# Modelling the Water Balance of Sembakkam lake, Chennai, India and Evaluating Low Impact Developments

Civil Engineering - Bachelor Thesis

Sembakkam lake (own figure)


Mark van den Brink


20 July 2019


External supervisor: prof. B. Narasimhan
Indian Institute of Technology, Chennai, India

First supervisor: L. Wohler
Second supervisor: S. Bhochhibhoya
University of Twente, Enschede, The Netherlands

# Table of Contents

# 1. Summary

This study aimed to propose management options for the improvement of water issues at Sembakkam lake. There are three major concerns in this study area. First, there is severe water scarcity during the dry period of the year in the catchment area. Second, flooding occurs during the wet period in the catchment area. Third, untreated sewage inflow contaminates the lake through the year. This study focused on the problems related to water quantity by proposing and evaluating two Low Impact Developments (LIDs) at the household level: percolation pits and cisterns.

In order to evaluate their impact on Sembakkam lake, a hydrological model of the water balance of the lake was established using SWMM software. The runoff was estimated using GIS data and a literature research. Climate data of evaporation and precipitation and local arbitrary measurements of the dry weather inflow and overflow were used. Human consumption was estimated by literature review and making assumptions and in the end the seepage at the lake was arbitrarily calibrated. Moreover, the drainage network, infiltration parameters and dry weather inflow were found to be sensitive and uncertain parameters, which makes the results for infiltration and overflow volume uncertain. Further research and data collection should be carried out in order to increase the reliability of the results. Furthermore, the amount of percolation pits and cisterns was estimated based on the three scenarios that 5, 15 and 25% of households in the catchment area implement these LIDs. The dredging of the lake, proposed by experts from IITM, was also evaluated for different post-development hydraulic conductivities of the lake bed.

The dry weather inflow appeared to be a major inflow of Sembakkam lake (26-38%). The outflows are overflow (68-78%), seepage (12-18%), evaporation (5-7%) and human extraction (1-4%). Moreover, the lake is always full throughout the year, resulting in the inability to store the runoff caused by rainfall events higher than 2 mm/hr. Therefore it is suggested to empty the lake during dry season by lowering the weir to create free storage capacity.

The results indicated that the implementation of cisterns and percolation pits would not effect the runoff enough to have an impact on the water balance of Sembakkam lake. Implementing these LIDs in the quantities used in this study is therefore not recommended. Percolation pits however can increase the infiltration volume in the catchment by 5-25%. Although the increase in infiltration volume is too little to mitigate the water scarcity during dry season, implementing this LID could be effective for increasing the small infiltration volume at the catchment, especially in larger quantities than modelled in this study. Further research should be done on the water quality of the runoff infiltrating and its effect on the groundwater quality. More research could also be done on the question if cisterns are a cost-effective option for water supply since they can provide 5-9% of a households yearly water demand. Another subject for future research could be the impact of cisterns on local flooding.

The dredging of the lake could increase the lake’s seepage by 150-200%, leading to a reduction in total overflow volume of 30-45%. Dredging the lake bed is therefore recommended, but it is important to find solutions for the lake’s detoriating water quality before dredging to prevent groundwater pollution. Also, further research on the downstream effects of an increase in groundwater and a decrease in overflow from Sembakkam lake is suggested.

# 2. Preface

About one year ago, I was invited by prof. B. Narasimhan to conduct this bachelor thesis in India at the Indian Institute of Technology of Madras. I didn't really know what to expect at that time, but now I can say that it was a very special and rewarding experience. The hospitality and openness of the Indian culture still amazes me. I'm so grateful to all the people who helped me to find my way in this beautiful country and to write this thesis. I would like to specially thank B. Sridharan and N. Nithila Devi, because they showed me great friendship and always gave me useful advice when I had a question regarding this research. I also want to express my recognition to the other people in our lab. Thank you for the jokes, political discussions, advice on interesting places to visit and the many cups of tea. I would also like to thank Raja, Kishore and Bindu for providing me with useful data of Sembakkam lake and, above all, practical and social support during the first weeks. Moreover, the people from Himaliya and Nilgiri mess deserve my gratitude because of the delicious Indian food they prepared every day.

Furthermore, I would like to thank prof. Balaji Narasimhan for giving me this opportunity and providing me with useful feedback. I would like to express my gratitude to Lara Wohler, my supervisor from the UT. She did not hesitate to have meetings of an hour long, answering my questions and asking about my experiences. The excellent feedback she provided me with shaped this thesis considerably.

I hope this thesis can contribute to the efforts made by all the people in Chennai working on the restoration of Sembakkam lake. Let's not forget the people suffering from water scarcity and flooding in this city and work hard on the improvement of its water management.

# 3. List of abbreviations

| Abbreviation | Meaning |
|---|---|
| CMA | Chennai Metropolitan Area |
| GA | Green-Ampt infiltration method |
| CN | Curve Number |
| MLD | Million Litre per Day |
| $Mm^3$ | $10^6$ $m^3$ |
| LID | Low Impact Development |
| SWMM | Storm Water Management Model |

# 4. Introduction

In the last few years, India has experienced a rapid population increase. In 2015, 1.31 billion people lived in India and it is expected that it will rise to 1.5 billion by 2030 (New York Times, 2015). 44.7% of them live in rural areas, but a rising part migrates to cities (World Bank Group, 2015).

In these hugely populated cities authorities have trouble with their water management. The distribution of water is often unequal, impairing people with lower income. Besides that, the treatment of waste water is a major problem in India. Roughly 100 million people lack basic sanitation (UNESCO, 2019). 80-90% of the waste water is discharged untreated into low-lying areas or water bodies, limiting the amount of water available for drinking and daily use (Nigam, 2005). Furthermore, the increase in impervious area, caused by urbanisation, does not let the water infiltrate. This induces an increment in runoff rates and volume, which makes cities more prone to flooding (Eckart et al., 2018).

India is further known for its monsoon dominated climate. In summer, this dominant wind blows from the ocean to the North-East, carrying vast amounts of rainfall. During winter, the monsoon blows to the South-West, coming from land and causing droughts. Extreme rainfall and extreme droughts become more common, due to global climate change, leading to both catastrophic flooding and water scarcity (The Guardian 2016; The Guardian 2017). Yearly, 17.5 million people are affected by droughts, causing agricultural loss and shortage of food. Besides that, 19 million people are yearly exposed to flooding, causing casualties and economic damage (UNESCO, 2019). Considering these problems, adequate water management is needed to keep the population safe and healthy.


Figure 1: India and its major cities. Chennai is indicated within the red box (Destination360, 2006)

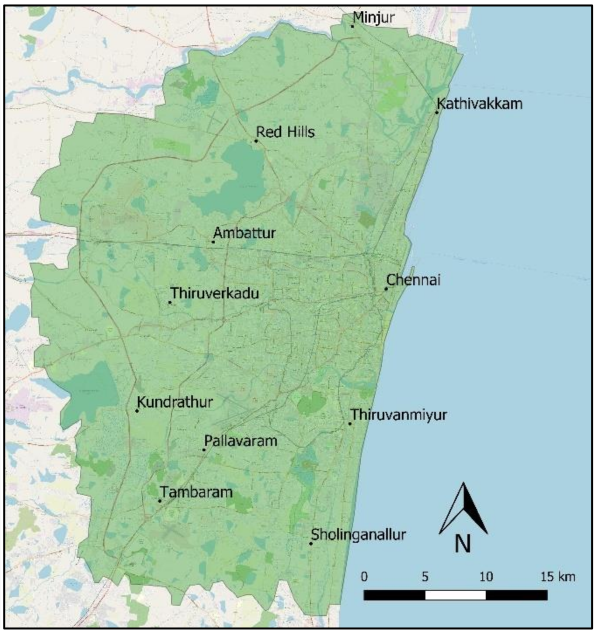


Figure 2: Chennai Metropolitan Area (CMA), indicated in green (own figure, based on (Chennai Metropolitan Water Supply and Sewerage Board, 2012; Open Street Maps, 2019)

## 4.1. Water management in Chennai

Chennai, situated on the shores of the Bay of Bengal, is the capital of the Tamil Nadu state (Figure 1). Chennai City, together with the surrounding villages, constitutes the Chennai Metropolitan Area (CMA) (Figure 2). It is the fourth largest metropolis in India (Chennai Metropolitan Development Authority, 2008a). CMA currently has 10.7 million inhabitants. About half of the CMA inhabitants live in Chennai City. The city grows fast, attracting migrants from the Tamil Nadu state and other Indian regions. From 1971 to until now, the city had an annual growth rate of approximately 2% (Chennai Metropolitan Development Authority, 2008a). Chennai has a tropical climate, with temperatures around 20$^{o}$C in January and 40$^{o}$C in May-June. The area is dominated by the monsoon, with a wet period from October till December. There can also be cyclones during this time (Chennai Metropolitan Development Authority, 2008a). Between January and April there is a dry period (Chennai Metropolitan Development Authority, 2008b).


*Figure 3: Water bodies in CMA. Sembakkam lake is indicated with red, the rivers Kosasthalaiyar, Adyar and Coоum with green, the water tanks Sholavaram, Red Hills and Chembarambakkam with purple and the Pallikaranai marsh with orange (Chennai Metropolitan Development Authority, 2008a).*

### Hydrology

The CMA is situated in a plain with contours ranging from 2 to 10 m above sea level. It is traversed by three major rivers, namely Kosasthalaiyar, Coоum and Adyar River (Figure 3). The discharge of the Coоum river varies between 266 million liters a day (MLD) in the dry season to 709 MLD in the wet season. Adyar river has a discharge of 515 MLD in the dry season and 2585 MLD in the wet season. During the dry season, these rivers discharge only domestic and industrial sewage. Furthermore, the low discharge of Coоum river is due to heavy silt disposition in the storm water drains (Gowri et al.,2007).

There are also many water storage systems for domestic water supply present in Chennai. The most important ones are Sholavaram Tank, Red Hills Tank and Chembarambakkam Tank (Figure 3). Beside these big tanks, CMA has 320 lakes, with one of them being Sembakkam lake (Chennai Metropolitan Development Authority, 2008b).

### Water scarcity

The water demand for households in 2017 was approximately 807 MLD, including water for domestic industrial purpose (Srinivasan et al., 2010). The water supply cooperation, Metrowater, supplies the 95% of the households with approximately 600 MLD, and is not able to supply constantly. Households cope with this irregular supply and water deficit by building their own wells. Approximately two thirds of the population has private wells, resulting in a total of 420,000 wells. During the dry period, when ground water tables are low, severe water scarcity is experienced (Natarajan & Kalloikar, 2017).

### Flooding

Despite the big storage capacity of water tanks and lakes and the high drainage capacity of the rivers, Chennai suffers from annual flooding of settled areas (Suriya et al., 2011). The drainage systems cannot process the amount of water that comes with the heavy rains, sometimes associated with cyclonic activity (Chennai Metropolitan Development Authority, 2008a). In 2015, an even bigger flood happened, submerging almost the whole city (The Indian Express, 2015).

This malfunctioning of the water systems has a number of reasons. Firstly, most of the waterways and water tanks are silted or blocked by buildings and other structures. Secondly, the areas around the water tanks or rivers have become more urbanized. Some water tanks have even been removed and made urban area. Urbanized areas increase both the volume and the rate of the runoff because the water cannot infiltrate into the ground (Suriya & Mudgal, 2012). Moreover, the infiltration of water in the soil is already low, especially in the south-west part of Chennai, due to a relatively small layer of soil (20 m) available for ground water storage (Chennai Metropolitan Development Authority, 2008a).

Measures are already being taken all over the city in order to mitigate flooding. These measures include creating additional storage capacity, developing a network of green environment, preventing encroachments of the macro drainage systems and improving micro drainage systems, like Sembakkam lake (Chennai Metropolitan Development Authority, 2008a).

### Water quality

Besides the problems with handling the water quantity, there are also problems with the water quality of the CMA. Only 30% of the sewage is being treated before it is disposed (Singh, 2004). Untreated waste water is dumped in the ground or discharged in water bodies. Also, solid waste ends up in the waterways, blocking drainage systems (Chennai Metropolitan Development Authority, 2008a). This leads to a high level of pollutants in ground- and surface water (Arunprakash, 2013). 57% of the households pump groundwater for drinking purposes, which makes the groundwater pollution problematic (Anand, 2001).

# 5. Study Area

There are three main problems at Sembakkam lake. The first is the water scarcity in the catchment area and the dropping ground water tables during the dry season. The second is that the capacity of the lake is too small to accommodate for the amount of inflow during monsoon. The third is that the inflow of sewage water is not treated, causing the lake to be polluted. In this section, these problems will be discussed in more detail.

## 5.1. General information

### Hydrology

The Pallikaranai marshland (indicated in orange in Figure 3), the only fresh water marsh in the city of Chennai, has recently been restored. However, it still receives polluted inflow from the upstream lakes in its watershed. One of these lakes is Sembakkam lake (indicated within the red circle in Figure 3 and in brown in Figure 4).

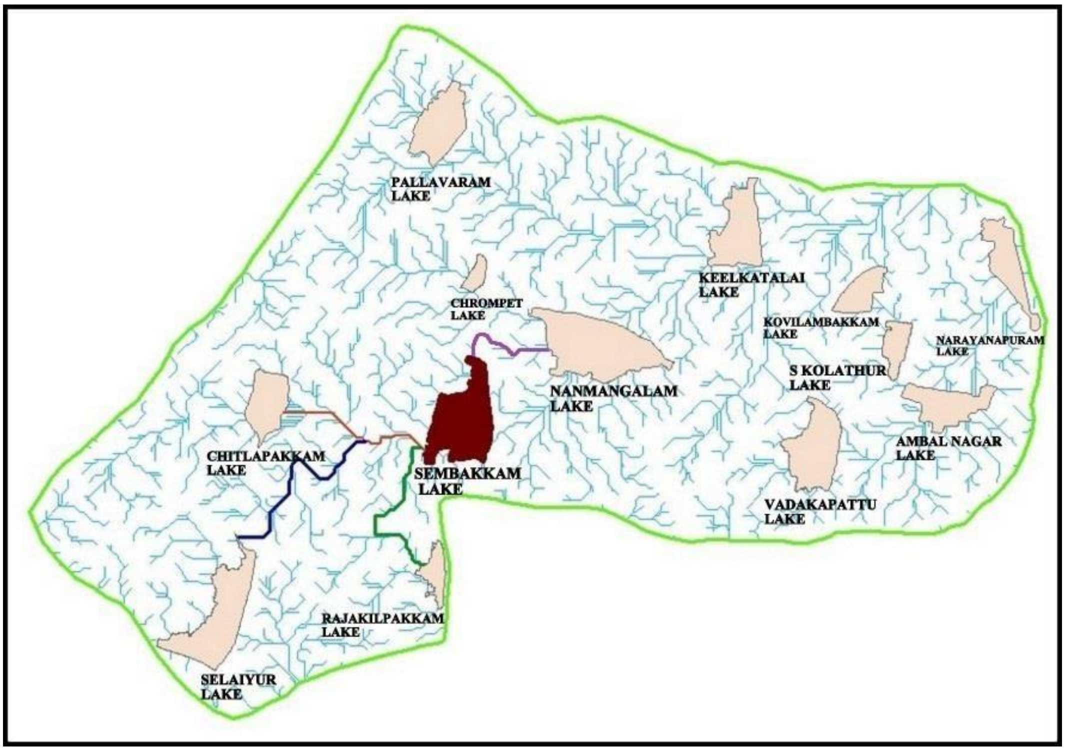


*Figure 4: Pallikaranai Marshland catchment area (Sembakkam lake indicated in brown) (Indian Institute of Technology Madras, 2018b)*

Sembakkam lake and its catchment receive an average yearly rainfall of 1350 mm. The average maximum air temperature is 33$^{o}$C and the average minimum air temperature is 23$^{o}$C.

In the last two decades, the catchment of Sembakkam lake have become heavily urbanized and encroached. There are three lakes which are located in the catchment area: Chitlapakkam, Selaiyur and Rajakilpakkam Lake (Figure 4). These lakes constitute a cascading system: when a lake reaches its capacity, it discharges its surplus to the next downstream lake. Before the urbanisation of the catchment area took place, it mostly consisted of agricultural lands. The lake would fill up during monsoon and be empty at the end of the dry season. Nowadays, the lake is completely full for most of the year due to the dry weather flow from the urban area, consisting of untreated sewage water.

### Site layout

The layout of Sembakkam lake is presented in Figure 5. It consists of a water spread area, a former dump yard and a wetland portion with a size of 34, 2 and 4 ha respectively. (Figure 5). This wetland mainly exists of marshlands and is heavily silted due to the high amount of drainage inlets situated at the western side of the lake (Indian Institute of Technology Madras, 2018b). The dump yard has been cleared in 2018, but dispersion of the garbage has contaminated the soil and the lakes water and there is still waste in the soil (Indian Institute of Technology Madras, 2018b). The 22 inlets are all situated at the western and southern sides of the lake. The outfall of the lake, a weir and a sluice, are situated at the northern edge. The well in the northwest of the lake is used by water tankers for water extraction. More detailed figures can be found in appendix I.

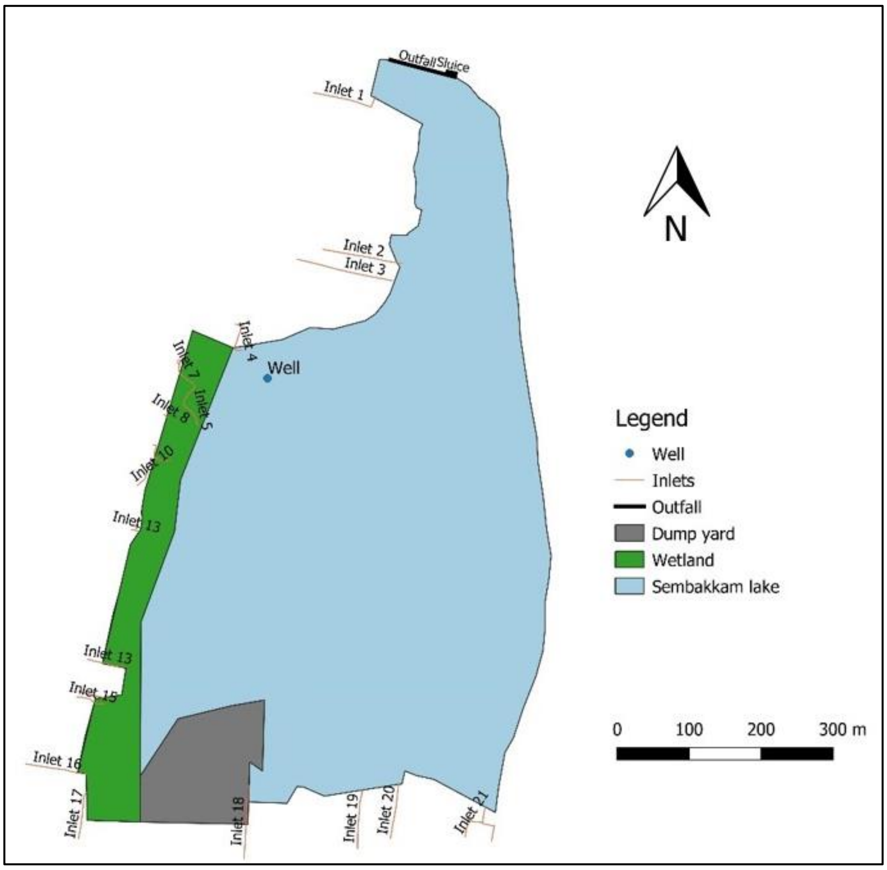


*Figure 5: Layout of Sembakkam lake with position of inlets (own figure, based on (Indian Institute of Technology Madras, 2018a))*

## 5.2. Water management problems

### Water scarcity & flooding

During the dry season the surrounding neighbourhoods of Sembakkam lake encounter water scarcity. Ground water tables are dropping and the surface water of the lake is too polluted for domestic use (Viswanathan, 2018). On the contrary these neighbourhoods experience yearly flooding during the monsoon season, due to an insufficient drainage system.

### Water quality

Garbage and sewage dumping into this lake has been going on for decades, resulting in polluted water and soil (The Times of India, 2017). Moreover, during the dry season, the drains of these catchments carry mostly sewage water into the lake. As a result, the concentration of heavy metals, TDS, BOD and COD are too high to be used for human consumption or swimming. Furthermore, the amount of ammonical nitrogen in the water is exceeding standards, causing a lot of hyacinth growth in the northern and western parts of the lake. These hyacinths stagnate the water flow. Also, the wells around the lake are influenced by the water in the lake, which makes them polluted. This is problematic, because the ground water is used for (commercial) drinking purpose (Indian Institute of Technology Madras, 2018b; Indian Institute of Technology Madras, 2018c). These problems do not only occur at Sembakkam lake.

