^2 - 4450\ m^3} = 2.92$	1 < SR < 4 Dredge from there $\text{DD} = \frac{2438.93 + 4450}{5300 \times 1} = 1.308$ Dredge 0.5 m more

		1 m contour area = 5300 m^2 Volume = 2438.93 + 4450 = 6933.93 m^3 Form eq. 07 Bottom area = 3945.24 m^2 Bottom area < Top area Acceptable!

For the Paalkulam pond as well, dredging depth calculation was carried out and its recommendations are consequently determined.

Table 3.16: Dredging Notes of Downstream Ponds; Paalkulam cascade

Pond	**Dredging note**
Maravakulam	Dredge 0.5 m where the –0.5 m contour area is 3945.24 m^2
Paalkulam	Dredge 0.5m where the -0.5 m contour area is 5248.09 m^2

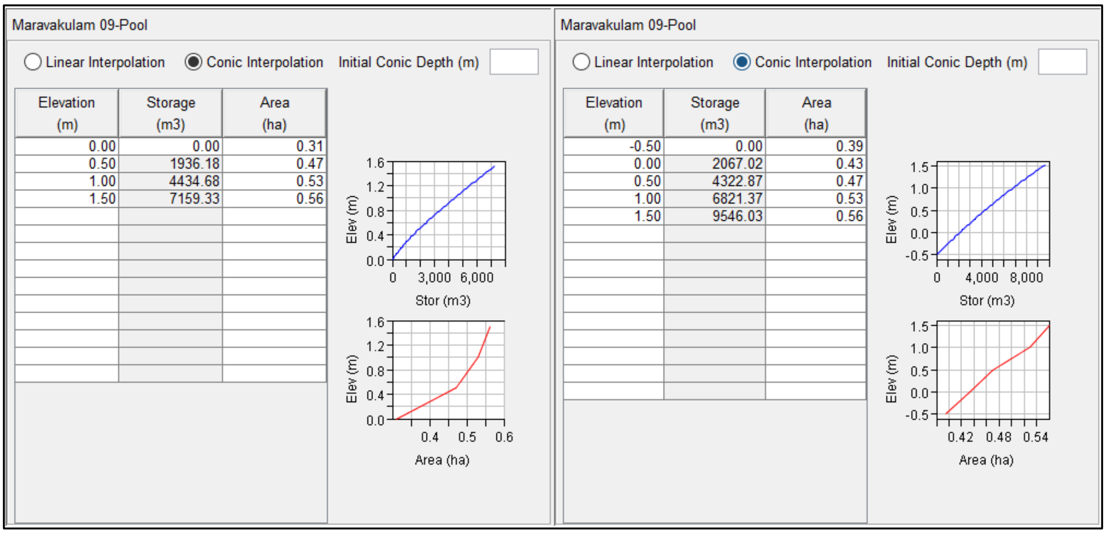

Figure 3.30: Adjusting the Elevation-Area-Storage Relationship of Maravakulam Pond

Elevation-Area-Storage relationship of the Maravakulam pond after dredging is shown in Figure 3.30 and Figure 3.31.

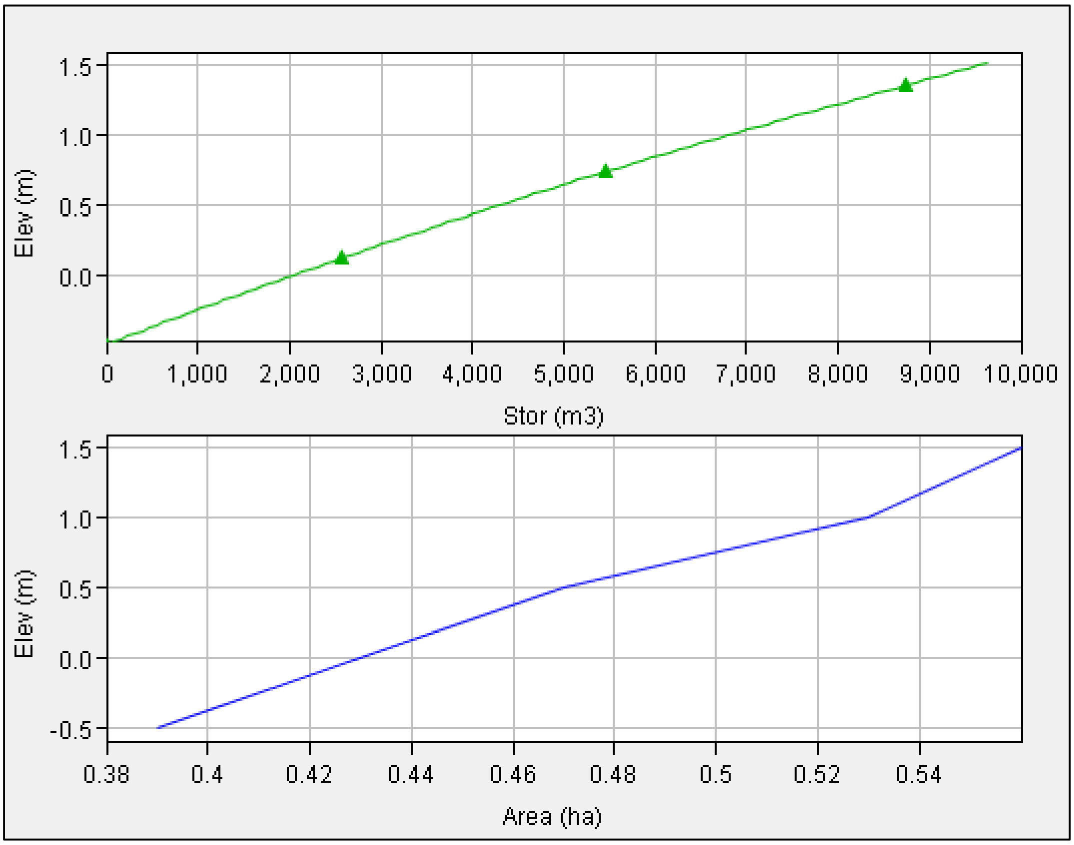

Figure 3.31: Elevation-Area-Storage Relationship of Dredged Maravakulam

Then for the new contour values after dredging, Elevation-Area-Storage relationships were developed and HEC-ResSim simulations were carried to identify the spill water quantity and later inundation areas were developed using the DEM of the catchment area. Again, the 2017 flood data values were compared with and the inundation area reduction is determined.