For example, Rajakilpakkam lake, Madipakkam lake and Medavakkam lake are also heavily polluted and their water is unusable for domestic purposes (Chennakrishnan et al., 2008).

### Improvements

Residents of the surrounding neighbourhoods of Sembakkam lake, united in active welfare associations, have long been discussing these issues with governmental bodies. Since 2017, there have been initiatives to improve the situation. Experts from IITM have started investigating the water quality of the lake. Following from this research, the hyacinths that were a result of nutrient pollution and covered the lake's surface have been partly removed. They also proposed to dredge the top part of the lake bed to increase storage capacity. The aim is to make Sembakkam lake a retention area for storm water and a good source of drinking water (Deccan Chronicle, 2018).

# 6. Research Aim & Questions

The aim of this research is to give water management options of Low Impact Developments (LIDs) which can be implemented in the catchment and lake area of Sembakkam lake. The focus of these LIDs is to mitigate flooding and recharge groundwater. Advice will be given based on the impact of the proposed LIDs, which will be calculated using a model of the water balance of Sembakkam lake, developed with the Storm Water Management Model (SWMM) software.

The main research question for this research is:

- How is the water balance of Sembakkam lake currently composed and what efficient Low Impact Developments could be implemented in its catchment area and lake bed?

The sub-questions are:

1. How is the water balance of Sembakkam lake currently composed and what are accompanying uncertainties?
2. What Low Impact Developments could be implemented in the catchment area and the lake bed of Sembakkam lake?
3. What is the quantitative impact of these LIDs on the overflow and storage of Sembakkam lake and the infiltration in the catchment area during a dry, average and wet year?
4. How does the impact of these LIDs influence the handling of Sembakkam lake's water problems?

# 7. Background Theory

In this section, background theory regarding the SWMM model and LIDs is provided.

## 7.1. Storm Water Management Model

The software that was used for modelling the water balance of Sembakkam lake is the Storm Water Management Model (SWMM) developed by the U.S. Environmental Protection Agency and the consultancy engineering firm Camp Dresser & McKee Inc. It is a dynamic hydraulic-hydrologic model, able to model the quantity as well as the water quality of runoff (Zhu et al., 2019). It is dominantly used for modelling urban areas (Rossman, 2015).

The concept of SWMM is to divide a catchment in smaller sub-watersheds in order to account for spatial variability of characteristics and to get a more detailed computation of the precipitation to runoff processes. A SWMM model (visualised in Figure 6) consists of a collection of these sub-watersheds with different parameters: area, slope, percent imperviousness, Manning-N for pervious and impervious areas, depressions storage for pervious and impervious areas, the percentage of impervious area without depression storage and infiltration parameters. Additionally, there is the width of the sub-watershed. These sub-watersheds receive precipitation and generate infiltration, evaporation and runoff. The runoff is calculated based on a non-linear reservoir model (Palla & Gnecco, 2015). Runoff is generated as soon as the depression storage is exceeded. Its flow and quantity are calculated based on the Mannings equation (Zhu et al., 2019). The runoff is then handled by the transport component of the SWMM software. It represents the drainage system and consists of junctions (which can also be storage units) and links (e.g. canals, pipes, weirs), each with its own dimensions and parameters. The flow is also calculated based on the Manning equation (Rossman, 2015).

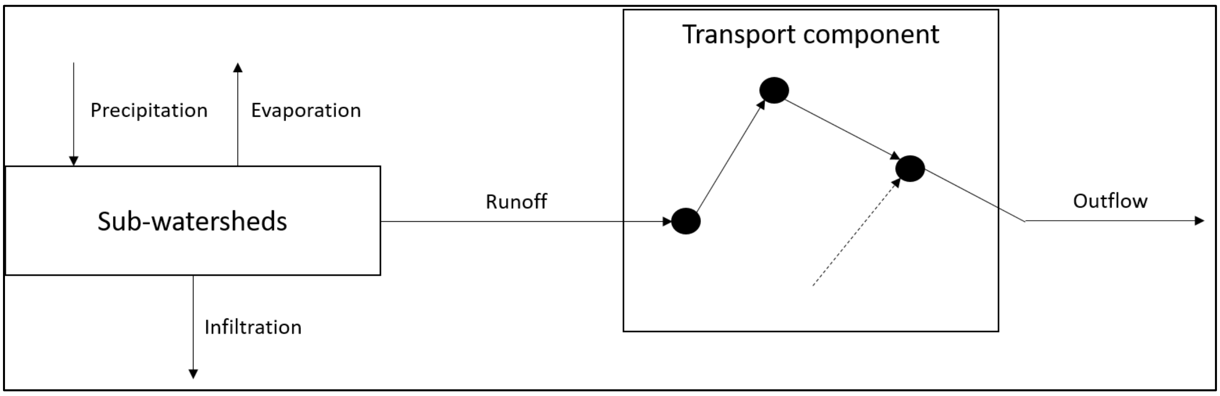


*Figure 6: Basic representation of the SWMM model (own figure, based on (Rossman, 2015))*

## 7.2. Low Impact Developments

Low Impact Developments (LIDs) are decentralised hydrological controls using natural processes and resources (Yang & Chui, 2018; Huang et al. 2018). The aim is to restore the pre-development hydrological situation (Eckart et al., 2018; Yang & Chui, 2018). They are meant to mitigate the quantitative influence of the high imperviousness in urban areas by reducing the peak and the total runoff, replenish ground water and reduce the pollutant load (Palla & Gnecco, 2015; Huang et al., 2015). They also mitigate the qualitative influence of urban areas on the runoff by filtering runoff. Storage, infiltration and evapotranspiration are the main parameters to accomplish this (Palla & Gnecco, 2015). Examples of LIDs are bioretention ponds, rain barrels, vegetative swales, porous pavements and green roofs.

Their emergence in the field of water management is relatively new and their effect is debatable, mainly due to the fact that big scale experiments have not been conducted (Palla & Gnecco, 2015). Moreover, it is often hard to determine the type, the size and the location (Xu, et al., 2018). Especially the latter is very important for its effectiveness (Martin-Mikle et al., 2015). Furthermore, there are often trade-offs between economic and environmental stakes when it comes to the implementation of LIDs (Liu, et al., 2016). The cost effectiveness of a certain LID determines it favourability (Xu, et al., 2018).

Last but not least, LIDs can also have an adverse effect. For example, in areas with shallow ground water, the ground water can drain out and become extra water load on the surface. Besides that, there will be less filtering of the infiltrating water due to the short travel distance through soil layers to the ground water. This can have ground water contamination as a consequence (Zhang et al., 2018).

In SWMM, LIDs are modelled per unit of area. Different layers (e.g. surface and storage layer) have their own properties and SWMM calculates the flow between these different components (Figure 7) (Rossman, 2015).

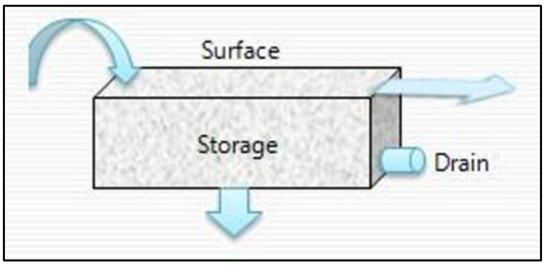


*Figure 7: SWMM modelling of LIDs (Rossman, 2015)*

# 8. Methods

This section describes the approach of modelling the water balance of Sembakkam lake in SWMM. Additionally, it outlines the method of performing the sensitivity analysis and the modelling of the LIDs. The steps undertaken are visualised in Figure 8.

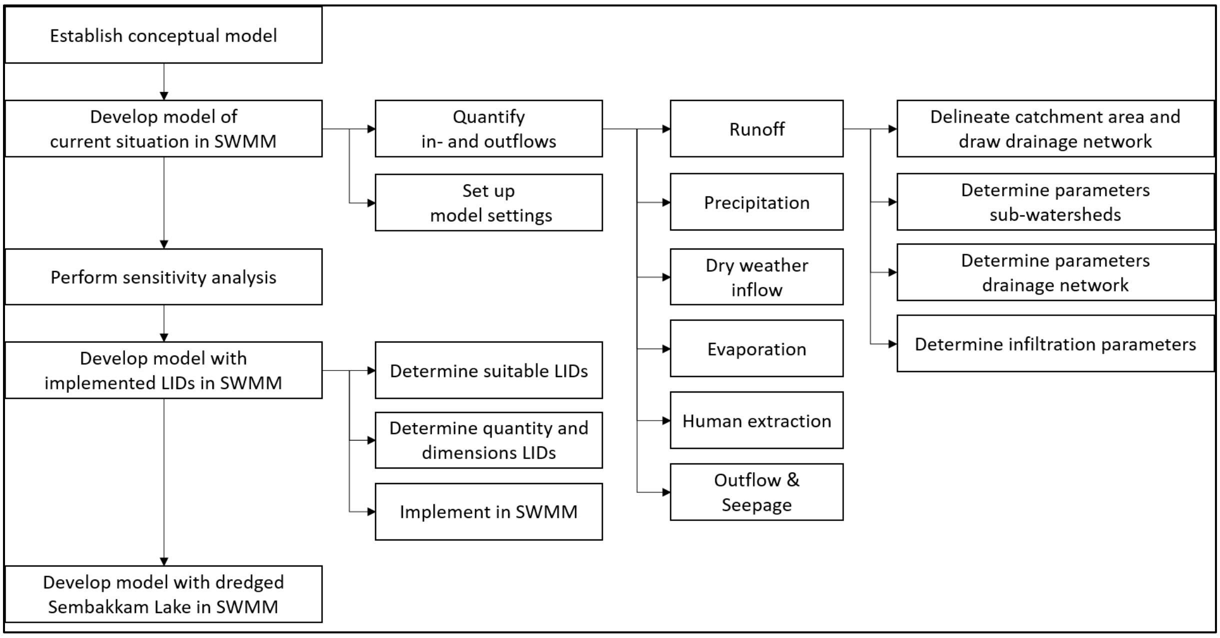


*Figure 8: Overview of methods*

## 8.1. Conceptual model

A visualisation of the conceptual model of Sembakkam lake is presented in Figure 9. Sembakkam lake was modelled as a storage reservoir with in- and outflows. It receives four inflows: Precipitation on the lake, the overflow from upstream lakes, the runoff of its own catchment and dry weather inflow which is sewage water from the urbanized area. Latter is a combined flow with overflow from upstream lakes due to dry weather flow and the dry weather flow of the catchment of Sembakkam lake. This combination was made because there was only data available of the dry weather inflow in Sembakkam lake. There are four ways how water leaves Sembakkam lake: evaporation, seepage to the ground water, overflow and human use. Especially during the dry period of the year water supply companies pump big amounts of water from the lake for commercial purposes.

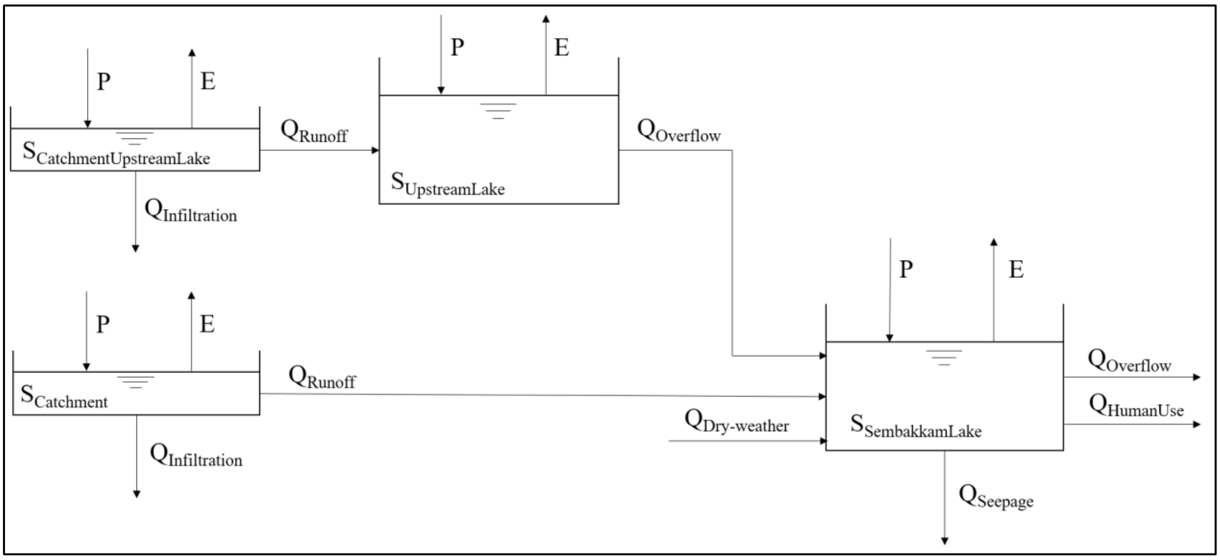


*Figure 9: Conceptual model of Sembakkam lake (P = precipitation, E = evaporation, Q = flow, S = storage)*

The catchment areas of Sembakkam lake and upstream lakes receive precipitation. A part of this precipitation is stored in small depressions and eventually evaporates, a part infiltrates into the ground and the remaining water becomes runoff. The upstream lakes receive runoff and precipitation. This inflow is stored and some part evaporates. Once the amount of inflow exceeds the storage capacity, the surplus is discharged towards Sembakkam lake. The seepage at upstream lakes has not been taken into account, due to the absence of data.

## 8.2. Modelling current water balance

### 8.2.1 Runoff

*Delineation of sub-watersheds & drawing of drainage network*

To delineate the sub-watersheds that drain into Sembakkam lake and to find the drainage network, this study used a 10 meter Digital Elevation Map (DEM) supplied by Digital Globe Quickbird Imagery. QGIS was used to perform analysis. Because the study area is mostly urbanised, the drainage network is artificial and depends more on the city layout than on elevation levels. To compensate for that, the DEM was manipulated. It was assumed that most drainage canals are located along roads (Ji & Qiuwen, 2015). Therefore, the main roads and secondary roads were lowered. More detailed information can be found in appendix II.

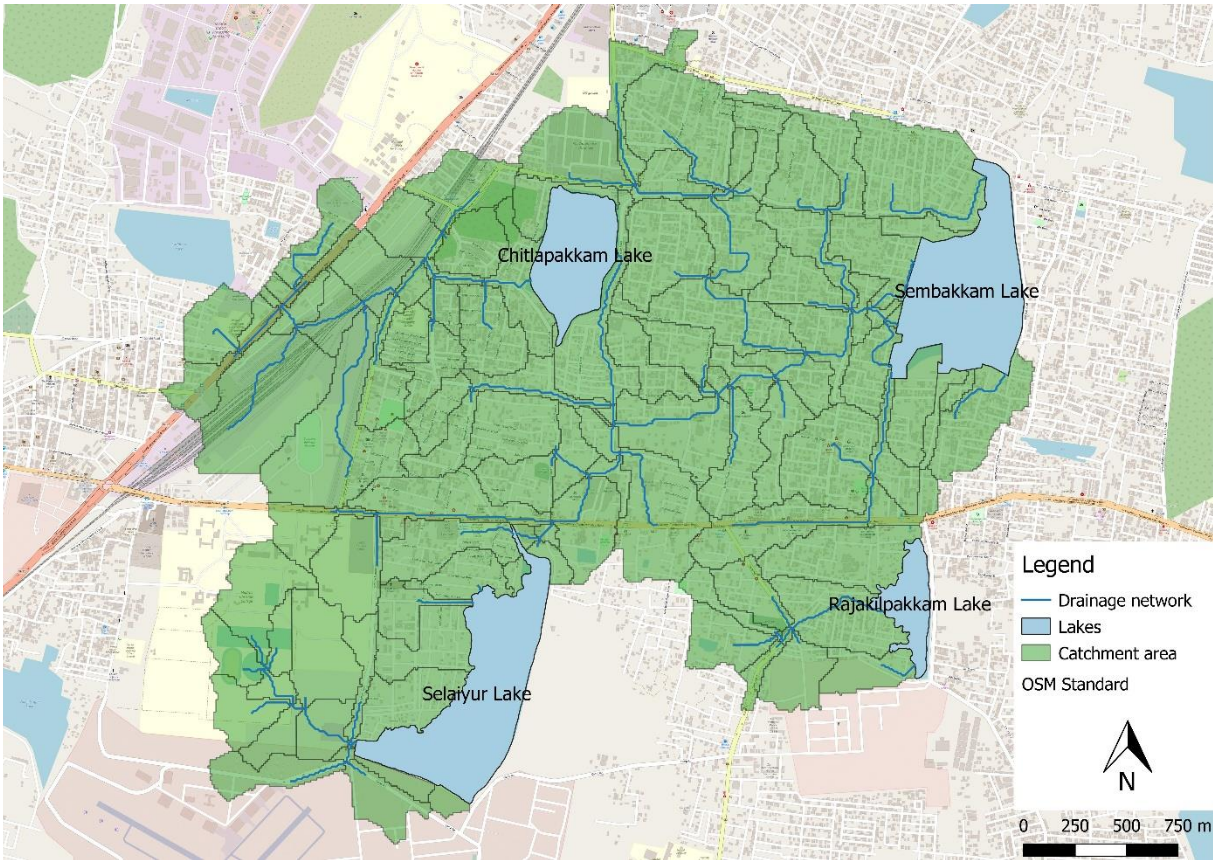


*Figure 10: Catchment of Sembakkam lake, divided in 49 sub-watersheds (own figure, based on (Open Street Maps, 2019))*

The 'GRASS r.watershed'-tool was used to delineate the sub-watersheds and draw the drainage network. After a process of trial and error the minimal external watershed area was assumed to be 5 ha in order to have sub-watersheds which were not too small and not too big. To define the total catchment area, besides the sub-watersheds draining directly in Sembakkam lake, the sub-watersheds draining into Chitlapakkam, Selaiyur and Rajakilpakkam lake were also selected. Experts of IITM discovered that these lakes also discharge on Sembakkam lake, although for Rajakilpakkam Lake the generated drainage network did not indicate this. Furthermore, the sub-watersheds were manually edited.

Because the dominant flow direction is eastwards, all parts of sub-watersheds east of Selaiyur, Rajakilpakkam and Sembakkam lake were deleted. Furthermore, all sub-watersheds which discharged on secondary streams were merged with the primary sub-watersheds. This resulted in 49 sub-watersheds with areas ranging from 3.9 to 34 ha and a total catchment area of 796 ha (Figure 10).

### *Determination parameters sub-watersheds*

A 50 meter land use map from the National Remote Sensing Centre (NRSC) from 2004 was used to determine the impervious area of each sub-watershed. This study only considered 'Build-up' area as impervious area. Using the 'zonal histogram' tool of QGIS, the percentage of impervious area was determined. This impervious area is the Total Impervious Area. Sahoo and Sreeja (2014) however stressed the importance of using the Effective Impervious Area because using the TIA often results in overestimates. The EIA was determined for every sub-watershed and used in calculation of the runoff and can be approximated with the empirical formula: (Alley & Veenhuis, 1983)

$$EIA = 0.15 * TIA^{1.41} \qquad \text{Equation 1}$$

Where EIA is Effective Impervious Area in ha, TIA the Total Impervious Area and 0.15 and 1.41 factors which were used to fit the trendline to the data.

The slope of each sub-watershed was determined using the original DEM and the GRASS 'r.slope.aspect'-tool. The default parameters were taken as input. The 'zonal statistics'-tool of QGIS was used to calculate the average slope for every sub-watershed. This study calculated the width parameter of the sub-watersheds by dividing the sub-watershed area by the longest flow path in the sub-watershed to the beginning of the drainage network. Because the shape of each sub-watershed is capricious, an arbitrary mean flow path was taken based on visual inspection of the sub-watershed. Remaining parameters were estimated based on literature and set equal for all sub-watersheds. Their values are presented in Table 1.

*Table 1: Parameters sub-watersheds*

| Parameter | Value | Unit | Source |
|---|---|---|---|
| Manning-n impervious area | 0.014 | $s/m^{1/3}$ | (Kumar et al., 2019; Li et al., 2016; Tsai et al., 2017) |
| Manning-n pervious area | 0.1 | $s/m^{1/3}$ | (Kumar et al., 2019; Li et al., 2016; Tsai et al., 2017) |
| Depression storage impervious area | 2 | mm | (Li et al., 2014; Rossman, 2015; Vemula et al., 2019) |
| Depression storage pervious area | 7.5 | mm | (Kumar et al., 2019; Vemula et al., 2019) |
| Fraction of impervious area without depression storage | 50 | - | (Li et al., 2014) |

### *Determination parameters drainage network*

#### Junctions

In SWMM, the complete runoff from a sub-watershed enters the drainage system at one point, a junction. Runoff cannot enter the drainage system at a conduit. In reality, the sub-watershed will drain in different places along the drainage network. To compensate for that the junction point in the drainage network at which the whole sub-watershed drains was chosen closest to the centre of gravity of the sub-watershed. The invert elevation of these junctions was determined by subtracting 1 meter of the DEM elevation at their locations, because it was assumed that the drainage network has a depth of 1 meter. In some parts of the drainage network, an adverse elevation was found. This was resolved by taking the invert elevation of the last junction before and the first junction after the adverse slope, assuming a linear descend between them and adjusting the invert elevation of intermediate junctions accordingly.

The SWMM software allows flooding only to happen at the junctions and not at the conduits. The amount of water that flows into the junction which cannot be discharged by the outflow conduit, will be counted as 'flooding loss' and does not come back in the system. However, it was assumed that no water was lost but that area is temporarily flooded. Eventually the drainage system transfers all runoff to the lake. To account for that, the option 'Allow ponding' was used, to create a ponding area at each junction, where the water can be temporarily stored. The surcharge depth was taken as 1 meter and the ponded area at 1000 $m^2$.

### Storage elements

The four lakes were modelled as storage elements in SWMM, which cannot receive precipitation directly because they are part of the drainage network. Therefore, this study created a sub-watersheds for each storage element with the area of the corresponding lake. Its parameters can be found in appendix III. They were chosen in such a way that the runoff would almost immediately flow in the storage element.

The invert elevation of each storage element was estimated similarly to the invert elevation of the junctions. Furthermore, a contour map of Sembakkam lake was used to determine the depth profile of Sembakkam lake (Appendix IV). Experts from IITM asserted that the maximum depth was approximately 1.5 meter, which was also assumed for the upstream lakes. Since there was no contour map of the upstream lakes, their depth profile was assumed to be rectangular, having the same area for all water depths. The storage capacities of each lake are shown in Table 2. Furthermore, the initial depth was set to 1.5, because it was assumed that each lake is full at the start of the year, which is right after the wet period.

*Table 2: Capacity of Sembakkam, Chitlapakkam, Selaiyur and Rajakilpakkam Lake (Tank Memoir, n.d.)*

| Lake | Capacity ($Mm^3$) |
|---|---|
| Sembakkam | 0.28 |
| Chitlapakkam | 0.20 |
| Selaiyur | 0.46 |
| Rajakilpakkam | 0.31 |

### Conduits and weirs

This study determined the length of the conduits using build in functions of QGIS. Because it was observed that the models results were very sensitive to the width and height of the conduits, measurements of the dimensions of the drainage network at 18 locations in the catchment area were carried out (Appendix XV). The researcher discovered that all conduits were made of concrete and were rectangular in shape. The dimensions of the conduits at measurement locations were directly implemented in the SWMM-model. To estimate the dimensions of the remaining conduits, three kind of roads were distinguished. The average of the measured dimensions for each kind of these roads was calculated (Table 3). The conduits without direct measurement were then categorised in one of the three kinds of roads and the corresponding average dimensions were used.

*Table 3: Average conduit dimensions for primary, secondary and tertiary roads in Sembakkam catchment area*

| Road type/category | Average width (m) | Average height (m) |
|---|---|---|
| Primary | 0.78 | 0.63 |
| Secondary | 1.01 | 0.66 |
| Tertiary | 0.68 | 0.61 |

Furthermore, this study assumed the Manning-n coefficient of the conduits to be the same for the whole drainage network. Ranges from 0.011 to 0.024 were used for areas in Taiwan and China (Tsai et al., 2017; Li et al., 2016). A study in Mumbai (India) used 0.014 as coefficient, whereas a study in Hyderabad (India) used ranges from 0.02 to 0.035 and a study in West-Bengal (India) 0.01 to 0.03

(Vemula et al., 2019; Bisht et al., 2016; Ranger et al., 2011). Ranges from 0.011 to 0.02 are typical for concrete open channels. However, during the field visit, it was observed that many conduits are clogged by solid waste (Appendix XV). Therefore, taking a higher value seemed more reasonable. Taking the studies from Vemula et al. (2019) and Bisht et al. (2016) into account, a value of 0.022 was chosen.

The system of upstream lakes is a cascading system, which means that when a lake's storage capacity is fully reached, it will start discharging into Sembakkam lake. This was modelled by using a weir for the lake's outflow conduit. By visiting the weir in Sembakkam lake it was assumed that its properties also count for the weirs of the upstream lakes. Their parameters can be found in Table 4.

*Table 4: Parameters weir at Sembakkam lake and upstream lakes*

| Parameter | Value |
|---|---|
| Height | 1.5 m |
| Length | 50 meters |
| Inlet offset | 1.5 meter |
| Discharge coefficient | 1.6 (Rossman, 2015) |
| Type | Transverse |

#### *Determination of infiltration parameters*

To determine the infiltration, the model provides three different methods. The first is the Green-Ampt method (GA) which is a physically based model. The second is Horton, a semi-empirical method and the third is a method based on the Curve Number (CN), which is completely empirical. A review, done by Mishra et al. (2003), showed that the GA-method is popular, because its parameters can be derived from the soil type. However, Horton was considered to be more suitable than GA, also for Indian soils. This conclusion was also made by Chandramouli (2016). Furthermore, Innes (1980) found that the CN-method predicted the infiltration in dry soil the best and Eckart et al. (2018) mention the responsiveness of this method on the characteristics of the runoff production in urban areas as a strength. Suribabu and Bhaskar (2014) stated that this method was only useful for the infiltration processes of short events. CN was chosen because of the ease to determine its parameters. The parameters of the Horton can only be found by conducting a regression analysis on infiltration measurements, which was not in the research scope. No proper soil map was available so the GA method was also not usable. The available land use map however was enough for determining the CN parameters.

The curve number for each sub-watershed was chosen based on its land use and hydrologic soil group. Based on a soil map of Tamil Nadu Agricultural University (2004), the hydrologic soil group was found to be D[1]. The corresponding Curve Numbers per land use for Indian conditions are presented in appendix V. The final Curve Number for each sub-watershed was calculated by taking the weighted average of the area.

### 8.2.2 Precipitation

This study used precipitation data from a Self Recording Rain Gauge (SRRG) of the Indian Meteorological Department (IMD) at Meenambakkam, which is approximately 7 km away from the study area, to find an appropriate precipitation pattern for a dry, average and wet year. This data consisted of hourly precipitation amounts for 47 years, from 1969 to 2016. The data was prepared for use by inserting zero precipitation values for missing hours (0.1%) and omitting five incomplete years.

[1] *Soils from hydrological soil group D have a high runoff potential and a low infiltration rate* (Booij, 2017).

To determine which year would be used as a dry, average and wet year, the mean and standard deviation of the yearly precipitation amounts were calculated. Years that had a yearly rainfall more than the mean plus one standard deviation were counted as wet years, years with a yearly rainfall less than the mean minus one standard deviation were counted as dry years, and the remaining years were taken as average years (Leary, Conde, Kulkarni, Pulhin, & Nyong, 2008). After that, the average yearly precipitation for each of these batches was computed. The representative year for each batch was the year which had a yearly precipitation closest to the average yearly precipitation of that batch. In this way the representative dry, average and wet year were found to be 1982, 1971 and 1990 respectively. Their precipitation pattern is illustrated in Figure 11.

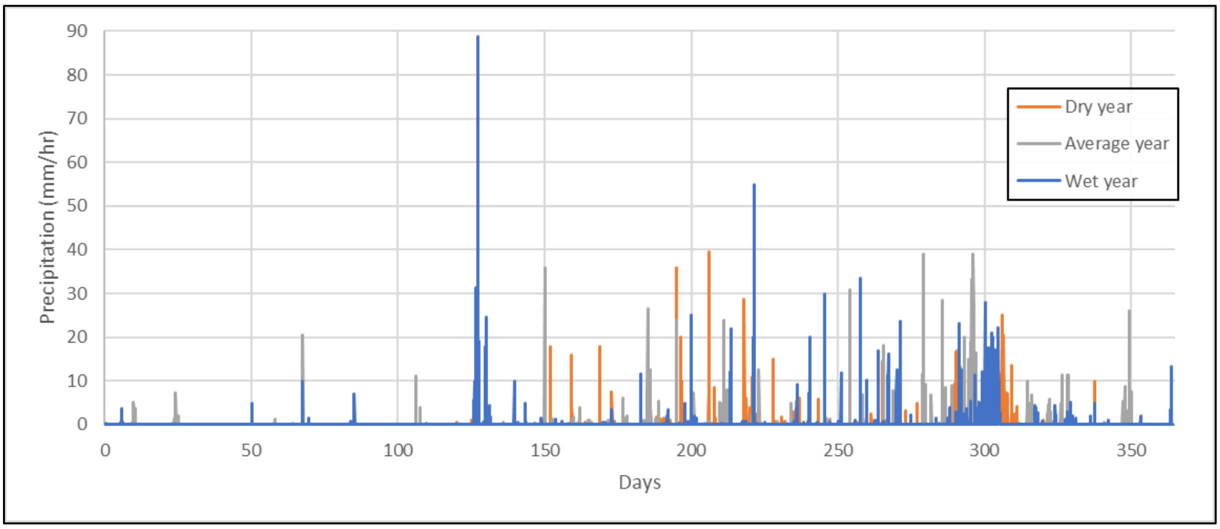


*Figure 11: Precipitation pattern in catchment area of Sembakkam lake during a dry, average and wet year*

### 8.2.3 Dry weather inflow

The dry weather inflow into Sembakkam lake was measured in an arbitrary way by experts of IITM. Only the flow of six inlets was measurable (Appendix VI). This study modelled the total inflow of 8.78 MLD as a direct constant inflow into Sembakkam lake.

### 8.2.4 Evaporation

To model the evaporation, a climate file containing daily minimum and maximum air temperature data from the IMD was used. The location of the closest measurement point is at 12.5, 79.5, which is 85 km away from the lake in a rural area. Other location points were further away or located in the sea, which was considered to be unreliable. SWMM uses the Hargreaves equation to estimate the evaporation (Rossman, 2015; Hargreaves et al., 2003).

### 8.2.5 Human extraction

Private and public water supply companies extract water from the well in the northwest of the lake by water tankers for human usage. Most households in Chennai are connected to private or public pipe supply, but this supply is often irregular and insufficient, especially in the dry period. Shortages in water supply are compensated by water supply by tankers. Because extractions of these tankers happen irregularly and without any governmental control, no data is available for this outflow. An estimation was made, based on the daily water use per capita from water tankers, the amount of inhabitants and the amount of tanks in the neighbourhood.

The consumption per capita from private tankers and mobile/standpipe public supply for a dry, average and wet year in Chennai can be found in Table 5. The three different periods were based on the rainfall pattern: there is a dry period from January to May. From June to September, some rain falls and from October to December the raining season is there. Only values from January to March for a dry and a wet year could be derived from (Srinivasan 2010). For April and May, it was assumed to be the same water demand, because rainfall patterns are similar during these months. Concerning the period from October to December, which is the raining season, this study assumed that for all types of years the regular water supply would be enough to meet the water demand. The water demand for tankers would be small and was assumed to be the same as the demand in January to March during a wet year. Furthermore, this study estimated the period from June to September to be the average of the other two periods. Lastly, the water use during an average year was calculated by taking the average of a dry and wet year for every period.

*Table 5: Daily water use in litres per capita in Chennai*

| Year | Jan-May | June-Sep | Oct-Dec |
|---|---|---|---|
| Dry | 31 | 19 | 6 |
| Average | 19 | 12 | 6 |
| Wet | 6 | 6 | 6 |

The total population in 2011 of the surrounding three districts and the amount of water tanks in these districts is shown in Appendix VII. The total population was divided by the amount of water tanks, resulting in a rough estimation of 42,600 people in the Sembakkam lake area being dependent on tanker supply. By multiplying this value with the water demand per capita per day, the human water extraction from Sembakkam lake for the different types of years and periods was determined and presented in Table 6. The monthly-weighted average is used in the model, as a constant outflow of the lake.

*Table 6: Human extraction in $m^3/s$ from Sembakkam lake*

| Year | Jan-May | June-Sep | Oct-Dec | Weighted average |
|---|---|---|---|---|
| Dry | 0.0153 | 0.0091 | 0.0030 | 0.0102 |
| Average | 0.0092 | 0.0061 | 0.0030 | 0.0066 |
| Wet | 0.0031 | 0.0030 | 0.0030 | 0.0031 |

### 8.2.6 Calibration seepage Sembakkam lake

SWMM models the seepage from a storage element using the Green-Ampt method. Three input parameters, the suction head, hydraulic conductivity and initial deficit, are given as input. To find these parameters, calibration of these parameters during the dry weather season was done. The overflow of the lake during the dry season was arbitrarily measured by experts of IITM. The initial parameters were chosen based on a soil type profile of the lake bed (Appendix VIII). The lake bed consists mostly of a mixture of sand and clay, therefore the parameters of sandy clay were chosen from the SWMM manual (Table 7) (Rossman, 2015). This study assumed that the lake is always full causing the soil to be always saturated. The initial deficit was set to zero accordingly. The overflow of the lake was measured in the last week of January 2019 and amounts 0.03 $m^3/s$. Calibration was carried out with the human extraction of an average year. The final values are displayed in Table 7.

*Table 7: Calibration of lake seepage parameters*

| Parameter | Initial | Final |
|---|---|---|
| Saturated Hydraulic conductivity (mm/hr) | 0.51 | 0.50 |
| Suction head (mm) | 240 | 240 |
| Initial deficit (-) | 0 | 0 |

### 8.2.7 Other model settings

There are three modes for calculating the water flows. The first is Steady Flow Routing, which assumes uniform and steady flow and is only useful for preliminary analysis of long-term simulations. The second is Kinematic Wave Routing, which solves simplified continuity equations for every time step. The third and most detailed method is Dynamic Wave Routing, which solves the complete one-dimensional Saint

Venant flow equations and takes backwater effects into account (Rossman, 2015). For running the model, the 'Kinematic Wave'-method was chosen. The 'Dynamic Wave'-mode was regarded to be too detailed for the amount and precision of data available and the 'Steady Flow'-method to be too simplistic.

This study used a reporting time step of an hour because this was considered detailed enough for a run length of a year. The runoff time step for dry weather was also set to 60 minutes because the dry-weather inflow was a constant flow which is not necessary to determine for a smaller time-step. To strike a balance between computational time and level of detail, the runoff for wet weather was set to 5 minutes and the routing time step to 2.5 minutes. The latter was taken more precise than the first because this was considered to be the time step of the most important process which should be calculated more precisely.

## 8.3. Sensitivity and uncertainty analysis

This study conducted a sensitivity analysis in order to determine the reliability of the simulation results because of the absence of adequate calibration data. All input parameters for the sub-watersheds were included except for the area, because it was assumed that the total catchment area is reliable and only areas of sub-watersheds are variable. All parameters from the conduits were included. From the storage unit representing Sembakkam lake, only the parameters concerning seepage, dry weather inflow and human extraction were taken into account. The shape and maximum depth were considered to be reliable by reason of the used shape file. The only parameter of the final weir that was included was the discharge coefficient. The width and height of the weir were considered to be reliable because they were measured. The modelling of LIDs was not included in the sensitivity analysis because this study evaluated them for different scenarios.

The ranges of the input parameters were determined by conducting a literature research. Studies were filtered based on the study area. Only studies conducted in Asia were taken into account, because of comparable conditions in these countries. The results of the literature research and the final chosen ranges for each parameter are presented in Table 8. The maximum value of Manning-n of the pervious area in the sub-watersheds was chosen lower based on the field visit. For some parameters a factor was used as range because no literature value could be found or the parameter is different for every single sub-watershed or conduit. This study used a range of -25% and +25% for all parameters that no literature value could be found for (Kumar et al., 2019). Furthermore, the sensitivity analysis was performed for an average year. Lastly, chapter 7 evaluates the uncertainties of the model.

*Table 8: Chosen and literature ranges of input parameters*

| | Parameters | Minimum chosen | Maximum chosen | Literature minimum | Literature maximum | Source |
|---|---|---|---|---|---|---|
| SUB-WATERSHEDS | Manning-N impervious | 0.01 | 0.03 | 0.011 | 0.035 | (Kumar et al., 2019; Vemula et al., 2019; Vemula et al., 2019; Li et al., 2016) |
| | Manning-N pervious | 0.05 | 0.15 | 0.05 | 0.8 | (Kumar et al., 2019; Vemula et al., 2019; Vemula et al., 2019; Li et al., 2016; Li et al., 2014) |
| | Depression storage - impervious | 1 | 3 | 0 | 3 | (Kumar et al., 2019; Vemula et al., 2019; Li et al., 2016; Li et al., 2014; Rossman, 2015) |
| | Depression storage - pervious | 5 | 10 | 2.5 | 10 | (Kumar et al., 2019; Vemula et al., 2019; Li et al., 2016; Li et al., 2014; Rossman, 2015) |
| | % impervious area no depression storage | 25 | 75 | 50 | 80 | (Li et al., 2014) |
| | Slope (factor) | 0.75 | 1.25 | 0.75 | 1.25 | (Kumar et al., 2019) |
| | Width (factor) | 0.75 | 1.25 | 0.75 | 1.25 | (Kumar et al., 2019) |
| | % impervious area (factor) | 0.75 | 1.25 | 0.75 | 1.25 | (Kumar et al., 2019) |
| | Curve number (factor) | 0.75 | 1.25 | - | - | |
| | Days to dry | 3 | 8 | | | |
| CONDUIT | Manning-N | 0.01 | 0.035 | 0.011 | 0.035 | (Vemula et al., 2019; Li et al., 2016; Tsai et al., 2017) |
| | Width (factor) | 0.75 | 1.25 | - | - | |
| | Height (factor) | 0.75 | 1.25 | - | - | |
| | Length (factor) | 0.75 | 1.25 | - | - | |
| STORAGE UNIT | Suction head (factor) | 0.75 | 1.25 | - | - | |
| | Conductivity (factor) | 0.75 | 1.25 | - | - | |
| | Dry weather flow (factor) | 0.75 | 1.25 | - | - | |
| | Human Use (factor) | 0.75 | 1.25 | - | - | |
| Outfall weir discharge coefficient | | 1.38 | 1.83 | 1.38 | 1.83 | (Rossman, 2015) |

## 8.4. Modelling LIDs and dredging

The catchment area of Sembakkam lake is heavily urbanised. There is hardly any space for rain gardens or other kinds of green infiltration areas. This study therefore only evaluated LIDs which could be implemented at a household level, which was assumed to be the same as the level of a single residential building. The Rain Center is a corporation which stimulates and facilitates the implementation of rain water harvesting measures in Chennai (Rain Centre, 2017). This study evaluates two of them using the SWMM model: rain barrels, typically build as underground cisterns, and percolation pits. The likelihood of these two LIDs being implemented is higher because of the efforts of this organisation. Furthermore, this study also evaluated the dredging of the lake as an improvement for groundwater recharge at the lake itself.

### 8.4.1 The amount of LIDs implemented

It is uncertain how many households would implement cisterns and percolation pits. Therefore, three different scenarios were modelled, differentiating in the share of households that implement the LIDs: 5%, 15% and 25%. As there was only data available about the amount of residents in the Tambaram neighbourhood, from which the catchment area of Sembakkam lake is a part of (Appendix VII), this study approximated the amount of households in the latter. Based on Google Satellite imagery, residential areas within Tambaram neighbourhood were delineated. The area of these residential areas was calculated with a built in tool of QGIS. After that, the fraction of these residential areas located inside the catchment area of Sembakkam lake was calculated. The amount of residents in Tambaram neighbourhood was multiplied with this fraction and after that divided by the average household size of four persons to obtain the amount of households (Express News Service, 2017). This study assumed that there were no multiple storey buildings based on observations from the field visit. Consequently the amount of households per hectare was calculated by dividing the total amount of households in the catchment area by the total residential area in de catchment area. Finally, this value was used to calculate the amount of households in each sub-watershed.