4 RESULTS AND DISCUSSION

4.1 Pond Storage Analysis using Water Balance

After following the water balance approach to find the monthly end water storage values using 75% probable rainfall data, storage data was summarized as shown in Table 4.1 and Table 4.2. (Monthly storage variation of Ilanthaikulam pond is shown in Figure 4.1)

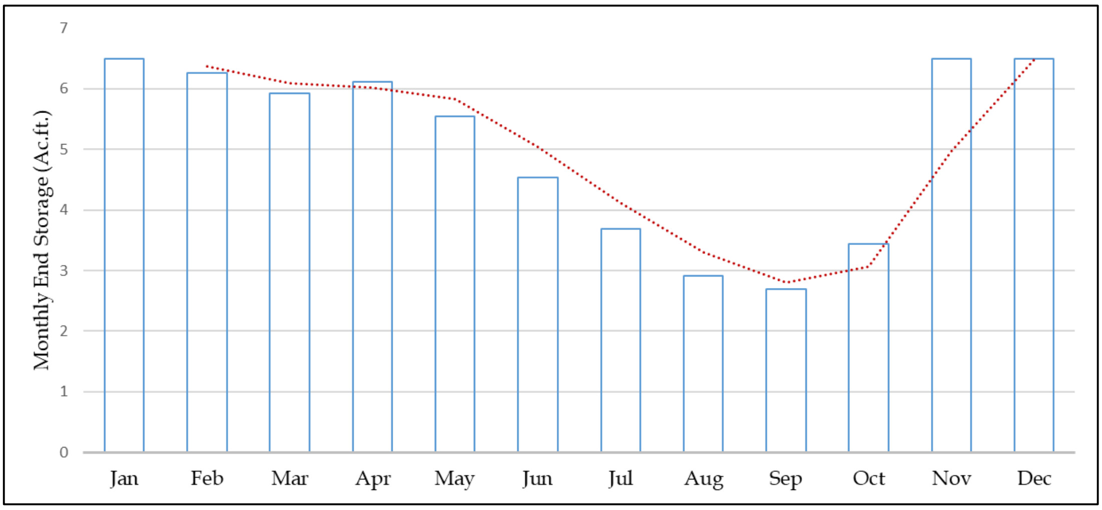

Figure 4.1: Monthly Storage Variation of Ilanthaikulam Pond

4.1.1 Monthly End Storage Values of Nayanmarkaddu Kulam Cascade

The monthly end storage variation and monthly end storage percentage of ponds in Nayanmarkaddu kulam cascade is shown in Table 4.1 and Table 4.2.

Table 4.1: Monthly End Storage Values from Water Balance Approach of Nayanmarkaddu Kulam Cascade (Ac.ft.)

Pond JMC No	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
05	6.486	6.261	5.920	6.112	5.547	4.535	3.688	2.908	2.694	3.435	6.486	6.486
26	18.282	18.282	18.282	18.282	18.245	16.620	15.144	13.685	13.874	13.287	18.282	18.282
27	4.043	4.043	3.968	4.043	3.832	3.230	2.722	2.251	2.239	2.182	4.043	4.043
28	1.277	1.277	1.277	1.277	1.277	1.084	0.910	0.740	1.277	1.277	1.277	1.277
50	1.713	1.706	1.670	1.713	1.622	1.377	1.161	0.951	0.916	0.855	1.713	1.713

Table 4.2: Monthly End Storage Percentage from Water Balance Approach of Nayanmarkaddu Kulam Cascade

Pond JMC No	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
05	1.000	0.965	0.913	0.942	0.855	0.699	0.569	0.448	0.415	0.530	1.000	1.000
26	1.000	1.000	1.000	1.000	0.998	0.909	0.828	0.749	0.759	0.727	1.000	1.000
27	1.000	1.000	0.981	1.000	0.948	0.799	0.673	0.557	0.554	0.540	1.000	1.000
28	1.000	1.000	1.000	1.000	1.000	0.849	0.713	0.580	1.000	1.000	1.000	1.000
50	1.000	0.996	0.975	1.000	0.947	0.804	0.678	0.555	0.535	0.499	1.000	1.000

4.1.2 Monthly End Storage Values of Paalkulam Cascade

The monthly end storage variation and monthly end storage percentage of ponds in Paalkulam cascade is shown in Table 4.3 and Table 4.4

Table 4.3: Monthly End Storage Values from Water Balance Approach of Paalkulam (Ac.ft.)

Pond JMC No	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3	4.479	4.479	4.479	4.479	4.407	3.960	3.557	3.160	3.161	2.201	4.479	4.479
9	5.817	5.817	5.817	5.817	5.817	5.041	4.339	3.648	5.817	5.817	5.817	5.817
31	5.501	5.100	4.579	4.400	3.667	2.641	1.731	0.905	0.676	2.970	4.848	5.743
33	1.277	1.277	1.277	1.277	1.277	1.124	0.987	0.854	1.164	1.277	1.277	1.277
f37	9.566	9.566	9.566	9.566	9.566	8.544	7.612	6.685	7.006	9.566	9.566	9.566
39	4.033	4.033	4.033	4.033	3.970	3.564	3.194	2.827	2.818	2.287	4.033	4.033
63	3.405	3.405	3.405	3.405	3.405	3.014	2.673	2.347	2.526	2.889	3.405	3.405

Table 4.4: Monthly End Storage Percentage from Water Balance Approach of Paalkulam

Pond JMC No	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3	1.000	1.000	1.000	1.000	0.984	0.884	0.794	0.705	0.706	0.491	1.000	1.000
9	1.000	1.000	1.000	1.000	1.000	0.867	0.746	0.627	1.000	1.000	1.000	1.000
31	0.659	0.611	0.548	0.527	0.439	0.316	0.207	0.108	0.081	0.356	0.581	0.688
33	1.000	1.000	1.000	1.000	1.000	0.880	0.773	0.669	0.912	1.000	1.000	1.000
37	1.000	1.000	1.000	1.000	1.000	0.893	0.796	0.699	0.732	1.000	1.000	1.000
39	1.000	1.000	1.000	1.000	0.984	0.884	0.792	0.701	0.699	0.567	1.000	1.000
63	1.000	1.000	1.000	1.000	1.000	0.885	0.785	0.689	0.742	0.849	1.000	1.000

4.2 Pond Storage Analysis using HEC-ResSim Simulation

HEC-ResSim model results of Paalkulam cascade are summarized in Table 4.5. The results were compared with the manual water balance calculations and recommendations were derived accordingly. Based on above, the applicability of the HEC-ResSim simulation method is verified for future water balance approaches. The Figure 4.2 shows that the Paalkulam cascade ponds' average, maximum and minimum storage, water elevation and uncontrolled spill values. Average storage of each pond was used for the calculation of average storage index.