### 8.4.2 SWMM modelling of cisterns

In India, common dimensions for cisterns are 1.8 x 1.8 x 2.7 m resulting in a volume of 9 $m^3$ (Narasimhan, 2019). The draining flow from the cistern was used to model the human usage of the stored water. Srinivasan et al. (2010) estimates the water use per capita from 40 to 100 litres per day for the Chennai region. Shaban and Sharma (2007) state that the low-middle income class, which is the class of most of the households in the catchment area, uses 40 to 60 litres per capita per day. Finally, Anand (2001) found that the towns in CMA, which Tambaram is one of, use 40 litres per capita per day. Therefore, 40 litres per capita per day was chosen as the water consumption of residents in the Sembakkam catchment area, which makes the consumption of an average 4 person household 160 litres a day. It was assumed that all of this water was taken from the cistern whenever there is sufficient water in it. Furthermore, only 67% of the runoff is directed to the cisterns. Cisterns only store runoff from rooftops and the percentage of impervious area being rooftops was estimated 67% of the total impervious area.

### 8.4.3 SWMM modelling of percolation pits

The design of a percolation pit build by the Rain Center can be found in Figure 12. The dimensions for the storage space at the top are typically 1.8 x 1.8 x 0.9 meter in India (Narasimhan, 2019). The void ratio was taken as 0.4 (Ven, 2016), the surface roughness as 0.2 and the slope as 0.5, in order to have most of the runoff going into the storage space instead of flow over it. As the seepage rate, the hydraulic conductivity of sand (120 mm/hr (Rossman, 2015)) was taken, because the borehole will extend to the depth of a sand layer.

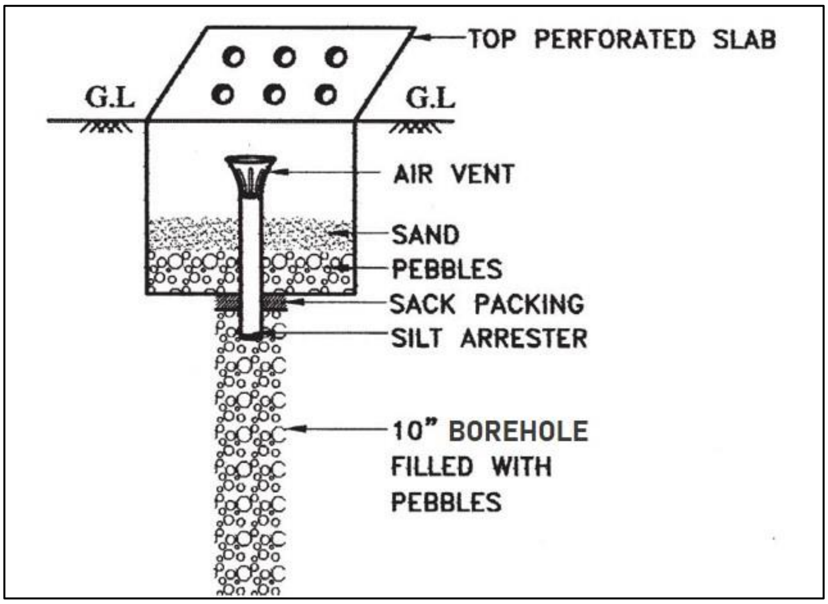


*Figure 12: Design of a percolation pit (Rain Centre, 2017)*

Furthermore, this study modelled the percolation pits by creating a new sub-watershed for every original sub-watershed. Since percolation pits are probably implemented at the edge of a lot near the street all runoff was directed from the original sub-watershed to the percolation pit sub-watershed. When the capacity of the percolation pit is reached, the remaining runoff is directed to the drainage network.

### 8.4.4 SWMM modelling of lake dredging

Based on the soil profile of the lake bed (Appendix VIII), experts from IITM proposed to dredge the lake up to 1 meter, in such a way that the maximum elevation would be 14.25 m (Figure 33). This study evaluated the expert suggestion by modelling a new capacity and storage curve for the lake accordingly. Because it is highly uncertain what the new hydraulic conductivity of the lake would become, results were generated for a range of hydraulic conductivities. This study took 0.5 mm/hr as lower bound because it is the current hydraulic conductivity. Based on the soil composition and the contour file of Sembakkam lake (Appendix VIII and IV respectively), it was estimated that a maximum of 10% of the lake bed would be dredged by 1 m, reaching sandy layers. The hydraulic conductivity of sand is 120 mm/hr. Assuming a seepage rate of 1.5 mm/hr for the remaining lake bed area, this study took the weighted average of approximately 15 mm/hr as upper bound. As intermediate values, this study chose 1.5 and 5 mm/hr. The first is the hydraulic conductivity of sandy clay (Rossman, 2015). A detailed table on the derivation of the hydraulic conductivity can be found in Appendix IX. Since many soil layers of the lake bed consist of a mixture of sand, silt or clay, this was regarded as an appropriate summarizing soil type.

# 9. Results

This section presents results of the storage dynamics and overflow of the lake as well as the infiltration of the current situation. Further, it demonstrates the impact of the LIDs and the sensitive parameters of the developed model.

## 9.1. Current water balance

Table 9 shows a summary of the water balance of the catchment of Sembakkam lake. Only 4.3-6.4% of the precipitation infiltrates whereas more than 80% becomes runoff. The precipitation pattern of the wet year shows less rain events with higher intensity compared to the precipitation pattern of the average year (Figure 11). This can be an explanation of the reduction in infiltration in a wet year compared to an average year. Because the water cannot infiltrate properly during these high intensity rain events due to saturated soil, it instead becomes runoff.

Table 10 shows the water balance of Sembakkam lake itself. It can be inferred that the lake's average storage is approximately its capacity. Between 26.8% and 38.5% of the lake's inflow is dry weather inflow, indicating the importance of this inflow for the water balance of Sembakkam lake. The most substantial outflow is the overflow at the weir (68-78%). After that the seepage is the most contributing outflow (12-18%) and evaporation (5-7%) and the human extraction (1-4%) are minor outflows.

*Table 9: Total water flows of catchment area of Sembakkam lake in the current situation during a year. Between brackets the percentage of the total precipitation*

| Year | Total precipitation ($Mm^3$) | Evaporation catchment ($Mm^3$) | Infiltration catchment ($Mm^3$) | Runoff ($Mm^3$) |
|---|---|---|---|---|
| Dry | 9.09 | 1.21 (13.3%) | 0.51 (5.6%) | 7.38 (81.2%) |
| Avg | 13.57 | 1.55 (11.4%) | 0.87 (6.4%) | 11.17 (82.3%) |
| Wet | 19.50 | 1.79 (9.2%) | 0.84 (4.3%) | 16.87 (86.5%) |

*Table 10: Water balance of Sembakkam lake. Between brackets the percentage of the total inflow*

| Year | Average storage ($Mm^3$) | Total inflow ($Mm^3$) | Dry weather inflow ($Mm^3$) | Evapo-ration ($Mm^3$) [2] | Lake seepage ($Mm^3$) [2] | Human extrac-tion ($Mm^3$) | Overflow ($Mm^3$) | Maximum overflow ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|
| Dry | 0.278 | 8.34 | 3.21 (38.5%) | 0.58 (7.0%) | 1.50 (18.0%) | 0.32 (3.8%) | 5.66 (67.9%) | 3.93 |
| Avg | 0.279 | 9.77 | 3.21 (32.9%) | 0.67 (6.9%) | 1.46 (14.9%) | 0.21 (2.1%) | 7.13 (73.0%) | 4.86 |
| Wet | 0.280 | 12 | 3.21 (26.8%) | 0.60 (5.0%) | 1.44 (12.0%) | 0.10 (0.8%) | 9.37 (78.1%) | 5.85 |

The water level, volume and overflow of Sembakkam lake during a dry, average and wet year can be found in Figure 13 to Figure 15 respectively. From the figures, it can be derived that during a small rain event, the lake's water level increases to a maximum of 1.54 m, its storage to 0.29 $Mm^3$ and its overflow to 0.5 $m^3/s$. During a moderate rain event, the water level increases to a maximum of 1.6 m, the lake's storage to 0.31 $Mm^3$ and its overflow to a maximum of 2 $m^3/s$. In case of a large rainfall event, the lake's water level can increase up to 1.67 m, its storage to 0.34 $Mm^3$ and the maximum overflow to 5.8 $m^3/s$. Generally, the lake's storage remains constant around the lakes capacity throughout the year. Consequently, it is incapable of storing runoff from big rainfall events which is instead discharged downstream.

[2] *SWMM doesn't provide the lake seepage as a result directly, but returns a percentage, rounded to zero decimals, of the total storage lost to seepage. The total storage was interpreted as the initial storage plus the sum of all inflows.*

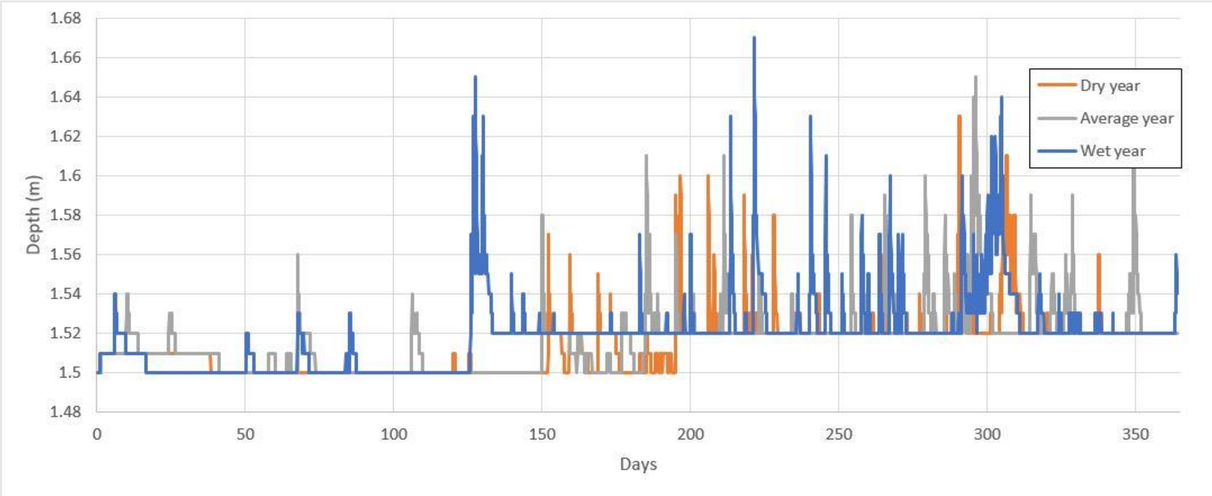


*Figure 13: Water level of Sembakkam lake during a dry, average and wet year*

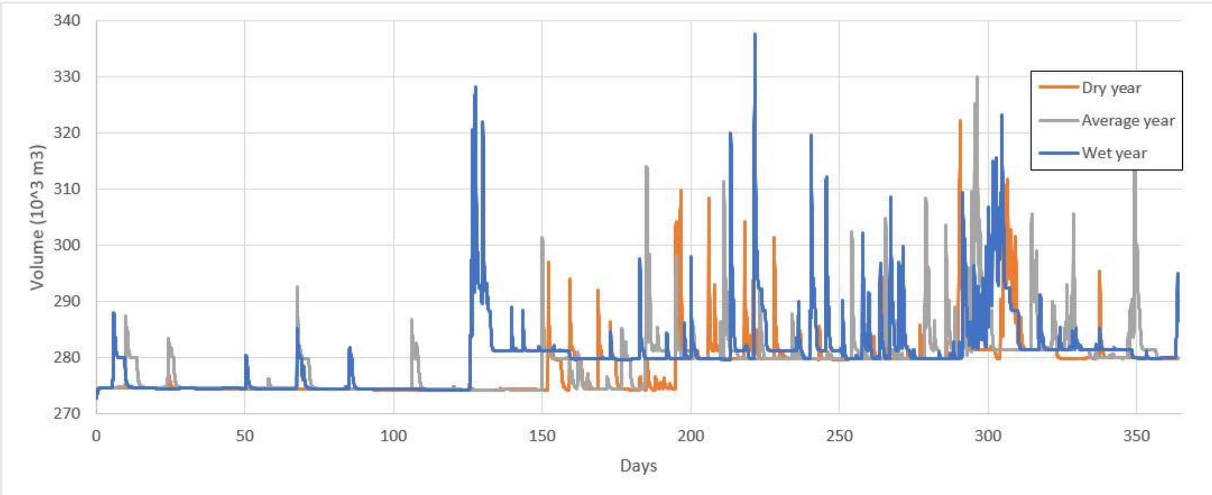


*Figure 14: Volume of Sembakkam lake during a dry, average and wet year*

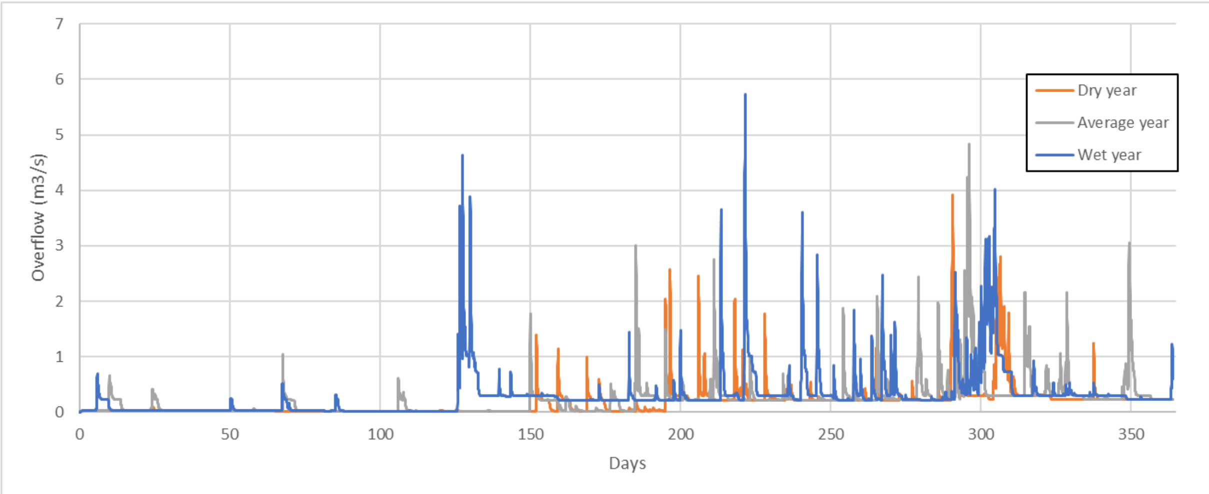


*Figure 15: Overflow of Sembakkam lake during a dry, average and wet year*

## 9.2. Impact LIDs

This paragraph shows the impact of the cisterns, percolation pits and the combination of them on Sembakkam lakes overflow, storage and infiltration in the catchment area. As SWMM only shows results of lake seepage as a percentage of the total storage rounded to zero decimals, the impact of LIDs on the lake seepage was untraceable. In this section the results are only presented as relative changes. Detailed data and absolute changes can be found in Appendix X.

### 9.2.1 Cisterns

Figure 16 shows the impact on the water balance of the lake for different scenarios of households implementing cisterns over one year. The impact on the infiltration volume in the catchment area, the storage volume of the lake and the maximum and total overflow is smaller than 0.3% in an average and wet year. In a dry year, there is a slight difference in impact the infiltration volume (0.8-1%).

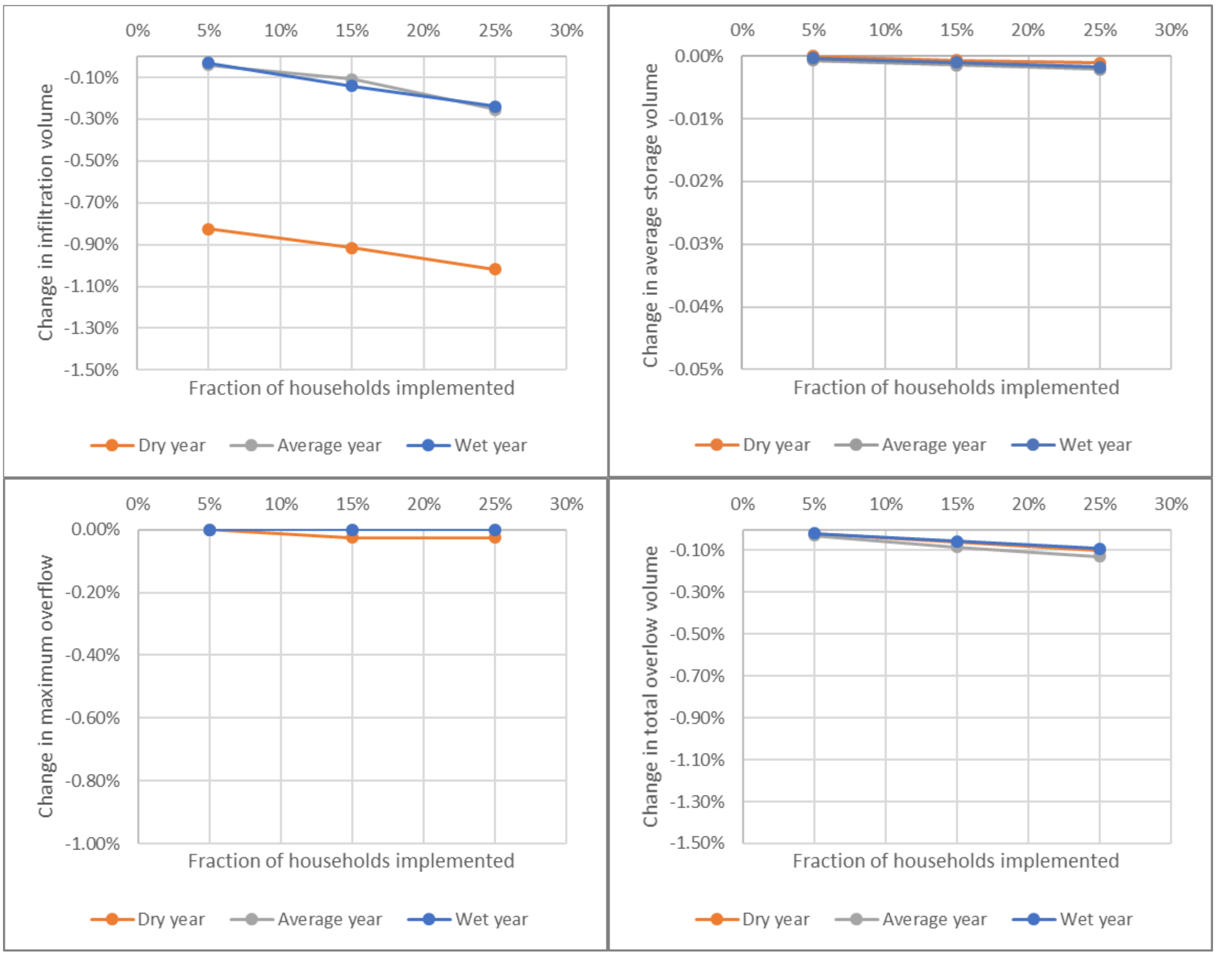


*Figure 16: Range of change in infiltration volume (upper left), storage volume (upper right), maximum overflow (lower left) and total overflow (lower right) for different percentages of households implementing cisterns for a dry, average and wet year*

While the cisterns have hardly any effect on the lake's storage and overflow, there is an impact on the water supply of households (Table 11). For a minimum water demand of 160 ltr/day (Srinivasan, 2010) a cistern supplies 5-9% of a households water demand yearly. They provide water mostly during wet season. During the dry season cisterns hardly contribute to a households water demand. More detailed data can be found in appendix XI.

*Table 11: Impact cisterns on the water supply of a household in the dry and wet period of the year and the total year*

| Year | Scenario | Percentage supplied dry period (Jan-Jun) | Percentage supplied wet period (Jul-Dec) | Percentage supplied complete year |
|---|---|---|---|---|
| Dry | 5% | 1% | 8% | 5% |
| | 15% | 1% | 9% | 5% |
| | 25% | 1% | 9% | 5% |
| Aver age | 5% | 3% | 12% | 7% |
| | 15% | 3% | 13% | 8% |
| | 25% | 3% | 12% | 8% |
| Wet | 5% | 4% | 13% | 8% |
| | 15% | 4% | 14% | 9% |
| | 25% | 4% | 13% | 9% |

### 9.2.2 Percolation pits

Figure 17 shows the impact of percolation pits on the water balance of Sembakkam lake for different scenarios of households implementing percolation over one year. It can be inferred that this LID has a considerable effect on the infiltration volume in the catchment area. There is an increase of 0.120 $Mm^3$ (25%) during dry years and 0.160 $Mm^3$ (20%) during average and wet years if 25% of the households implement percolation pits. Consequently, the total overflow volume of the lake decreases up to 0.060 $Mm^3$ (1%). There is still an increase in infiltration volume of 0.035 $Mm^3$ (5%) in the 5% implementation scenario.

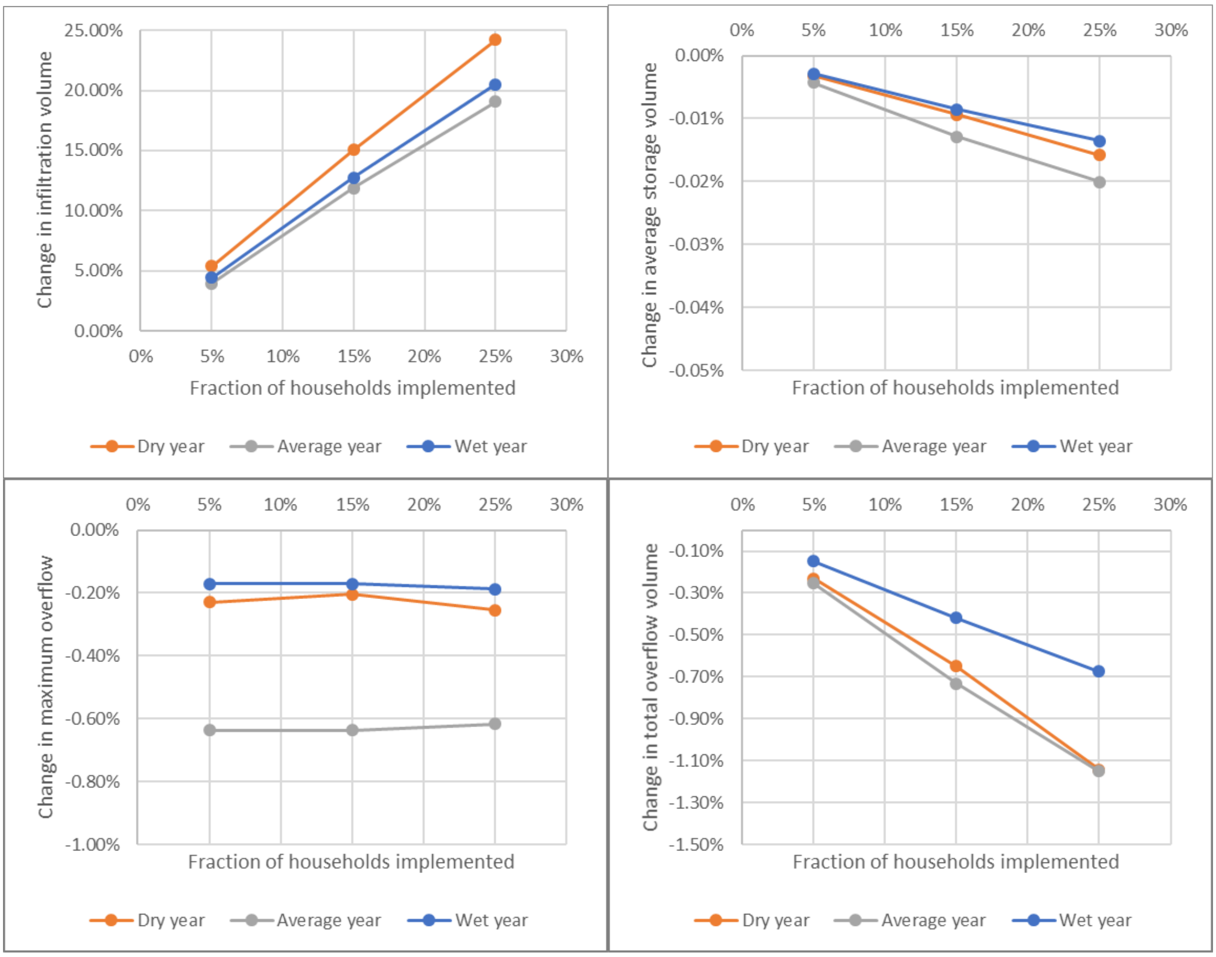


*Figure 17: Range of change in infiltration volume (upper left), storage volume (upper right), maximum overflow (lower left) and total overflow (lower right) for different percentages of households implementing percolation pits for a dry, average and wet year*

### 9.2.3 Combination of cisterns and percolation pits

Figure 18 shows the impact of different scenarios of households implementing a cistern as well as a percolation pit on the infiltration, storage and overflow of the lake. These results do not differ much from the impact of percolation pits. This can be explained as a result of the small impact of cisterns.

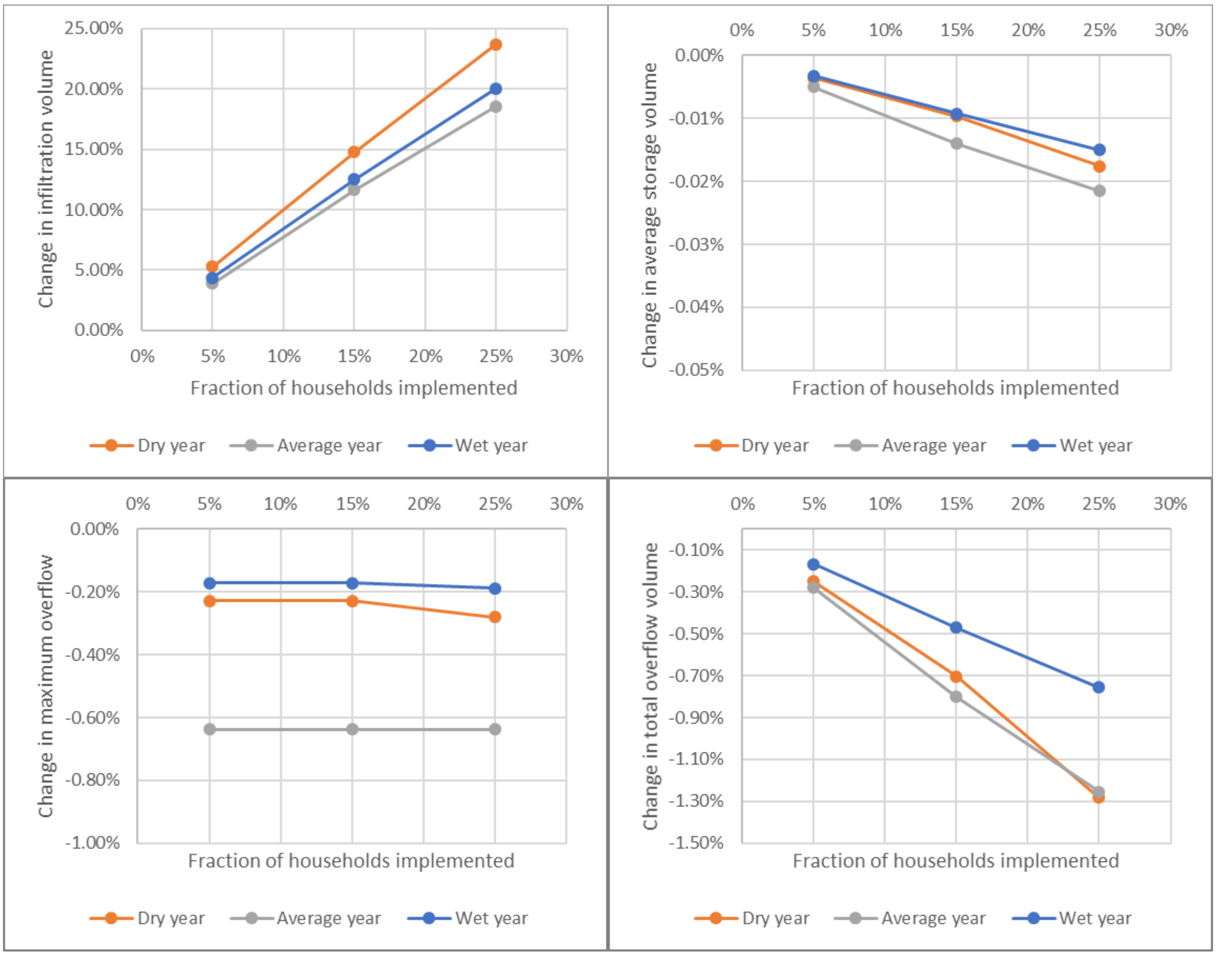


*Figure 18: Range of change in infiltration volume (upper left), storage volume (upper right), maximum overflow (lower left) and total overflow (lower right) for different percentages of households implementing cisterns and percolation pits for a dry, average and wet year*

## 9.3. Impact of dredging the lake

In Figure 19 the impact of dredging the lake on the storage and overflow for different hydraulic conductivities over one year is visualised. If there is no change in the hydraulic conductivity of the bottom of the lake, besides an obvious increase in storage volume, there will be no change in the total overflow and the maximum overflow will even slightly increase. Possibly this is an effect due to the change of the lake's shape.

If the hydraulic conductivity increases to 1.5 mm/hr, which is the conductivity of sandy clay and covers a big portion of the lakes bed, the total overflow will decrease up to 40%. Depending on the year, the average storage capacity will be different, but in all modelled cases, it will be much smaller than the maximum capacity. The maximum overflow will however remain the same as in the current situation, indicating that the lake will still not be able to catch the runoff of a big rainfall event.

When some sandy layers can be uncovered and the hydraulic conductivity increases up to 5 mm/hr there will be almost no overflow, which means that seepage becomes the major overflow of the lake. The storage will be decreasing with approximately 80%, 60% and 40% in a dry, average and wet year respectively, which can be explained by the difference in total rainfall. The maximum overflow will decrease with 40% in an average and wet year and 60% in a dry year. A probable explanation for this difference is the variation in lake storage. The storage in a dry year is small enough to catch the complete runoff during a peak of rainfall. Furthermore, in case the hydraulic conductivity increases up to 15 mm/hr, the lake will be empty.

These changes in storage and overflow are caused by an increase in seepage (Figure 19). A detailed table on the change in seepage can be found in Appendix XII. An increase in hydraulic conductivity to 1.5 mm/hr would increase the seepage by 150%-180%, which is in increase of approximately 2.5 $Mm^3$. Higher hydraulic conductivities lead to increases from 400% to 700%.

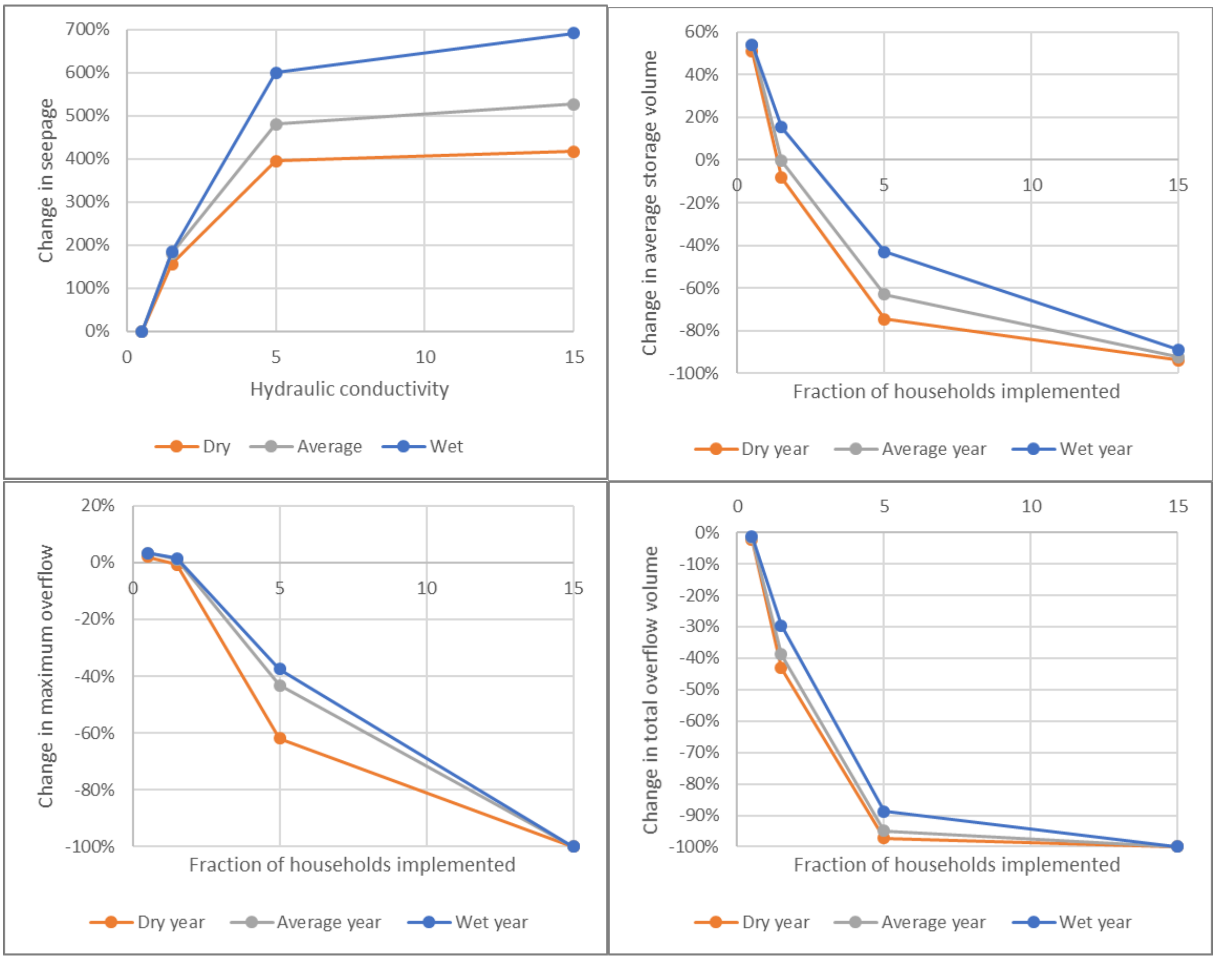


*Figure 19: Range of change in seepage (upper left), storage volume (upper right), maximum overflow (lower left) and total overflow (lower right) for different hydraulic conductivities for a dry, average and wet year*

## 9.4. Sensitive parameters

In this paragraph, the sensitivity of the output variables is evaluated. Due to the large number of parameters tested for sensitivity, only those which made a change bigger than 0.5% are drawn in the figures, with the exception of Figure 21 where a threshold of 0.01% was taken.

The infiltration volume is highly sensitive to the percentage of impervious area and the curve number (Figure 20). With a decrease of 10%, the increase in infiltration volume can be 40% and with an increase of 10%, the decrease in infiltration volume can be 30-60%. Furthermore, the infiltration volume is slightly sensitive to the days until the soil is dry again.

Figure 21 shows the sensitivity of the average storage volume. First of all, the overall change in volume is less than 0.5%. The sensitivity of the storage volume to the input parameters is therefore neglectable. Having stated that, the most sensitive parameters are the dry weather flow and the discharge coefficient.

The maximum overflow is only sensitive to parameters associated with the drainage network (Figure 22). The most sensitive parameter is the Manning-n coefficient. If it is 50% smaller, the maximum overflow increases with 50%. The conduit length and width are similarly sensitive parameters, increasing or decreasing the maximum overflow with 15% when varied by 20%. Lastly, the length of the conduits can in- or decrease the maximum overflow with 5%, which makes them less sensitive parameters.

Manning-n, the conduit height and width are also parameters where the total overflow volume is sensitive to (Figure 23). Especially Manning-n, can increase the volume by 27% when it is decreased by 45% and decrease the volume by 15% when it is increased by 60%. These outer ranges are however unlikely. Similar to average storage volume, the overflow volume is also sensitive to the dry weather flow. Furthermore, the hydraulic conductivity, conduit length, curve number and the percentage of impervious area are less sensitive parameters. The hydraulic conductivity however is a highly sensitive parameter for the seepage loss (Figure 24).

To conclude, the most sensitive parameters of the SWMM model of Sembakkam lake are the parameters associated with the drainage network, the percentage of impervious area, the Curve Number, the dry weather flow, the weir discharge coefficient and the hydraulic conductivity of the lake's bed.