Simulation: 2017.01.01-0100
Alternative:ALT_01

Lookback: 01 Jan 2017 24:00
Start Time: 01 Jan 2017 01:00
End Time: 01 Jan 2018 24:00

Location/Parameter	Average	Maximum	Minimum
Makkiyakulam 31			
Storage (m3)	8158.43	11227.75	4515.12
Elevation (m)	1.26	1.62	0.80
Controlled Release (cms)	0.00	0.00	0.00
Uncontrolled Spill (cms)	0.00	0.05	0.00
Maravakulam 09			
Storage (m3)	6803.39	7690.60	4115.48
Elevation (m)	1.44	1.59	0.94
Controlled Release (cms)	0.00	0.00	0.00
Uncontrolled Spill (cms)	0.01	0.14	0.00
Mudalikulam 33			
Storage (m3)	1490.90	1625.35	981.57
Elevation (m)	1.93	2.05	1.43
Controlled Release (cms)	0.00	0.00	0.00
Uncontrolled Spill (cms)	0.00	0.02	0.00
Paalkulam 37			
Storage (m3)	10731.30	12615.34	7645.53
Elevation (m)	1.86	2.12	1.43
Controlled Release (cms)	0.00	0.00	0.00
Uncontrolled Spill (cms)	0.00	0.14	0.00
Pasaiyoor kulam 39			
Storage (m3)	3591.43	5244.96	1752.19
Elevation (m)	1.51	2.10	0.84
Controlled Release (cms)	0.00	0.00	0.00
Uncontrolled Spill (cms)	0.00	0.05	0.00
Vannankulam 03			
Storage (m3)	5295.86	6008.66	3749.90
Elevation (m)	2.44	2.66	1.93
Controlled Release (cms)	0.00	0.00	0.00
Uncontrolled Spill (cms)	0.00	0.05	0.00
Vilaththikulam 63			
Storage (m3)	3980.26	4458.03	2732.90
Elevation (m)	1.92	2.09	1.43
Controlled Release (cms)	0.00	0.00	0.00
Uncontrolled Spill (cms)	0.00	0.04	0.00

Figure 4.2: Paalkulam Cascade Summary Report

Table 4.5: Paalkulam Cascade Model Results

Pond	**Average Monthly end storage (m^3)**	**Capacity (m^3)**	**Average Storage Index**
Vannankulam	5295.86	5525	0.9585
Maravakulam	6803.39	7175	0.9482
Makkiyakulam	8158.43	10300	0.7921
Mudalikulam	1490.90	1575	0.9466
Paalkulam	10731.3	11800	0.9094
Pasaiyoorkulam	3591.43	4975	0.7219
Vilaththikulam	3980.26	4200	0.9477

The average storage index is calculated for each pond in all two cascades, and is summarized in Table 4.2. It clearly shows that, as the water is conveyed from upstream to downstream, the downstream water retention capacities should be increased with respect to the increments of the total water sustainability of the cascade.

4.3 Results Comparison between Water Balance Approach and HEC-ResSim Simulation

A simple water balance approach is carried out to find the monthly end storage values and then HEC-ResSim modelling is conducted for verification. The comparison is completed to validate the model outputs and if it can be validated, model can be used for future analyses. The HEC-ResSim modelling is typically carried out for larger scale reservoirs and in this study area where relatively very minor scale reservoirs (ponds) are present, therefore this results would do a justification on the applicability of the HEC-ResSim computer simulation application. Storage variation of Ilanthaikulam, Nayanmarkaddu kulam, Pirapankulam, Purakulam and Neernochchithalvu kulam are shown in Table 4.6~4.10.

Table 4.6: Ilanthaikulam Monthly End Storage Values (Ac.ft.)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBA	6.486	6.261	5.920	6.112	5.547	4.535	3.688	2.908	2.694	3.435	6.486	6.486
HEC-ResSim	5.213	5.703	5.689	5.943	5.858	5.166	3.652	3.194	2.838	3.520	6.573	6.531

Table 4.7: Nayanmarkaddu Kulam Monthly End Storage Values (Ac.ft.)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBA	18.282	18.282	18.282	18.282	18.245	16.620	15.144	13.685	13.874	13.287	18.282	18.282
HEC-ResSim	14.217	16.815	16.419	15.639	16.234	15.471	15.916	11.844	12.199	14.418	18.474	18.394

Table 4.8: Pirapankulam Monthly End Storage Values (Ac.ft.)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBA	4.043	4.043	3.968	4.043	3.832	3.230	2.722	2.251	2.239	2.182	4.043	4.043
HEC-ResSim	2.659	2.611	2.548	3.527	3.439	3.316	3.207	2.108	2.081	2.356	4.581	4.188

Table 4.9: Purakulam Monthly End Storage Values (Ac.ft.)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBA	1.277	1.277	1.277	1.277	1.277	1.084	0.910	0.740	1.277	1.277	1.277	1.277
HEC-ResSim	0.965	0.913	0.942	1.355	0.999	1.069	0.948	0.915	1.530	1.448	1.315	1.330

Table 4.10: Neernochchithalvu Kulam Monthly End Storage Values (Ac.ft.)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBA	1.713	1.706	1.670	1.713	1.622	1.377	1.161	0.951	0.916	0.855	1.713	1.713
HEC-ResSim	0.705	0.627	0.808	1.669	1.699	1.401	1.989	0.927	0.908	1.069	1.699	1.701

In HEC-ResSim analysis, the lookback elevation is referred to the first contour line as default (a variation lesser than 10% is considered as negligible).