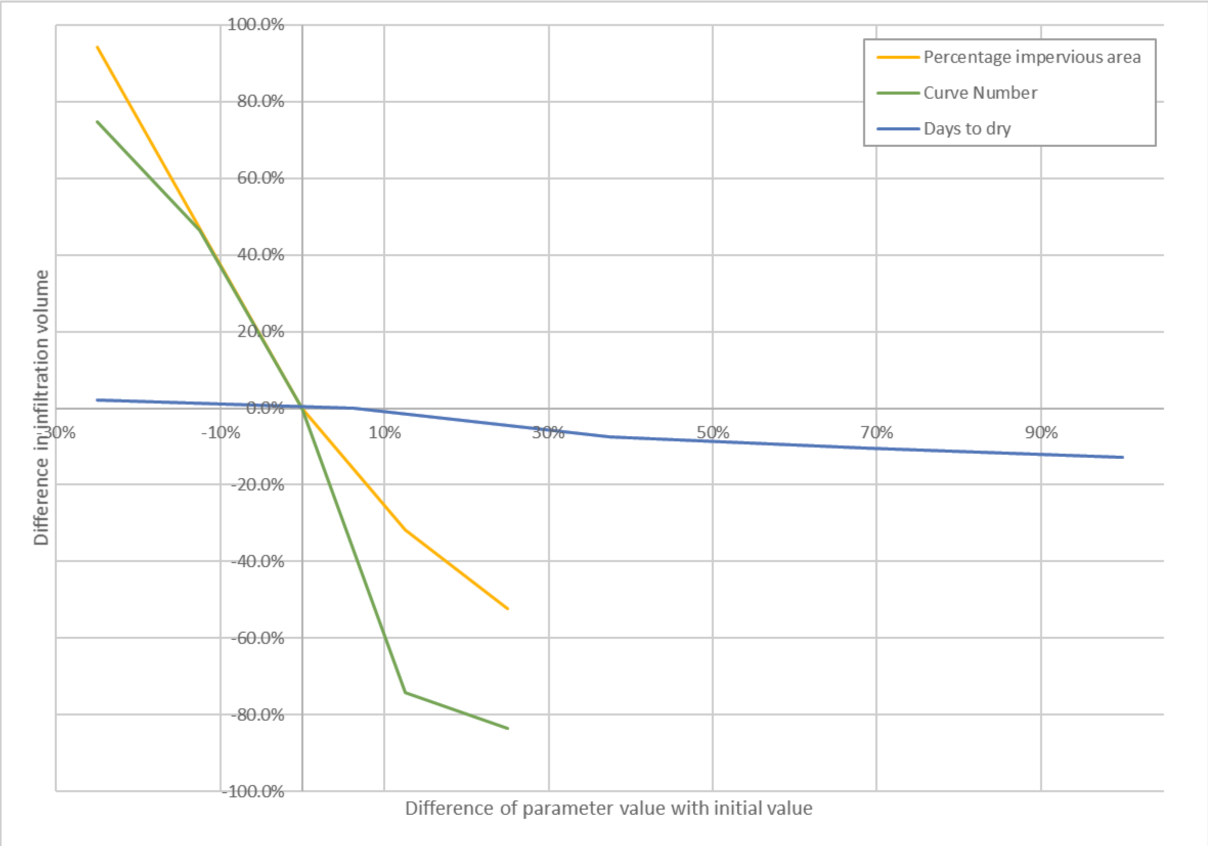


*Figure 20: Sensitivity of infiltration volume*

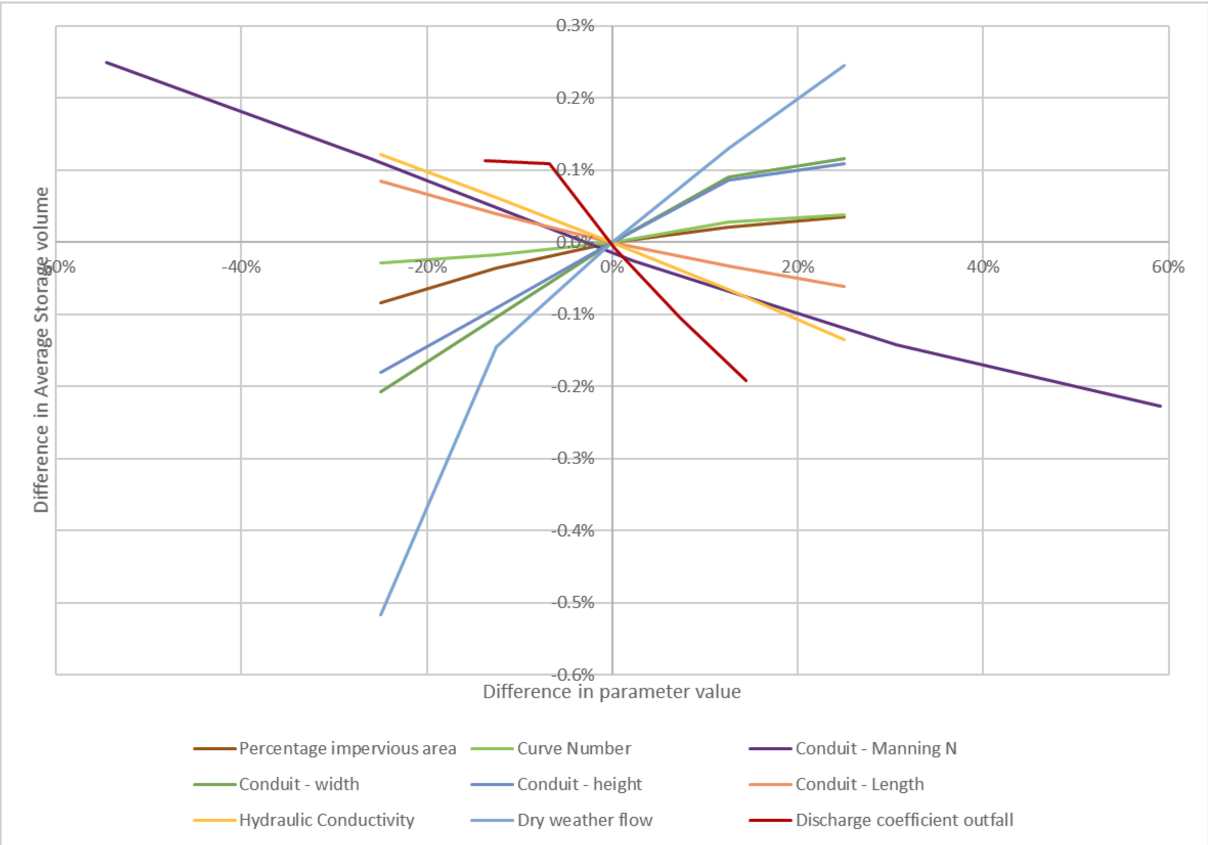


*Figure 21: Sensitivity of average storage volume*

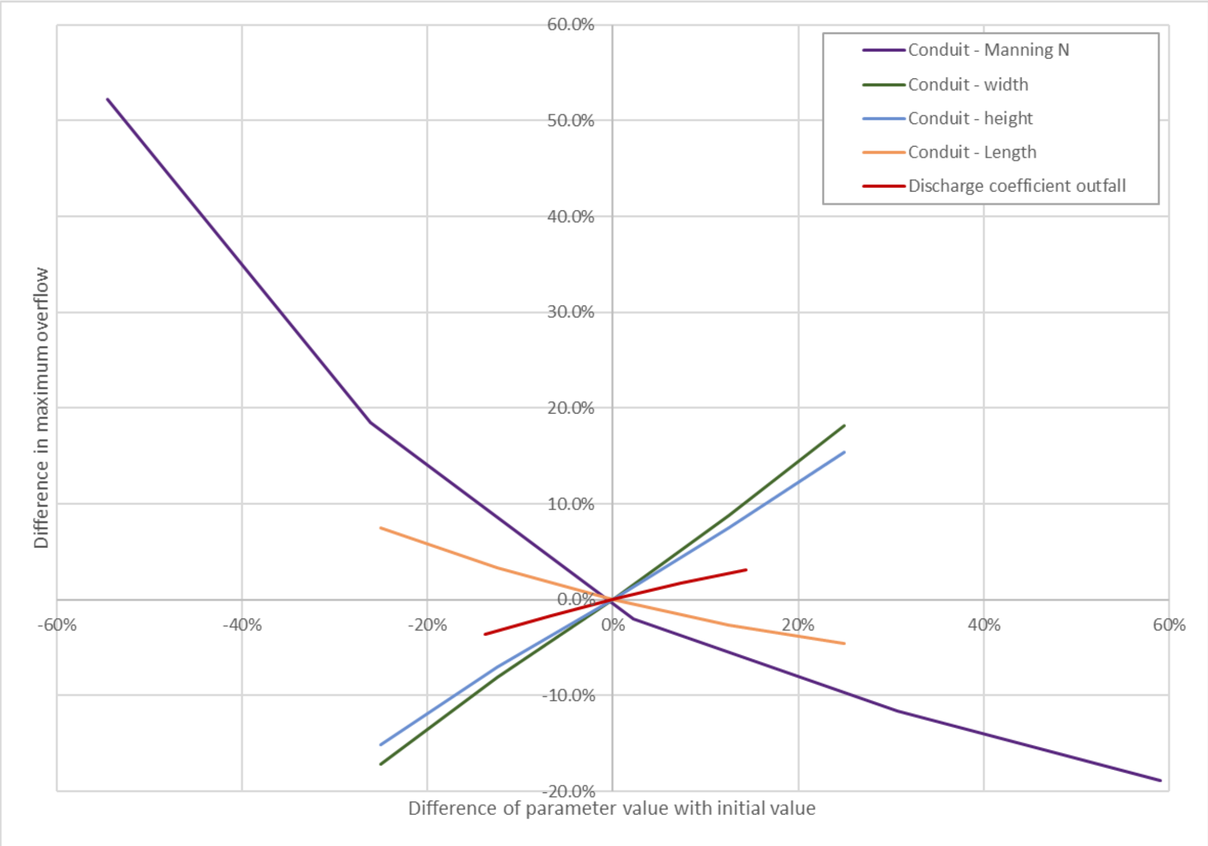


*Figure 22: Sensitivity of maximum overflow*

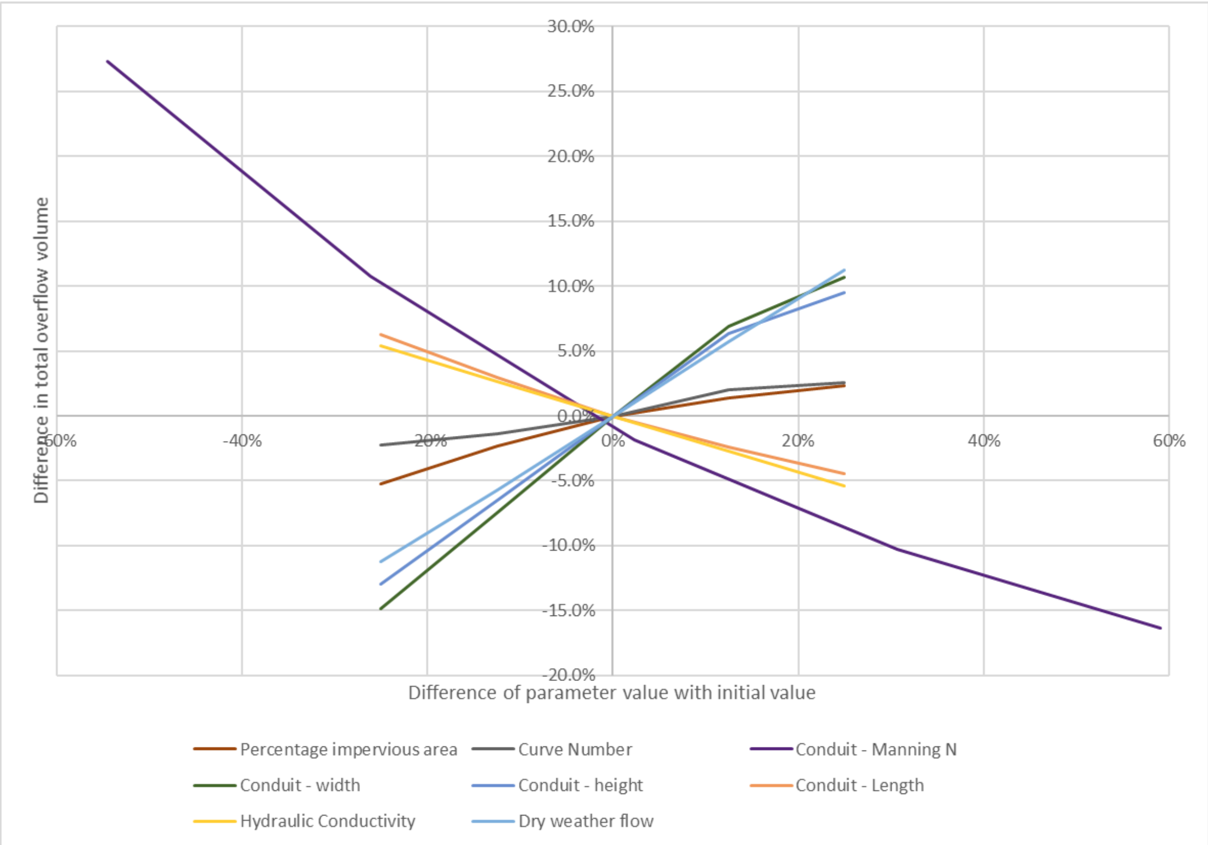


*Figure 23: Sensitivity of total overflow volume*

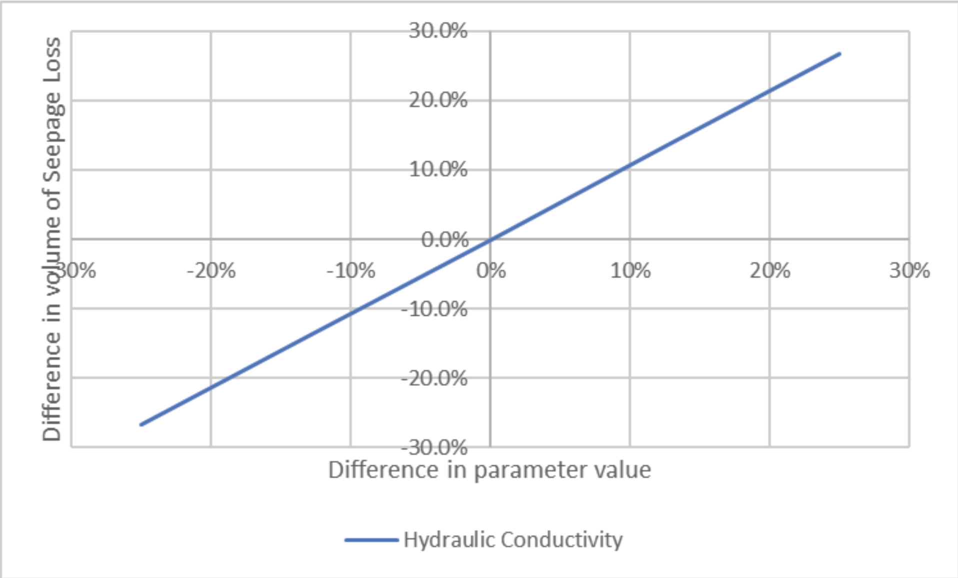


*Figure 24: Sensitivity of seepage loss*

# 10. Discussion

This section firstly reflects on the input data, the conceptual model, the implementation of the developed model and discusses related uncertainties. After that, the results are evaluated, considering these uncertainties and the sensitivities of the model (Sargent, 1998).

## 10.1. Reflection on uncertainties

### 10.1.1 Input data

A summary of all input data is shown in Table 22 in Appendix XIII. Uncertainties related to model input parameters are evaluated in this paragraph.

The rainfall record was measured at Meenambakkam, which is 7 km away from the study area. While there could be differences in local rainfall, McMillan et al. (2011) found that rainfall patterns for rainfall events bigger than 1 mm/hr are consistent within such an area when aggregated to hourly data. A larger uncertainty can be expected for  the temperature data as the distance from the measuring location to the study area is around 85km. In addition, the locations differ in their characteristics. Unlike the study area, the region where temperature measurements were taken can be described as rural. Because the temperature in cities is higher than in rural areas (Sun et al., 2019), the temperatures used as input data for the model are likely to be an underestimate.

The used DEM has a sufficient resolution for the size of the study area. However, as small streets, which can have an influence on the flow direction, can be substantially smaller than 10 meters in Indian urban areas, a DEM with a higher resolution would be preferable. The land use map has a low resolution, which can result in the neglection of small green areas and a overestimation of the TIA and the CN. The major concern with the land use map however is that it is outdated (2004). Some fallow and scrublands are now build up area (Appendix XIV). Therefore, the TIA and CN could also be an underestimate.

The values for the dry weather inflows and discharge of Sembakkam lake are arbitrary. For example, the flow velocity was determined by measuring the velocity of a floating object in the stream. The contour map however was generated  based on a total station survey and can be considered as reliable. The measurements of the dimensions of the drainage network are significant up to 5 cm. Furthermore, this research estimated the remaining parameters based on literature research. Studies from India were used as primary source and studies from China were used as background information. Whereas the urban conditions of Indian cities are similar and therefore useful, local conditions can vary much within India. It would still be better to have local measurements, especially for the Manning-n of conduits.

### 10.1.2 Conceptual model

Concerning the validity of the conceptual model, the most important flaw is the neglection of the seepage in the upstream lakes. As observed at Sembakkam lake, this is an important flow with much influence, and should therefore not be neglected. Further research should incorporate this flow, even in a simplistic way.

### 10.1.3 Implementation

#### Runoff

The delineation of the sub-watersheds and drainage network done in this research is a constructive approximation considering the amount of data available. However, some parts of the generated drainage network and the sub-watersheds do not follow the urban layout. For example, at the edges of the catchment area, there are some parts which are likely to not be part of the catchment of Sembakkam lake because they are divided from it by a big road or railroad. Besides, the drainage network is too coarse. In the current model, a whole sub-watershed concentrates its runoff on a single junction, from which the water is handled by a single conduit. In reality, there is a multitude of small canals handling the runoff. The amount of inlets into Sembakkam lake is a good indicator: In the current model there are four inlets, while in reality there are 22 (Figure 5). The result of using a more dense drainage network will be that the flow will be less concentrated, resulting in less flooding in the catchment. This could change the unrealistic behaviour of the model after a big rainfall event: the constant inflow, storage rise and overflow (Figure 13 to Figure 15). In further research, a map of the drainage network should be used, especially considering the models sensitivity to this input parameter. The sub-watersheds should be delineated based on areas with similar characteristics (e.g. land use) instead of elevation, so that parameters could be estimated more accurately.

The sensitivity analysis carried out within this research showed that the model is highly sensitive to the imperviousness and the Curve Number of sub-watersheds. It was assumed that build up area is completely impervious area, resulting in 10 catchments having a TIA of 100%, which is implausible. By converting this TIA to the EIA, this effect was reduced. However, the EIA was derived from this TIA by an empirical formula based on a study in Denver (US) (Alley & Veenhuis, 1983). It could be better estimated by using high resolution satellite imagery on which roads and roofs could be distinguished. Furthermore, the width of the sub-watersheds was determined in an arbitrary way. Considering the low sensitivity of the model to this parameter, this is neglectable.

As mentioned before, the model is also sensitive to the Curve Number. Choosing the Curve Number method for calculating infiltration was necessary because of data shortage, but using Horton or GA could give more accurate results. More studies confirm their reliability (Mishra et al., 2003; Chandramouli & Natarajan, 2016; Suribabu & Bhaskar, 2014; Viji et al., 2015; Machiwal et al., 2006). Infiltration measurements should be conducted in representative locations in the catchment area to determine the parameters for these methods.

The model is also sensitive to the drainage network dimensions and Manning-n. The used measurements and averages per street type is a good approximation. However, street types on a map Open Street Maps can be different from the street type in reality. Moreover, having one Manning-n for all conduits is a simplification. These conduits are all from the same material, concrete, but there are differences in building quality and the amount of waste clogging the stream (Appendix XV).

Another part of the drainage system, the storage elements representing the upstream lakes, were also simplified by assuming their shape as rectangular. This is a reliable/decent assumption because most lakes are shallow and without much difference in bed level height. Their area does not decrease much when the water level lowers. However, it would be more realistic if the shape would be trapezoidal and have a gradual small decrease in area for lower water levels. It can be expected that this influences the results by having too little evaporation when the lake is full and too much when it is emptying.

### Precipitation

For determining dry, average and wet years, a broader recognised method as the Standard Precipitation Index (SPI) or Standard Precipitation Evapotranspiration Index (SPEI) could have been used. These methods are based on monthly precipitation data and monthly precipitation and temperature data respectively. By fitting the data to a Gamma function, the probability of the rainfall in each month can be calculated, which can be used for calculating the index (McKee et al., 1993). The SPEI differs from the SPI by using the difference between the precipitation and the potential evapotranspiration instead of only the precipitation (Vicente-Serrano et al., 2010). The amount of large rainfall events and the length of the dry period between rainfall events are also indicators for recognising dry and wet years (Knapp, et al., 2015).

### Dry weather inflow

Concerning the sensitivity of the model to this parameter, a time-dependent dry-weather inflow would be preferable instead of the currently used constant inflow. Variation in the dry-weather flow is likely, since there will be less dry-weather flow when there is less water available for consumption during the dry period. Measuring the dry weather flow with good measurement tools every month would make this flow more reliable.

### Evaporation

The evaporation rates of the current model are solely based on the air temperature. However, evaporation is influenced by more parameters such as air humidity, radiation, water vapor pressure and heat fluxes (Vicente-Serrano et al., 2010). This notion, in combination with the underestimated temperatures (Paragraph 10.1.1), creates uncertainty for the evaporation parameter. It is likely that the evaporation in the current model is too low. Consequently, the calibrated lake seepage is too high.

### Human extraction

The method of estimating the human extraction is useful in the absence of data, but there are three assumptions which do not necessarily hold: Firstly, the water usage per capita per day for Jun-Dec is the same as the consumption in the dry period of a wet year. Secondly, all water tanks in Tambaram, Alandur and Sholinganallur are evenly used for water extraction. Srinivasan et al. (2010) found that tankers extract water mostly from outside the city in rural areas. Lastly, the people in the three neighbourhoods get water from inside the neighbourhoods and not from outside. Furthermore, modelling this outflow as a constant outflow is a simplification, but necessary due to limitations in SWMM. Especially in the dry period the extraction will be higher. However, since the model is not sensitive to this outflow, further improvements are not decisive.

### Seepage

Using only two parameters to describe the complex process of interaction between the surface and groundwater of Sembakkam lake is too simplistic. Winter (1999) showed that there are regional, local and climatological factors which influence the amount of seepage. If the regional hydraulic head distribution continuously decreases downstream, there will be ground water flowing in the lake. However, if there is a high permeable zone downstream of the lake, there will be seepage from the lake to the groundwater. More important in the case of Sembakkam lake is the influence of different sedimental layers in the lake bed. Since they are heterogenous and spatially different (east to west is different from north to south), seepage rates and directions will be different across the lake (Appendix VIII). Furthermore, Winter (1999) also explains that the seepage at the shore is higher. Evaporation processes extract extra seepage from the lake because the groundwater table approaches the ground level. Considering these factors, the usage of a simple parameter to model complex processes results in rough estimates of the seepage volume.

The calibration of the seepage using one value is improvable. Moreover, the assumption that the lake is always full is not true. During the field visit on 8 June 2019, the lake level was approximately 0.4 m lower than the maximum level. Data from a longer time frame is essential in order to calibrate the lake's seepage, the more because of the models sensitivity to this parameter. To conclude, the most notable uncertainties and sensitivities are presented in Table 12. The major sensitive parameters are also uncertain.

*Table 12: Major uncertainties and sensitivities of the developed model, comparatively ordered*

| Sensitive parameters | Uncertainty |
|---|---|
| Drainage network dimensions and Manning-n | Drainage network layout and dimensions |
| Percentage impervious area | Effective impervious area |
| Curve number | Curve number |
| Dry weather flow | Dry weather flow |
| Hydraulic conductivity | Seepage |

## 10.2. Reflection on results

### 10.2.1 Current water balance

There are some anomalies in the results regarding the current water balance. In Figure 13 to Figure 15 a higher constant depth, volume and overflow can be observed around day 125 for a wet year and later for the dry and average year. This is due to the high rainfall at this period. Some parts of the catchment area get flooded. After that, this excess of water is discharged at a constant rate, equal to the maximum capacity of the drainage network. However the discharge will be higher in reality, because the catchment area is flooded. The water will find more ways, for example roads, to enter the lake. So, instead of a constant inflow, the inflow is more likely to be higher than this constant value right after the rainfall event and decrease over time to an inflow below this constant value. The depth, storage and overflow at Sembakkam lake will have a similar pattern.

Besides that, the results also indicate that the lake is full and even exceeding its capacity for approximately 200 and 250 days in a dry and average, and wet year respectively, always having a constant base overflow. It is however untrue that the lake is always full and having an overflow, especially during a dry year, which was observed during the field visit. The developed model can be underestimating the evaporation or the seepage. Either way, the average storage volume and the total overflow volume should be lower than indicated by the model. During the wet period of the year, the lake will be full however, leading to the correctly modelled inability to accommodate for big rainfall events.

As discussed in Section 10.1, the results do not come without uncertainty. However, there are still some inferences which can be made about the water balance of Sembakkam lake. The first is that around 80% of the precipitation becomes runoff, while only approximately 5% infiltrates in the ground. Since the catchment of Sembakkam lake is highly urbanised, this result is in accordance with Trudeau and Richardson (2016) who found that urban land use highly influences the amount of runoff. Furthermore this runoff does not stay within the catchment of Sembakkam lake. 68-78% of the inflow in Sembakkam lake is discharged downstream, which could cause considerable stress on the downstream drainage network. The lake is not able to store the runoff as it was 20 years ago (Narasimhan, 2019).

This can be explained by the dry weather inflow which makes up for 26-38% of the inflow. This constant inflow causes the lake to be always at its capacity. Tazyeen and Nyamathi (2015) also observed this effect in a lake in Bangalore (India). There are two options to restore the lakes storage function. The first is to divert this inflow to a separate drainage network like a sewerage system. This would also be beneficial since this inflow contains untreated sewage water and it could be treated in this way. However, building such a network is very costly. The other option is to increase the outflows during dry periods. Since human extraction is a minor outflow, increasing it would contribute little. Increasing the seepage or the overflow are more viable options. The first would also recharge groundwater and is discussed in Section 10.2.4. Increasing the overflow of Sembakkam lake during the dry period could be done by building a sluice.

Recently, a sluice was built at the northern edge (Appendix I, Figure 30) but its bottom is not low enough to discharge when the lake level is lower than its full capacity (Appendix I, Figure 31). Further research should be done on the amount of overflow the downstream drainage network can handle during the dry period. If this is found to be considerable compared to the dry weather inflow of Sembakkam lake, lowering the sluice bottom elevation is recommended.

Furthermore, the dry weather inflow contains untreated sewage water. If this would be treated before it is discharged into the lake, the effect on the lake's water quality could be big because of the substantial contribution of this inflow to the lake's total inflow. Besides that, pollutants in the runoff could also be an important cause for the deteriorating water quality of Sembakkam lake (Kumar et al., 2019). More research should be done on the pollutants in the runoff to verify if this is the case.

Besides the overflow, the seepage at the lake bed and evaporation are major outflows from the lake. Ali et al. (2008) and state that evaporation is often is a large component in the water balance of a surface water body. In another study of Ali et al. (2015), the evaporation losses from a small recharge pond in a semi-arid region in north-India varied between 7.7% and 9.2%. Although the order of magnitude is similar to the evaporation at Sembakkam lake, these results are highly site-specific. For example, the seepage loss in the same study ranged from 83-90%, while Ghosh et al. (2015) found that the infiltration rate of a waterbody in an urban area in Raipur (India) ranged between 3.75 and 4.82 mm/day, which is a third of the hydraulic conductivity of Sembakkam lake.

### 10.2.2 Cisterns

The impact of cisterns on the lake's storage and overflow are minimal. This was unexpected, since temporary storage could decrease the amount of runoff flowing to the lake, mitigating the maximum and total overflow of Sembakkam lake. The small impact of cisterns on the water balance of Sembakkam lake can be explained by a low amount of cisterns per ha (13, 39 and 65 per ha for 5, 15 and 25% of households implementing respectively) and the small storage volume that they provide. There is a total storage volume of 0.010, 0.031 and 0.052 $Mm^3$ for 5%, 15% and 25% of the households implementing this LID respectively. These capacities are too small to accommodate for the large amounts of runoff (Table 9) ranging from 7 to 17 $Mm^3$. The number of residents used to calculate the number of households in the catchment area was derived from a survey from 2011. Considering that the study area is situated in a rapidly urbanising part of Chennai (Devi et al. 2019), the used amount of households can be an underestimation. If this increase could be incorporated in the model, the effect could be higher. It would however probably be a reduction lower than 1%, considering the slope of the line in Figure 16.

Petrucci et al. (2012) also investigated the effect of rain barrels implemented at 30% of the households in Paris. The rain barrels had a neglectable effect on runoff. This inefficiency was linked to the small volume of the tanks. Huang et al. (2018) however found that rain barrels reduced inundation losses in the catchment area critically. This can be attributed to the higher amount of rain barrels per hectare: approximately 1200 $m^3$ of rain barrel storage was implemented in 10 ha of residential area. Huang et al. (2015) used a similar storage volume of rain barrels per hectare as in this study and reports a reduction of approximately 70% in flooding loss. These studies show that rain barrels have good potential for reducing local floods in the catchment area. This research didn't focus on local flooding but on the effect on the lake. So, cisterns are possibly useful LIDs for reducing local floods, but on a catchment scale, their impact is hardly noticeable. Further research could be done on investigating if cisterns decrease the amount of flooding in the catchment area.

Also, the impact of cisterns on the domestic water use is also limited. While its impact can be 5-9% for a domestic use which is regular in this catchment area (Shaban & Sharma, 2007), this form of water supply will be only available during monsoon. During the dry period, when the water is needed most, the cistern can hardly store any water. Moreover, Hofman and Paalman (2014) state that using individual scale rain water harvesting options as a source of drinking water is economically not viable when local water prices are low. However, since water prices can rise high in Chennai and households often need to pay a substantial part of their income to obtain water (Jayashree, 2005), the supply from a cistern could still be cost-effective. Further research could be done on this cost-efficiency of cisterns especially since the water obtained from runoff from roofs is usable for domestic purposes such as washing and bathing after providing pre-treatment (Sanjeeva & Puttaswamaiah, 2018). As water from the well of Sembakkam lake exceeds IS-norms on hardness, iron and lead concentrations (Indian Institute of Technology Madras, 2018c), water from a cistern could be healthier to use than water provided by a tanker. So, cisterns are not a feasible LID to implement in the catchment of Sembakkam lake in order to influence its water balance. There could be potential for them being used as a source for domestic water or as a means to mitigate local flooding, but more research regarding these topics is necessary.

### 10.2.3 Percolation pits

Percolation pits increase the infiltration in the catchment area is by 5-25%. Contrarily, it has little effect on the storage and overflow of the lake. The storage remains the same and the total overflow is reduced by approximately 1% in a scenario where 25% of households implements percolation pits. This can be explained by the small absolute increase of infiltration volume. Because the infiltration in the catchment area was already small (Table 9), the relative change is high. As a comparison, the increase in total infiltration volume is equal to the yearly water demand of 0.5-3 households, assuming a daily demand of 160 l. Subsequently, the increase in infiltration volume has only a small effect on the water balance of Sembakkam Lake and it has little effect on the water scarcity in the catchment area.

The small increase could again be partially the result of an underestimate in the amount of households in the catchment area similarly to the case of the cisterns. As a comparison, Zhu et al. (2019) found that porous pavement, comparable to percolation pits, was able to reduce the peak overflow when applied in higher densities. 160-225 $m^2$ of porous pavement per ha was modelled, while this study used 3800-19,000 $m^2$ of percolation pit per ha. Therefore, would this LID be implemented in bigger amounts than calculated in this study, the impact on the water balance of Sembakkam lake and the reduction of flooding could become more considerable. The implementation in numbers used in this study should only be considered if improving the small infiltration volume in the catchment area is desired. Furthermore, Zhang and Chui (2019) stress the possibility of runoff contaminating the groundwater in areas with shallow water tables. When implementing percolation pits, this effect should be taken into consideration and further research should be done on the quality of the runoff and the necessary treatment before infiltrating the runoff into the soil.

### 10.2.4 Lake dredging

The effect of dredging the lake bed will be major if it increases the hydraulic conductivity of the lake bed. Following the results of this study, the total overflow and storage can even become close to zero when the hydraulic conductivity increases to 15 mm/hr. This is however unlikely to happen since the soil composition of the lake bed consists of other, less impervious layers. The sandy layers are only 0.5 to 1 m thick (Appendix VIII). An impervious layer of bedrock is situated at 3-5 meter below the lake bed, which will block big seepage flows. Also, this study simplified the lake’s interactions with the ground water greatly (Section 10.1.3), making these results unreliable.

Notwithstanding, it can still be inferred that an increase in hydraulic conductivity will increase the seepage and influence the water balance considerably. This increase in the hydraulic conductivity of the lake is likely since the top layers of the lake bed are clayey layers. If these would be removed, more sandy layers would become the top layers. If the hydraulic conductivity would rise to 1.5 mm/hr, the total overflow could decrease by 30-45% and increasing the groundwater recharge with 150-200%. The decrease in discharge could lead to a decrease in storage at Pallikaranai marshland (Figure 4). On the other hand, the drainage network of the downstream parts will be partly relieved, decreasing the probability on flooding. However, the maximum overflow of Sembakkam lake does not change, indicating that big rainfall events can still not be accommodated for, which can put pressure on the downstream drainage network.

This potential increase in groundwater recharge could have different effects. Since there is an impervious layer at 5 m depth, the water table is likely to rise. In the most extreme situation, high water tables can damage structures and properties due to flooding (Zhang & Chui, 2019; Yihdego et al., 2017). Furthermore, Abdalla and Khalil (2018) discovered that the unsafe disposal of sewage, which happens in the catchment of Sembakkam lake, can contaminate the ground water severely when the water table is shallow. So, during monsoon, these effects could happen. Further research should be done on how extra seepage from Sembakkam lake would influence the water table of the surrounding and downstream areas.

During the dry period these effects will be less likely since the water tables in Chennai can drop below 20 m (Srinivasan et al., 2010). In that case, the extra seepage would mean the availability of extra water to pump for domestic purposes. However, due to the unhealthy water quality of the lake, the groundwater could become contaminated. It is therefore important to find solutions to improve the water quality before dredging the lake and increasing the seepage.

# 11. Conclusion

This study aimed to make a hydrological model of the current water balance of Sembakkam lake and to assess its uncertainties. With this model, the quantitative impact on the water balance of the implementation of two LIDs in the catchment area, cisterns and percolation pits, as well as the dredging of the lake bed were calculated. With the results, the impact on the water problems at Sembakkam lake was discussed.

The results concerning the current water balance of Sembakkam lake indicate that the dry weather flow is a major inflow, constituting 26-38% of the total inflow. The remaining inflow is composed of runoff from its catchment and the overflow of upstream lakes. From these inflows, 68-78% is discharged downstream, 12-18% infiltrates at the lake bed, 5-7% evaporates and 1-4% is extracted for human consumption. Furthermore, the lake's storage is at its full capacity throughout the year and is not able to hold the runoff caused by big rainfall events. To restore the lake's storage function, this study recommends to empty the lake during dry season by lowering the weir at the northern edge. This could reduce the flooding downstream and at the borders of the lake. Further research could be done on the effects of this measure downstream during dry and wet season.

After implementing the LIDs, the results show that cisterns hardly have an influence on the water balance of Sembakkam lake. Whereas other studies report their positive influence on local flooding, their influence is not notable on the catchment level. Therefore, cisterns should not be implemented as a means to decrease the amount of runoff. Further research could be done on their influence on local flooding and the feasibility to use them as a source of water supply, since they can provide 5-9% of a yearly household water demand.

Percolation pits increase the infiltration volume in the catchment by 5% and 20-25% for 5% and 25% of the households implementing them respectively. They reduce the total overflow of the lake by 1% when implemented in 25% of the households, but they have no further influence on the water balance. So, as a means to reduce the runoff, percolation pits are not recommended. On the other hand, percolation pits should be implemented when the goal is to improve the infiltration of the catchment area, although the increase in infiltration volume is too small to mitigate the water scarcity during dry season. Moreover, considering other studies and the results from this study, percolation pits have potential to influence the water balance of Sembakkam lake when implemented in higher quantities than done in this study.

In contrast with the modelled LIDs, dredging the lake will influence the water balance considerably. It can lead to a reduction of 30-45% of the overflow volume and an increase of 4 $Mm^3$ per year of groundwater recharge in case the hydraulic conductivity reaches 1.5 mm/hr. This can have considerable effect for water scarcity and flooding downstream and at the surroundings of the lake. The decrease in total overflow volume can relieve the downstream drainage network. An increase in groundwater recharge can raise the groundwater table, which can cause flooding during monsoon. During the dry season however, downstream households can profit from the extra groundwater. Dredging the lake is therefore recommended after a solution is implemented for improving the lake's water quality and after investigating the effects on the ground- and surface water of the downstream area.

These results of the model concerning the infiltration and overflow of Sembakkam lake come however with uncertainty. The major uncertain input data and also sensitive parameters of the model are the drainage network, the Curve Numbers of the sub-watersheds, the effective impervious area, the hydraulic conductivity and the dry weather flow. Besides that, only arbitrary calibration data of the lake's overflow was available. However, this study used the available data to approach the water balance of Sembakkam lake as good as is currently possible. To improve the reliability of the results, further research and data acquisition could be done on these parameters.

# 12. References


Abdalla, F., & Khalil, R. (2018). Potential effects of groundwater and surface water contamination in an urban area, Qus City, Upper Egypt. *Journal of African Earth Sciences*, 141: 164-178.

Ali, S., Ghosh, N., & Singh, R. (2008). Evaluating best evaporation estimate model for water surface evaporation in semi-arid region, India. *Hydrological Processes*, 22: 1093-1106.

Ali, S., Singh, R., & Sethy, B. (2015). Field Application of a Dynamic Potential Groundwater Recharge Simulation Model For Small Recharge Ponds. *Applied Engineering in Agriculture*, 31(2): 267-281.

Alley, W., & Veenhuis, J. (1983). Effective Impervious Area in Urban Modelling. *Journal of Hydraulic Engineering*, 109(2): 313-319.

Anand, P. (2001). Water scarcity in Chennai, India: Institutions, entitlements and aspects of inequality in access. *WIDER Discussion Paper*. Helsinki: The United Nations University World Institute for Development Economics Research.

Arunprakash, M., Giridharan, L., Krishnamurthy, R., & Jayaprakash, M. (2013). Impact of urbanization in groundwater of south Chennai City, Tamil Nadu, India. *Environmental Earth Sciences*, 71(2): 947-957.

Bisht, D., Chatterjee, C., Kalakoti, S., Upadhyay, P., Sahoo, M., & Panda, A. (2016). Modeling urban floods and drainage using SWMM and MIKE URBAN: a case study. *Natural Hazards*, 84: 749-776.

Booij, M. (2017). *Waterbeheer*. Enschede, Netherlands: University of Twente.

Chandramouli, S., & Natarajan, N. (2016). A Comparative Study on the Infiltration Characteristics of Soils in Srikakulam District, Andhra Pradesh, India. *Asian Journal of Water, Environment and Pollution*, 13: 73-79.

Chennai Metropolitan Development Authority. (2008a). *Second Master Plan For Chennai Metropolitan Area, 2026, Volume I, Vision, Strategies and Action Plans*. Chennai: Chennai Metropolitan Development Authority.

Chennai Metropolitan Development Authority. (2008b). *Second Master Plan For Chennai Metropolitan Area, 2026, Volume III, Sectoral Background*. Chennai, India: Chennai Metropolitan Development Authority.

Chennai Metropolitan Water Supply and Sewerage Board. (2012, January). *Orientation To Residents Welfare Association On Consumer Rights*. Retrieved from https://www.slideserve.com/Patman/orientation-to-residents-welfare-association-on-consumer-rights

Chennakrishnan, C., Stephen, A., Manju, T., & Raveen, R. (2008). Water quality status of three vulnerable freshwater lakes of suburban Chennai, India. *Indian Journal of Environment and Ecoplanning*, 15(3): 591-596.

Deccan Chronicle. (2018, May 1). *Restoration of Sembakkam lake work to start soon*. Retrieved from https://www.deccanchronicle.com/nation/in-other-news/010518/restoration-of-sembakkam-lake-work-to-start-soon.html

Destination360. (2006). *India*. Retrieved from http://www.destination360.com/asia/india

Devi, N., Sridharan, B., & Kuiry, S. (2019). Impact of urban sprawl on future flooding in Chennai city, India. *Journal of Hydrology*, 574: 486-496.

Digital Globe Quickbird Imagery. (n.d.). Digital Elevation Map, 10m resolution.

Directorate of Census Operations Tamil Nadu. (2011). *Census of India, Series 34 part XII-A, District Census Handbook Kancheepuram, Village and Town Directory.* Chennai: Ministry of Home Affairs.

Eckart, K., McPhee, Z., & Bolisetti, T. (2018). Multiobjective optimization of low impact development stormwater controls. *Journal of Hydrology*, 562: 564-576.

Express News Service. (2017, October 21). *State has lowest household size*. Retrieved from The New Indian Express: http://www.newindianexpress.com/cities/chennai/2017/oct/21/state-has-lowest-household-size-1679006.html

Ghosh, N., Kumar, S., Grutzmacher, G., Ahmed, S., Singh, S., Sprenger, C., . . . Arora, T. (2015). Semi-Analytical Model for Estimation of Unsteady Seepage from a Large Water Body Influenced by Variable Flows. *Water Resources Management*, 29(9): 3111-3129.

Google Maps. (2019). Satellite Images of Chennai.

Gowri, V., Ramachandran, S., Ramesh, R., Pramiladevi, I., & Krishnaveni, K. (2007). Application of GIS in the study of mass transport of pollutants by Adyar and Cooum Rivers in Chennai, Tamilnadu. *Environmental Monitoring and Assessment*, 138: 41-49.

Hargreaves, G., ASCE, F., & Allen, R. (2003). History and Evaluation of Hargreaves Evapotranspiration Equation. *Journal of Irrigation and Drainage Engineering*, 129(1): 53-63.

Hofman, J., & Paalman, M. (2014). *Rainwater harvesting, a sustainable solution for urban climate adaptation?* Nieuwegein, Netherlands: KWR Watercycle Research Institute.

Huang, C., Hsu, N., Liu, H., & Huang, Y. (2018). Optimization of low impact development layout designs for megacity flood mitigation. *Journal of Hydrology*, 564: 542-558.

Huang, C., Hsu, N., Wei, C., & Luo, W. (2015). Optimal Spatial Design of Capacity and Quantity of Rainwater Harvesting Systems for Urban Flood Mitigation. *Water*, 7: 5173-5202.

Indian Institute of Technology Madras. (2018a). *Assessment and Restoration of Sembakkam Lake, Quarterly Report I: Preleminary Technical Assessment Report on Sembakkam Lake.* Chennai: Unpublished report by Indian Institute of Technology Madras, Department of Civil Engineering, Environment and Water Resources Engineering Division.

Indian Institute of Technology Madras. (2018b). *Assessment and Restoration of Sembakkam Lake, Quarterly Report II.* Chennai: Unpublished report by Environment and Water Resources Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras.

Indian Institute of Technology Madras. (2018c). *Assessment and Restoration of Sembakkam Lake, Quarterly Report III.* Chennai: Unpublished report by Indian Institute of Technology Madras, Department of Civil Engineering, Environment and Water Resources Engineering Division.

Indian Institute of Technology Madras. (2018d). Data acquisitioned by expert team working on Sembakkam lake.

Indian Meteorological Department. (1969-2016). Precipitation and temperature data.

Innes, G. (1980). *Comparison of infiltration models of disturbed soils using parameter optimization.* Knoxville: Unpublished MS thesis, University of Tennessee.

Jain, G., Agrawal, R., Bhanderi, R., Jayaprasad, P., Patel, J., Agnihotri, P., & Samtani, B. (2016). Estimation of sub-catchment area parameters for Storm Water Management Model (SWMM) using geo-informatics. *Geocarto International*, 31(4): 462-476.

Jayashree, K. (2005). Water Pricing - water Economics of Chennai City (India). *Paper presented at second international Yellow River form on keeping healthy life of the river* (pp. 340-343). Chennai, India: Yellow River Conservancy Press, Chengdong Lu, Zhengzhou.

Ji, S., & Qiuwen, Z. (2015). A GIS-based Subcatchments Division Approach for SWMM. *The Open Civil Engineering Journal*, 9: 515-521.

Knapp, A., Hoover, D., Wilcox, K., Avolio, M., Koerner, S., Pierre, K. L., . . . Smith, M. (2015). Characterizing differences in precipitation regimes of extreme wet and dry years: implications for climate change experiments. *Global Change Biology*, 21: 2624–2633.

Kumar, S., Kaushal, D., & Gosain, A. (2019). Evaluation of evolutionary algorithms for the optimization of storm water drainage network for an urbanized area. *Acta Geophysica*, 67: 149-165.

Kumar, S., Kazmi, A., Ghosh, N., Kumar, V., & Rajpal, A. (2019). Urban stormwater runoff treatment of Nainital Lake's catchment: an application of ballasted sand flocculation technology . *Water Science and Technology-Water Supply*, 19(4): 1017-1025.

Leary, N., Conde, C., Kulkarni, J., Pulhin, J., & Nyong, A. (2008). *Climate Change and Vulnerability.* London: Earthscan.