4.4 Pond Prioritization using the Average Storage Index (ASI)

A simple check of whether the pond capacity should be increased or not can be carried out using the average storage index values in each pond. Their results are summarized as in Table 4.11~4.14

4.4.1 Pond Prioritization of the Nayanmarkaddu Kulam Cascade

Table 4.11: Nayanmarkaddu Kulam Average Storage Index

JMC No	Pond	Avg. Storage Index
5	Ilanthaikulam	0.778
26	Nayanmarkaddu kulam	0.914
27	Pirapankulam	0.838
28	Purakulam	0.928
50	Neernochchithalvu kulam	0.832

Table 4.12: Nayanmarkaddu Kulam Prioritization

Prioritization	JMC No	Pond	Avg. Storage Index	Location
1	28	Purakulam	0.928	Downstream
2	26	Nayanmarkaddu kulam	0.914	Downstream
3	27	Pirapankulam	0.838	Middle
4	50	Neernochchithalvu kulam	0.832	Upstream
5	05	Ilanthaikulam	0.778	Upstream

4.4.2 Pond Prioritization of the Paalkulam Cascade

Table 4.13: Paalkulam Cascade Average Storage Index

JMC No	Pond	Avg. Storage Index
3	Vannankulam	0.880
9	Maravakulam	0.937
31	Makkiyakulam	0.427
33	Mudalikulam	0.936
37	Paalkulam	0.927
39	Pasaiyoorkulam	0.886
63	Vilaththikulam	0.912

Table 4.14: Paalkulam Prioritization

Prioritization	JMC No	Pond	Avg. Storage Index	Location
1	9	Maravakulam	0.937	Downstream
2	33	Mudalikulam	0.936	Middle
3	37	Paalkulam	0.927	Downstream
4	63	Vilaththikulam	0.912	Middle
5	39	Pasaiyoorkulam	0.886	Upstream
6	3	Vannankulam	0.880	Upstream
7	31	Makkiyakulam	0.427	Upstream

The above results demonstrate that many of the downstream ponds carry storage values very close to their spill level throughout the year and therefore they should be prioritized for pond capacity enhancement projects. Moreover, it can be suggested based on analysis what is the most suited rehabilitation approach for each pond whether it is bund raising or pond bed dredging.

4.5 Scenario Analysis I: Cascade Behaviour for Flood Mitigation

The first scenario analysis (which was carried out considering the holistic behaviour of pond system for flood mitigation) results are discussed in this section.

4.5.1 Individual Pond Behaviour

The estimated inundation extents in each pond catchment are summarized in Table 4.15 when only the individual pond behaviour is considered. The results show the percent inundation area during the simulated 2017 flood event as a ratio against the total cascade area (156.7 ha) and was used for comparisons. Considering the summation of inundated area in each individual pond catchment, the total inundation area is found as 43.09 ha in the entire cascade.

Table 4.15: Sub-Catchment Details of Ponds

Pond	Sub-catchment area (ha)	Flood inundation area (ha)	Ratio (%)
Vannankulam	27.325	8.514	31.2
Maravakulam	29.954	6.237	20.8
Makkiyakulam	14.002	4.851	34.6
Mudalikulam	20.965	5.765	27.5
Paalkulam	33.036	9.085	27.5
Pasaiyoorkulam	8.667	2.383	27.5
Vilaththikulam	22.747	6.255	27.4

4.5.2 Holistic Behaviour of Seven Ponds

Next, the Paalkulam cascade was modelled considering its holistic behaviour and there the spill water from the upstream pond is accumulating into the pond in the immediate downstream. In the meantime, the pond storage will prevent the flood occurrence in the downstream of each pond by flood volume retention and peak attenuation. The flood inundation area thus estimated is 20.684 ha which is 13.2% of the total catchment area.

4.5.3 Results Comparison of Cascade Behavior Vs Individual Pond Behavior

A scenario analysis was carried out using 2017 flood data, considering the individual and holistic behaviors of identified ponds in the Paalkulam cascade. It clearly shows that the total flood affected area is significantly reduced when the cascade behaviour is introduced. The flood inundation area when the ponds are treated individually is 43.09 ha (24.5%) and when the holistic behaviour is considered it decreases to 20.68 ha (13.2%) which shows that about 22.41 ha (55.37 acres or 14.3%) area can be saved from the flooding during the rainy season. The total inundation area without cascade connectivity and the flood area reduction after the cascade connectivity is introduced are shown in Figure 4.3.

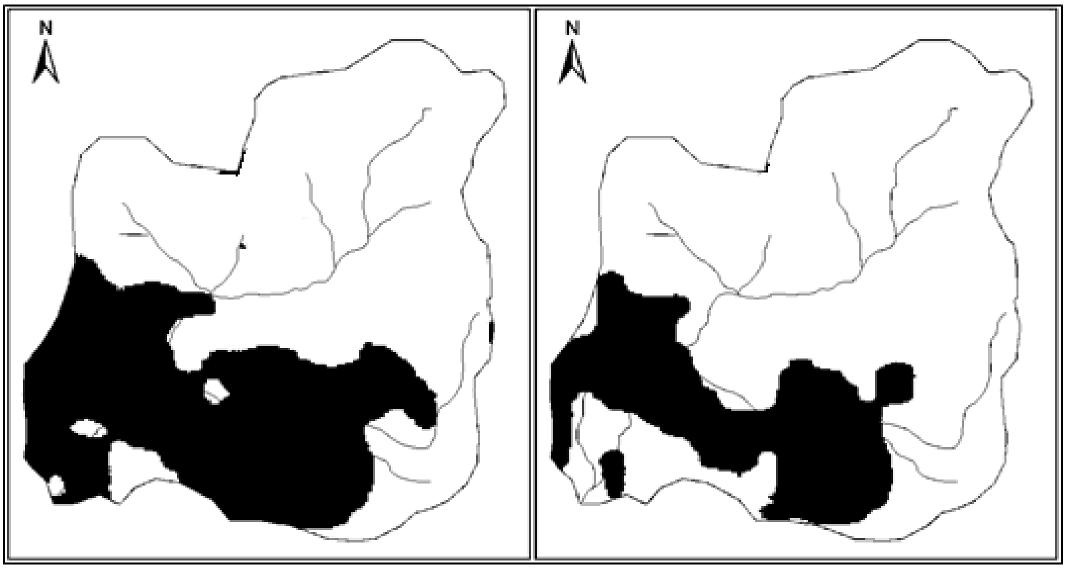

Figure 4.3: Inundation Area Reduction with the Introduction of Cascade System

a) without cascade connectivity b) with cascade connectivity

4.6 Scenario Analysis II: Rehabilitation Approaches for Flood Mitigation

The second scenario analysis (which was carried out to identify the most effective pond rehabilitation approach for flood mitigation considering the pond location in the cascade) results are discussed in this section.

4.6.1 Upstream Pond Rehabilitation: Raising of the Bund Levels

The total inundation area was established using the DEM generated for the cascade catchment area. The total area of the Paalkulam cascade is 156.7 ha and before the proposed rehabilitation by upstream bund raising, the estimated inundation area was 20.68 ha (13.2%). Moreover, after the rehabilitation, area has reduced to 15.23 ha (9.71%). That is a significant reduction in flood area of 5.45 ha (26.35% of the flood area).

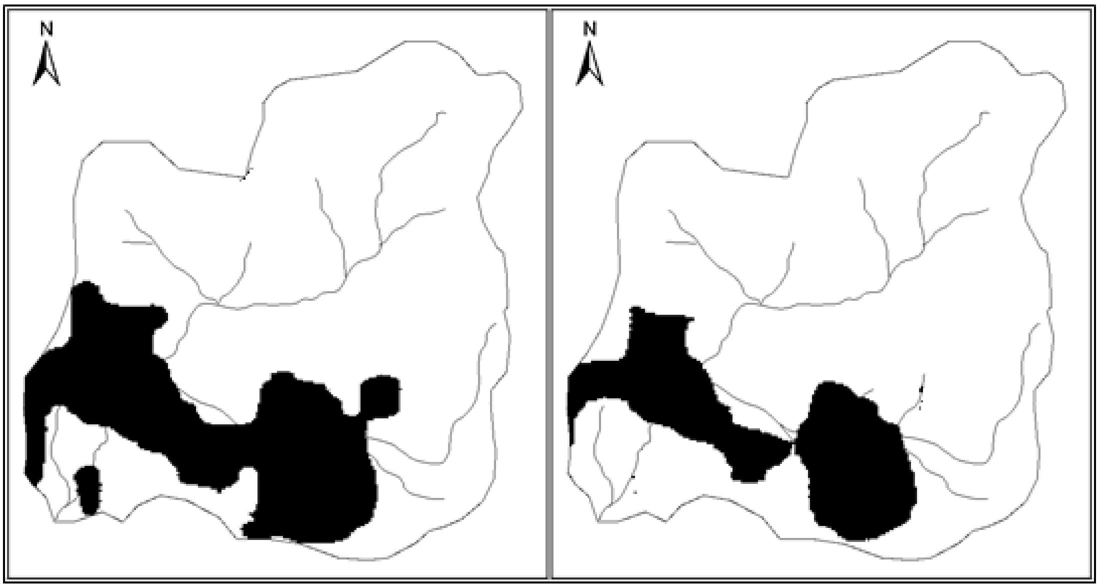

Figure 4.4: Inundation Area Reduction after the Upstream Bund Raising

4.6.2 Upstream Pond Rehabilitation: Pond Bed Dredging

The reduction in inundation area is shown in the Figure 4.5 where the total Paalkulam catchment area of 156.7 ha and after the upstream pond bed dredging is carried out as the rehabilitation approach, it is seen that the inundation area is reduced to 17.12 ha (17.21 %).

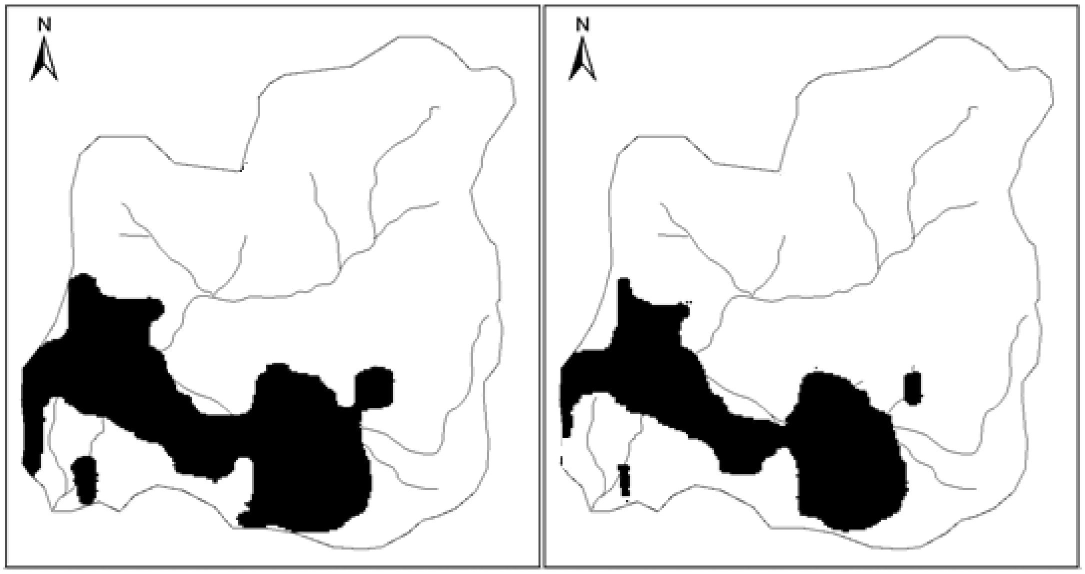

Figure 4.5: Inundation Area Reduction after the Upstream Bed Dredging

4.6.3 Downstream Pond Rehabilitation: Increasing the Bund Levels

Later, the total inundation area was determined from the generated Digital Elevation Maps of the cascade catchment area. The inundation area before implementing the rehabilitation is recorded as 20.68 ha (13.2%) and after the downstream bund level raising is hypothesized, the inundation area is reduced to 16.51 ha (a reduction of 20.16%).

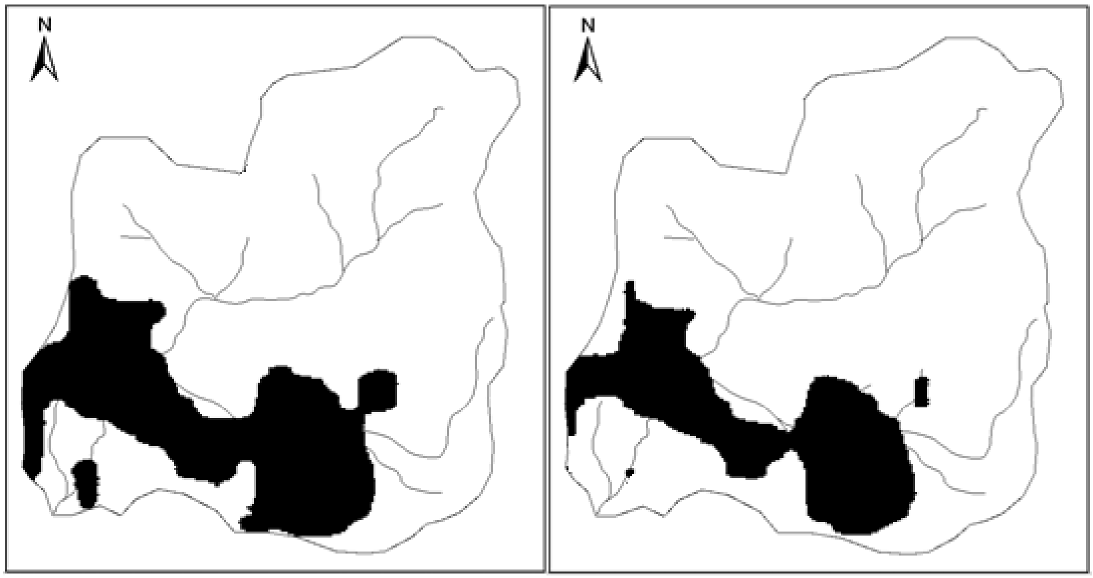

Figure 4.6: Inundation Area Reduction after the Downstream Bund Raising

4.6.4 Downstream Pond Rehabilitation: Pond Bed Dredging

Out of the 156.7 ha area of the Paalkulam catchment, 20.68 ha area is inundated from flood and after the downstream pond rehabilitation is introduced by pond bed dredging, the model results show that the total inundation area of 20.68 ha is reduced to a value of 13.8 ha (by 33.26%).

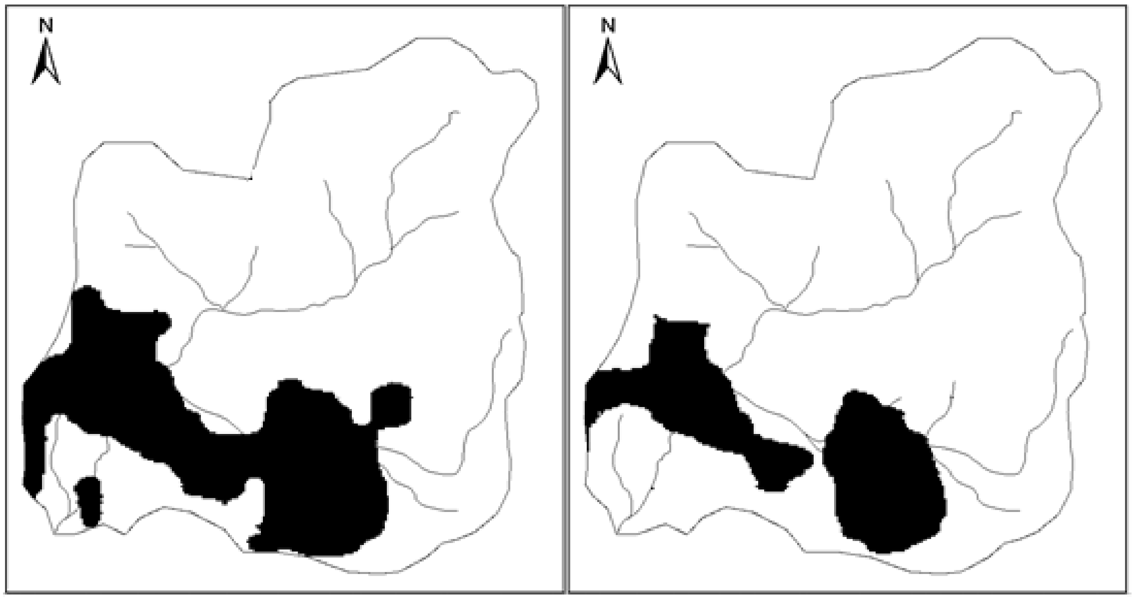

Figure 4.7: Inundation Area Reduction after the Downstream Pond Bed Dredging

4.7 Result Analysis and Discussion

4.7.1 Water Balance Approach

The first analysis was conducted to verify the applicability of HEC-ResSim simulation to the catchment area and check its validity under prevailing conditions. From the past literature, it was observed that any adjustments to a particular water balance approach should be made considering the physical, geological and geographical characteristics of the study area. Prior to the simulations, the water balance model was applied to check the monthly end water storage values. Though the 2017 flood was critical in the recent times, the 75% probable rainfall data was used for the analysis. The individual pond sensitivity for storage was approximated from the water inflow and outflow calculations.

When the Paalkulam cascade is considered, there were three upstream ponds and two downstream ponds. Similarly, in the Nayanmarkaddu Kulam cascade, two upstream ponds and two downstream ponds were identified. When generating the area and storage variation with pond water level elevation for each pond, individual survey contour maps were used.

When the monthly end storage values of each pond are considered, the variations were similar in all the cases. It was noted that at the beginning of the year, the storage keeps decreasing due to dry weather and during the South Western Monsoon (July to September), lower rainfall and higher evapotranspiration results in very low pond water storages. When the average storage indices (ASI) of Nayanmarkaddu Kulam cascade are considered, during July - September time period, it reduces to a minimum of 0.5 value indicating that the pond storage has come down to the dead storage level. One exception to this is the Purakulam (JMC pond ID: 28) where the ASI value has increased to 1.0 during the September and October months. The reason behind this must be that the pond is located at the downstream of the cascade and around the pond, many wastewater canals are draining into the pond. Moreover, the Purakulam pond is comparatively very small where it only has a detention capacity of 2.14 Ac.ft. at the HFL where the average pond detention of Nayanmarkaddu Kulam cascade at corresponding HFL is 8.84 Ac.ft. another exception to the identified storage pattern is the Nayanmarkaddu Kulam pond where the reservoir is located at the most downstream of the cascade. The higher water retention during the September ~ October time period is due to the many storm water and wastewater canals draining into this pond and therefore its storage value is high.

When the Paalkulam cascade is considered, the average storage index value reduces to a 0.356 value in Makkiyakulam pond (JMC ID: 31) which is the lowest. Maravakulam (JMC ID: 9), Mudalikulam (JMC ID: 33) and Paalkulam (JMC ID: 37) ponds are having an ASI value of 1.0 when reaching the October month and all these ponds are located at the downstream of the cascade. However, from September to October, a sudden raise of the ASI can be seen in these ponds where the indices show an average augmentation of 0.16. The pond storage of the November ~ December time period is at the HFL as expected and only the Makkiyakulam pond shows a high deviation of 0.58 and 0.69 during November and December, respectively. Makkiyakulam is the second most upstream pond of the Paalkulam cascade and there must be a connectivity issue with its upstream pond Vannankulam (JMC ID: 03).

When the HEC-ResSim model simulations were carried out for the Paalkulam and Nayanmarkaddu Kulam cascades for the monthly end storage, their analysis showed a similar variation with respect to the water balance results. In the water balance approach, water balance quantification was carried out on a monthly basis and in the HEC-ResSim model, hourly simulations were carried out. However, when the average monthly end storage values of Paalkulam cascade is considered, it was observed a variation between 0.7219 – 0.9585. In the water balance approach, the Makkiyakulam pond had a very low storage value during the water year and in the HEC-ResSim simulations as well it showed an undesirable water retention. When the Nayanmarkaddu Kulam pond is considered, the monthly end storage values from HEC-ResSim simulation gives the highest deviation in the month of January. When the HEC-ResSim simulations show a reduced value of 4.07 Ac.ft. water quantity in the monthly end storage value. In Ilanthaikulam pond as well, the highest deviation of monthly end storage is in January presumably due to the fact that the model results are carried out beginning from the January. For the HEC-ResSim simulations, an initial storage has to be fed in and it was assumed that the previous monthly end storage values are at the two third of the high flood level. For more accurate results, the initial data should be properly estimated based on field observation data.

This ASI was expected to be used as an indicator for the pond prioritization, assuming that the higher ASI number indicates that pond is capable of retaining a higher storage quantity. Therefore, the priority was given to the ponds with the highest average storage indices. When looking at the Paalkulam cascade, highest ASI were seen in the downstream ponds and the upstream ponds carried lower ASI. The lower ASIs represent that the pond is capable of retaining more water quantity with respect to the water quantity retained currently. Moreover, the prioritization was only hypothesized for pond capacity increment where this does not indicate the need for any rehabilitation work.

4.7.2 Scenario Analysis I: Cascade Behaviour for Flood Mitigation

The water balance approach with the comparison with the HEC-ResSim model showed a clear relationship and it can be said that model results are strongly suggesting the applicability of HEC-ResSim model for water balance analysis for individual ponds or pond cascades. According to the results obtained from the scenario analyses, it was expected to recommend the pond cascade behavior for higher stormwater retention and ultimately targeting a sustainable stormwater management for the Jaffna peninsula area. Therefore, for this scenario analysis, HEC-ResSim simulations were carried out considering the daily rainfall data of year 2017. The extreme flood in November 2017 had caused devastating social and environmental catastrophes and a proper solution for flood mitigation was one of the major intentions of this scenario analysis.

Analysis was carried out considering the Paalkulam cascade and individual ponds and pond cascade behavior were modeled. Data used for the water balance approach was used here and rather than using the 75% probable rainfall data, the 2017 historical rainfall data collected from Meteorological Department was used.

All seven ponds of the Paalkulam cascade were modeled individually and inundation area was calculated accordingly. The Inundation area (ha) of each pond is tabulated in the table 4.16.

Table 4.16: Inundation Area for Individual Ponds

Pond	Inundation Area (ha)
Vannankulam	8.51
Maravakulam	6.24
Makkiyakulam	4.85
Mudalikulam	5.77
Paalkulam	9.09
Pasaiyoorkulam	2.38
Vilaththikulam	6.26

When the ponds are individually acting as stormwater retention bodies, the total area of 43.09 ha is inundated and it is 27.5% of the total Paalkulam catchment area. Flood contours were generated for the peak flood situation and the flood area was calculated accordingly. Since a key objective of this study was to identify the effect of pond holistic behavior on flood mitigation, the reduction in inundation area according to the analysis will identify this as a better way to mitigate flood issues in the flood prone urban areas.

When the pond cascade behavior is considered, new flood contours show that only a 20.68 ha (13.2%) area will be inundated. This is only a 13.2% of the Paalkulam cascade area and in consideration of the recent flood extents, this could save a significant part of the flood prone areas in the peninsula. Furthermore, results demonstrate that the restoration of the pond cascade connectivity and implementation assistance to minimize the inundated area by 22.42 ha. As a percentage it is about 14.3%.

For the highly densified population areas in Jaffna peninsula, this is a critical value. However, it has been observed that though the rehabilitation of ponds reduces the flood damages, it will not totally eliminate the disastrous flood situation in the area. Furthermore, the results verify the applicability of the proposed methodology as a Decision Support System (DSS) in urban flood mitigation and evacuation guide. However, in this study, the seasonal drought effect is not addressed and the main focus was on the flood mitigation methodology. The study results further verify the importance of implementing holistic approach considering cascade behaviour of pond systems, especially in the urban areas where the flood occurrence is a major concern.

4.7.3 Scenario Analysis II: Rehabilitation Approaches for Flood Mitigation

The first scenario analysis clearly shows the importance of the pond cascade behavior for flood mitigation and this second analysis was carried out to identify the most sustainable rehabilitation approach for each pond. In this analysis, only the pond bund height raising and pond bed dredging were considered and however, for better results various other rehabilitation approaches are also recommended to follow.

Analysis was carried out considering the upstream ponds and downstream ponds separately. In this analysis as well, the 2017 extreme event rainfall data from Department of Meteorology was used and HEC-ResSim simulations were used to generate flood contours. When selecting the numerical value of 0.5 m for the step increment for bund rising, early rehabilitation approaches were considered and considering the practicability to increase the bund level, this initial value was considered. Furthermore, the bund level increment of 0.5 m simultaneously indicates that an increment of spill height of the pond as well. When a 0.5 m bund height raising is discussed, it indicates the raises of the existing HFL by 0.5 m and existing BTL by 0.5 m. The other important aspect considered during this scenario analysis is that when the bund height raising or bed dredging is considered, it was the only alteration incorporated to the existing pond physical properties. Moreover, the area storage elevation relationship of each pond was updated accordingly. One assumption made here was that the pond water surface area at the raised spill level is same as the area at the existing spill level.

When the upstream bund height raising was considered, it was noted that the inundation area of 20.68 ha has been reduced to 15.23 ha which is a reduction by 26.4%. The increased spill height and bund height enhance the stormwater retention in the pond and it results in a reduction of inundation area. However, an additional consideration should be given to the holistic cascade water balance during the dry season where the downstream ponds are highly dependent on the upstream water sources.

Subsequently, the upstream pond bed dredging was considered instead of bund height raising and the dredging quantity was decided by calculating the total capacity increment by spill height increment. Moreover, this quantity was distributed among the upstream ponds considering the individual pond capacity values. Makkiyakulam has twice the capacity than the Vannankulam and Pasaiyoorkulam and its dredging quantity (3664.42 m^3) was approximately twice than the other two (1965.63 m^3 and 1769.95 m^3). To which level dredging should be carried out is decided considering the ratio of dredging quantity and the maximum of dredging up to 0 m contour. It means that without changing the pond bed level, the pond capacity is increased by changing the area elevation profile of the pond. This methodology may give fabricated outcomes if applied to larger water retaining structures. Since all ponds in JMC area are minor in scale (when the surface area is considered), this dredging will not affect to its boundary stability.

Table 4.17: Methodology Used for Pond Bed Dredging

Dredging from contour	**Storage ratio**	**Depth to be dredged**
Beginning contour (xx) of the dredging	$\frac{Dredging\ quantity}{maximum\ dredgin\ upto\ 0\ m\ contour}$	*If SR < 1;* *0 m* *If 1 < SR < 4* *Dredge from there* *Calculate, (DD) dredging depth* $DD = \frac{dredgin\ quantity}{area\ at\ xx\ contour}$ *If DD < xx;* *Lowest contour won't change* *If DD > xx;* *That'll be the depth*

		to be dredged *If SR > 4* *Go to the next contour*

The starting contour for dredging is found out as shown in the Table 4.17 and the dredging is continued from there. The storage ratio (SR) is used as an indicator to start the dredging. It shows that the ratio of the required capacity increment and available capacity increment.

$$\text{SR} = \frac{\text{Dredging Quantity}}{(\text{contour Height} \times \text{Contour Area}) - \text{Reservoir Storage to the Contour}}$$

When the SR value becomes greater than four, it indicates that the dredging quantity is relatively larger and dredging should start from a higher elevation contour. When the SR value reaches the satisfactory region, dredging is continued from there and the bottom contour area is used as the indicator for change of pond bed level. The bottom contour area calculation is derived from the simple equation for the volume calculation of truncated cone.

$$\text{Volume} = \left\{\frac{\text{Top Contour Area} + \text{Bottom Contour Area}}{2}\right\} \times \text{Contour Level}$$

After the bottom contour area is calculated and if it is higher than the top contour area, then the pond bed level (dredging the pond bed further down) is recommended to be reduced by 0.5 m intervals until the satisfactory level is achieved. When the bottom contour area is lower than the top contour area, the reduced bed level is taken as the final bed level and dredging is continued accordingly. The bed area reduction from the Vannankulam pond is abstracted follows.

"*Bottom area = 2320.84*

Bottom area > Top area

Dredge 0.5 m more

From the Equation for Bottom area calculation;

Bottom area = 1215.63

Bottom area < Top area

Acceptable!"

Moreover, this upstream pond bed dredging shows an inundation area reduction by 3.88 ha, a percentage of 17.2% whereas the pond bund height raising was giving a 26.4% of an inundation area reduction.

The same procedure was followed for the downstream ponds as well and it showed a 20.2% of an inundation area reduction for bund level raising while the pond bed dredging gives an inundation area reduction of 33.3%. Overall, the second scenario analysis results summarized that the optimum rehabilitation decision depends on the location of the pond. However, if the used analysis is to be applied to a different set of ponds with different characteristics, suitable amendments should be made accordingly.

The analysis results evidently show that the upstream pond rehabilitation should be carried out by increasing the bund level and downstream pond rehabilitation would be more optimized by dredging the pond bed.

However, the deliberated pond and its catchment extents are relatively very low and when this particular analysis is applied to a larger catchment, used criteria should have been changed. Furthermore, in this analysis when the dredging quantity is determined by using the bund level raising and then that quantity is distributed among the upstream/downstream ponds. The dredging depth and contour lines were determined from iteration method. Here as well, the SR value limit was taken as 4. This value was derived from carrying out the many sample calculations and checking for the optimum dredging option.

4.7.4 Limitations of the Study

The terrain and hydrological characteristics of the Jaffna Municipal Council study area are highly specific and unique, and therefore the applicability of the proposed methodology directly as it is to any other area may not be feasible and further studies covering other areas are required before generalizing the findings of the study.

Comparisons are carried out considering only two pond cascades and the study results could have been strongly recommended if an additional number of cascade systems had been considered. However, due to the limited availability of time and other resources to conduct this study, the authors believe that this is a reasonably adequate sample to arrive at conclusions for the region.

The groundwater recharge is a critical scenario here and study does not describe its unique behavior with respect to the existing pond cascade systems. Furthermore, the seepage from pond beds highly depends on the soil bed characteristics and this part is not adequately covered in this research.

The rainfall isohyetal maps basically developed for water resources management purposes have been used to estimate catchment flow accumulation and further studies are required to identify the cascade behavior under peak discharge conditions and their impact on the flood inundation behavior in the system.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The conclusions are derived by considering the ponds restored in a holistic manner incorporating their cascade behaviour which help to decrease the probable inundation issues, a solution that many town and country planners are seeking in today. The hypothesis was that the cascade system connectivity will reduce the total flood affected area and in the results, it clearly shows that 14.3% of the total catchment area of Paalkulam cascade could have been protected from the 2017 flood effect. Moreover, the followings conclusions were derived from the research results.

1. Pond prioritization is vital prior to a rehabilitation project.
2. Pond cascade behavior is increasing the total water sustainability of the cascade and pond canal connectivity is vital in the pond efficiency augmentation plan.
3. Ponds have unique monthly storage behaviour characteristics and should be analyzed before the rehabilitation process.
4. HEC-ResSim model simulation results give sensible water flow simulations with compared to the water balance model analysis for individual ponds and pond cascade systems as well.
5. In many cases downstream ponds are with a higher need of rehabilitation and most suited rehabilitation approach is the pond bed dredging while for the upstream ponds pond bund raising is the most sustainable rehabilitation approach.
6. In higher rainfall conditions the downstream pond neighboring area is more prone for inundations.
7. HEC-ResSim model simulations for pond behaviour during the dry period does not give accurate results.
8. Probability of spilling (No controlled Outlets) is higher in upstream ponds, though the downstream pond has the total annual spill quantity

5.2 Recommendations

1. Study was carried out for minor scale reservoir (ponds) systems and applicability for larger reservoir systems should be validated in advance.
2. Conduct a questionnaire for the community living nearby on their mindset of the importance of the Jaffna pond system.
3. Identify the reasons for poor model performance in the low rainfall conditions.
4. Inclusion of more rehabilitation approaches such as restoring the pond operational structures and drain canal network.
5. Introduce sustainable water management policies to the community and society.
6. Model the groundwater recharge component in water balance approach for different scenarios.
7. Develop pond rehabilitation guidelines for pond cascade network for different storage values.
8. Focus on the individual pond efficiency after the rehabilitation approach.

In addition to the above recommendations, it is highly recommended to introduce this pond cascade behavior and rehabilitation guidelines for different geographical and geological locations to validate its adaptability.

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APPENDICES

Appendix A: Forty-seven ponds in the JMC area