Li, C., Liu, M., Hu, Y., Gong, J., & Xu, Y. (2016). Modeling the Quality and Quantity of Runoff in a Highly Urbanized Catchment Using Storm Water Management Model. *Polish Journal of Environmental Studies*, 4: 1573-1581.

Li, C., Wang, W., Xiong, J., & Chen, P. (2014). Sensitivity Analysis for Urban Drainage Modeling Using Mutual Information. *Entropy*, 16: 5738-5752.

Liu, Y., Cibin, R., Bralts, V., Chaubey, I., Bowling, L., & Engel, B. (2016). Optimal selection and placement of BMPs and LID practices with a rainfall-runoff model. *Environmental Modelling & Software*, 80: 281-296.

Machiwal, D., Jha, M., & Mal, B. (2006). Modelling Infiltration and quantifying Spatial Soil Variability in a Wasteland of Kharagpur, India. *Biosystems Engineering*, 95(4): 569-582.

Martin-Mikle, C., Beurs, K. d., Julian, J., & Mayer, P. (2015). Identifying priority sites for low impact development (LID) in a mixed-use watershed. *Landscape and Urban Planning*, 140: 29-41.

McKee, T., Doesken, N., & Kleist, J. (1993). The Relationship of Drought Frequency and Duration To Time Scales. *Paper presented at: Eighth Conference on Applied Climatology, Anaheim. California.* Fort Collins: Colorado State University Department of Atmospheric Science.

McMillan, H., Jackson, B., Clark, M., Kavetski, D., & Woods, R. (2011). Rainfall uncertainty in hydrological modelling: An evaluation of multiplicative error models. *Journal of Hydrology*, 400: 83-94.

Mishra, S., Tyagi, J., & Singh, V. (2003). Comparison of infiltration models. *Hydrological Processes*, 17: 2629-2652.

Narasimhan, B. (2019). Personal communication with prof. B. Narasimhan.

Natarajan, P., & Kalloikar, S. (2017). Urban resilient integrated water management pathways, to achieve sustainable water resources development in Chennai metropolitan city, Tamil Nadu, India. *Water Practice and Technology*, 12: 564-575.

National Remote Sensing Centre. (2004). Land use map, 50m resolution.

New York Times. (2015, July 29). *India Will Be Most Populous Country Sooner Than Thought, U.N. Says*. Retrieved from https://www.nytimes.com/2015/07/30/world/asia/india-will-be-most-populous-country-sooner-than-thought-un-says.html

Nigam, U. P. (2005). *Status of Water Supply, Sanitation and Solid Waste Management in Urban Areas.* New Delhi: National Institute of Urban Affairs.

Open Street Maps. (2019). *Map of Chennai*.

Palla, A., & Gnecco, I. (2015). Hydrologic modeling of Low Impact Development systems at the urban catchment scale. *Journal of Hydrology*, 528: 361-368.

Petrucci, G., Deroubaix, J., Gouvello, B. d., Deutch, J., Bompard, P., & Tassin, B. (2012). Rainwater harvesting to control stormwater runoff in suburban areas. An experimental case-study. *Urban Water Journal*, 9(1): 45-55.

Rain Centre. (2017, April 3). *Rainwater Harvesting in Urban Areas.* Retrieved from Akash Ganga Trust: http://raincentre.net/booklets_posters.php

Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., . . . Corfee-Morlot, J. (2011). An assessment of the potential impact of climate change on flood risk in Mumbai. *Climatic Change*, 104: 139-167.

Rossman, L. (2015). Storm Water Management Model User's Manual Version 5.1. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

Sahoo, S., & Sreeja, P. (2014). A methodology for determining runoff based on imperviousness in an ungauged peri-urban catchment. *Urban Water Journal*, 11(1): 42-54.

Sanjeeva, A., & Puttaswamaiah, S. (2018). Influence of Atmospheric Deposition and Roof Materials on Harvested Rainwater Quality. *Journal of Environmental Engineering*, 144(12).

Sargent, R. (1998). Verification and Validation of Simulation Models. *Paper presented at Winter Simulation Conference* (pp. 121-130). Syracuse, New York, U.S.A: Syracuse University.

Shaban, A., & Sharma, R. (2007). Water Consumption Patterns in Domestic Households in Major Cities. *Economic and Political Weekly*, 2190-2197.

Singh, R. (2004). Assessment of wastewater generation, management pattern and its re-use potential in urban India. *Paper presented at International Symposium on Wastewater Re-Use and Groundwater Quality, Sapporo, Japan.* Wallingford, England: International Association Hydrological Sciences, Institute Of Hydrology.

Srinivasan, V., Gorelick, S., & Goulder, L. (2010). A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India. *Water Resources Research*, 1-19.

Sun, Y., Gao, C., Li, J., Wang, R., & Liu, J. (2019). Evaluating urban heat island intensity and its associated determinants of towns and cities continuum in the Yangtze River Delta Urban Agglomerations. *Sustainable Cities and Society*, 50.

Suribabu, C., & Bhaskar, J. (2014). Evaluation of urban growth effects on surface runoff using SCS-CN method and Green-Ampt infiltration model. *Earth Science Informatics*, 8(3): 609-626.

Suriya, S., & Mudgal, B. (2012). Impact of urbanization on flooding: The Thirusoolam sub watershed – A case study. *Journal of Hydrology*, 412-413: 210-219.

Suriya, S., Mudgal, B., & Nelliyat, P. (2011). Flood damage assessment of an urban area in Chennai, India, part I: methodology. *Natural Hazards*, 62: 149–167.

Tamil Nadu Agricultural University. (2004). *Soil Map Tamil Nadu.*

Tank Memoir. (n.d.). Capacity of Sembakkam, Chitlapakkam, Selaiyur and Rajakilpakkam lake.

Tazyeen, S., & Nyamathi, S. (2015). Flood Routing in the Catchment of Urbanized Lakes. *Aquatic Procedia*, 4: 1173-1180.

The Guardian. (2016, April 27). *India's drought migrants head to cities in desperate search for water*. Retrieved from https://www.theguardian.com/global-development/2016/apr/27/india-drought-migrants-head-to-cities-in-desperate-search-for-water

The Guardian. (2017, August 31). *South Asia floods kill 1,200 and shut 1.8 million children out of school*. Retrieved from https://www.theguardian.com/world/2017/aug/30/mumbai-paralysed-by-floods-as-india-and-region-hit-by-worst-monsoon-rains-in-years

The Indian Express. (2015, December 4). *Chennai floods: Decoding the city's worst rains in 100 years*. Retrieved from https://indianexpress.com/article/india/india-news-india/chennai-floods-rains-jayalalithaa-imd-reasons-rescue-news-updates/

The Times of India. (2017, January 4). *Chennai: Sembakkam lake, a de facto dumping ground, to be restored*. Retrieved from https://timesofindia.indiatimes.com/city/chennai/chennai-sembakkam-lake-a-de-facto-dumping-ground-to-be-restored/articleshow/56326254.cms

Trudeau, M., & Richardson, M. (2016). Empirical assessment of effects of urbanization on event flow hydrology in watersheds of Canada's Great Lakes-St Lawrence basin . *Journal of Hydrology*, 541: 1456-1474.

Tsai, L., Chen, C., Fan, C., & Lin, J. (2017). Using the HSPF and SWMM Models in a High Pervious Watershed and Estimating Their Parameter Sensitivity. *Water*, 9(10): 780.

UNESCO. (2019). *The United Nations World Water Development Report 2019: Leaving no one behind.* Place de Fontenoy, France: United Nations Educational, Scientific and Cultural Organization.

Vemula, S., Raju, K., Veena, S., & Kumar, A. (2019). Urban floods in Hyderabad, India, under present and future rainfall scenarios: a case study. *Natural Hazards*, 95: 637–655.

Ven, F. v. (2016). *Water Management in Urban Areas, Lecture Notes.* Delft, Netherlands: TU Delft.

Vicente-Serrano, S., Begueria, S., & J.I.López-Moreno. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23: 1696-1718.

Viji, R., Prasanna, P., & Ilangovan, R. (2015). Modified SCS-CN and Green-Ampt Methods in Surface Runoff Modelling for the Kundahpallam Watershed, Nilgiris, Western Ghats, India. *Aquatic Procedia*, 4: 677-684.

Viswanathan, P. (2018, May 15). *Chitlapakkam residents seek solutions for flooding and water crisis*. Retrieved from Citizen Matters: http://chennai.citizenmatters.in/citizens-highlight-civic-issues-amid-sembakkam-lake-restoration-4763

Winter, T. (1999). Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal*, 7: 28–45.

World Bank Group. (2015, September 24). *Leveraging Urbanization in India*. Retrieved from http://www.worldbank.org/en/country/india/brief/leveraging-urbanization-india

Xu, T., Engel, B., Shi, X., Leng, L., Jia, H., Yu, S., & Liu, Y. (2018). Marginal-cost-based greedy strategy (MCGS): Fast and reliable optimization of low impact development (LID) layout. *Science of the Total Environment*, 640-641: 570-580.

Yang, Y., & Chui, T. (2018). Integrated hydro-environmental impact assessment and alternative selection of low impact development practices in small urban catchments. *Journal of Environmental Management*, 223: 324-337.

Yihdego, Y., Danis, C., & Paffard, A. (2017). Groundwater Engineering in an Environmentally Sensitive Urban Area: Assessment, Landuse Change/Infrastructure Impacts and MitigationMeasures. *Hydrology*, 4(3): article 37.

Zhang, K., & Chui, T. (2019). Effect of Spatial Allocation of Green Infrastructure on Surface-Subsurface Hydrology in Shallow Groundwater Environment. *Paper presented at World Environmental and Water Resources Congress 2019* (pp. 147-152). Pittsburgh, USA: University of Hong Kong.

Zhang, K., Chui, T., & Yang, Y. (2018). Simulating the hydrological performance of low impact development in shallow groundwater via a modified SWMM. *Journal of Hydrology*, 566: 313-331.

Zhu, Z., Chen, Z., Chen, X., & Yu, G. (2019). An assessment of the hydrologic effectiveness of low impact development (LID) practices for managing runoff with different objectives. *Journal of Environmental Management*, 231: 504-514.

# 13. Appendices

## Appendix I: Pictures Sembakkam lake

*Figure 25: Sembakkam lake, partially covered by hyacinth, view from the well in the northwest. The concrete structure is the cover of the well*

*Figure 26: Sembakkam lake, seen from the eastern embankment*


*Figure 27: Inlet 5 and 6*


*Figure 28: Cleared dumpyard*

*Figure 29: Weir: situated at the northern edge of the lake*

*Figure 30: Sluice, situation besides the weir at the northern edge of the lake, seen from the land side*

*Figure 31: The sluice at the northern edge, seen from the lake's side*

# Appendix II:DEM Manipulation

This study manipulated the DEM by lowering the main roads by 1 m and decreasing a buffer of 10 m width by 0.5 around it (Ji & Qiuwen, 2015). This manipulation process is displayed in Figure 32. Secondary roads were only lowered by 0.5 m without a buffer. Besides that, in order to have drainage points at the real locations, the elevation of locations of the inlets of Sembakkam lake was changed in the same way as main roads were manipulated.

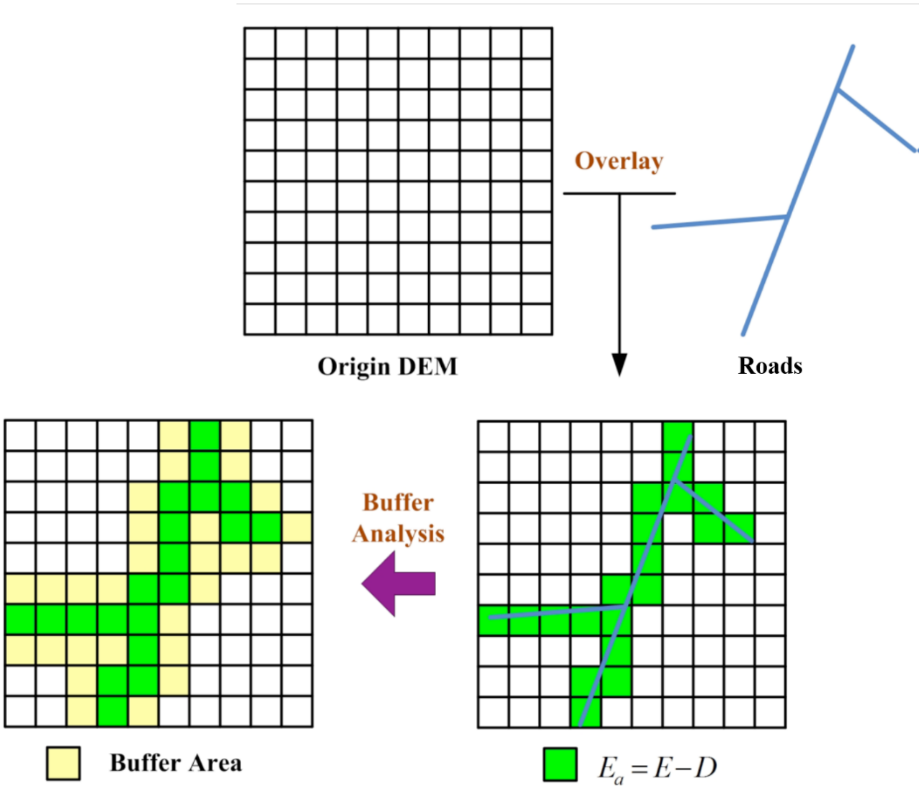


*Figure 32: Visualisation of DEM manipulation. Green raster cells are lowered by 1 m (with $E_a$ the manipulated elevation, E the original elevation and D 1 m) and the buffer area by 0.5 m (Ji & Qiuwen, 2015)*

# Appendix III: Parameters of sub-watersheds representing the lakes

*Table 13: Parameters sub-watersheds representing the lake area*

| Parameter | Value |
|---|---|
| Width | Area(m2)/1 |
| Slope | 10% |
| Percentage impervious area | 100% |
| Manning-n impervious area | 0.001 |
| Percentage of Impervious area without depression storage | 100% |

## Appendix IV: Contour map Sembakkam lake

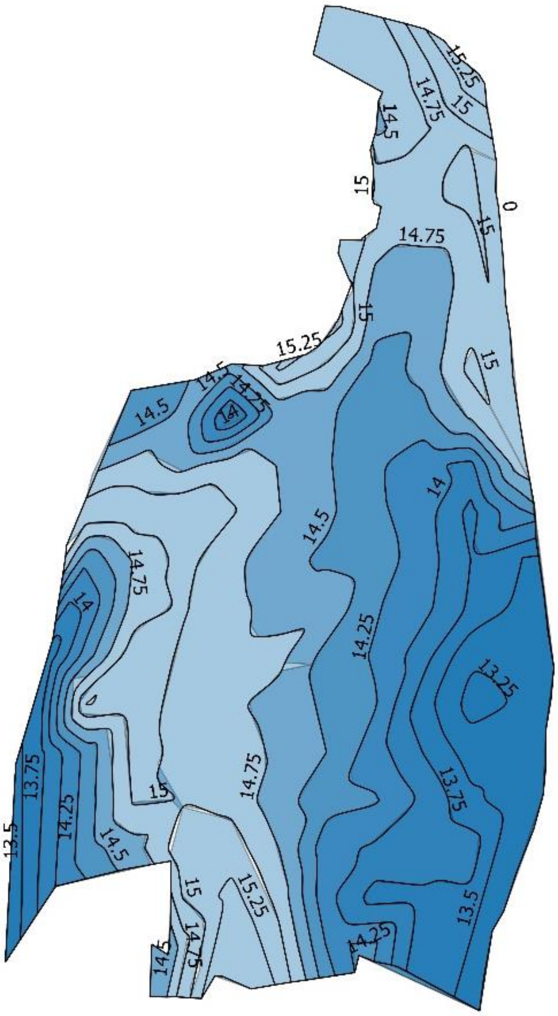


*Figure 33: Elevation of bed level Sembakkam lake (own figure)*

# Appendix V: Curve numbers per land use

*Table 14: Curve numbers per land use (Devi et al., 2019)*

| Land Use | Curve Number |
|---|---|
| Build-up | 93 |
| Agricultural | 79 |
| Fallow | 88 |
| Scrub | 67 |
| Water tanks | 100 |

# Appendix VI: Dry weather inflow for six major inlets

*Table 15: Dry weather inflow into Sembakkam lake*

| Inlet | Inflow (MLD) |
|---|---|
| Inlet 4 | 0.08 |
| Inlet 14 | 2.039 |
| Inlet 16 | 3.566 |
| Inlet 17 | 2.141 |
| Inlet 18 | 0.929 |
| Inlet 20 | 0.025 |
| Total | 8.78 |

## Appendix VII: Neighbourhoods around Sembakkam lake

Figure 34 shows three neighbourhoods surrounding Sembakkam lake. Table 16 presents the population and amount of water tanks for each of these neighbourhoods.

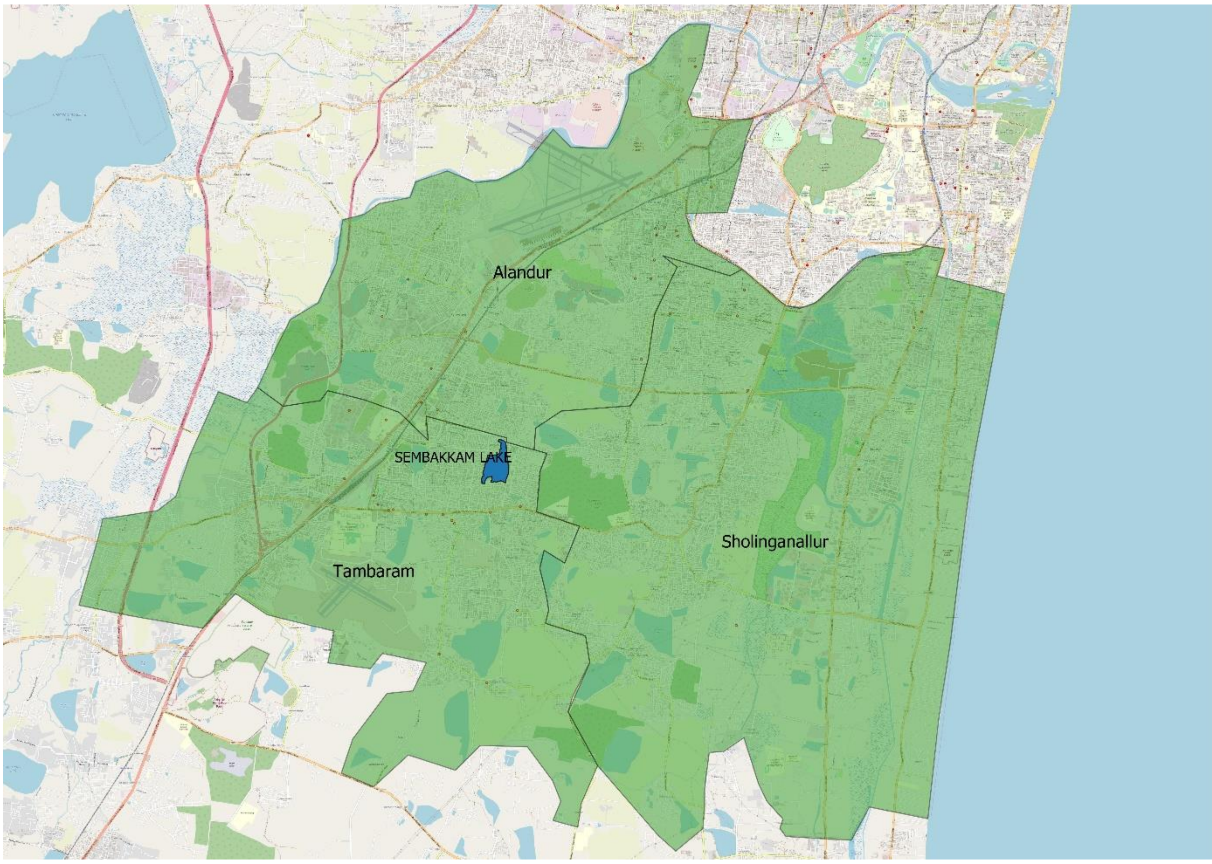


*Figure 34: Neighbourhoods around Sembakkam lake (own figure, based on (Open Street Maps, 2019))*

*Table 16: Population and amount of water tanks of surrounding districts of Sembakkam lake (Directorate of Census Operations Tamil Nadu, 2011)*

| Taluk | Population in urban areas | water tanks |
|---|---|---|
| Tambaram | 356322 | 18 |
| Alandur | 642237 | 7 |
| Shollinganauller | 492901 | 10 |
| Total | 1491460 | 35 |

# Appendix VIII: Lake bed soil profile

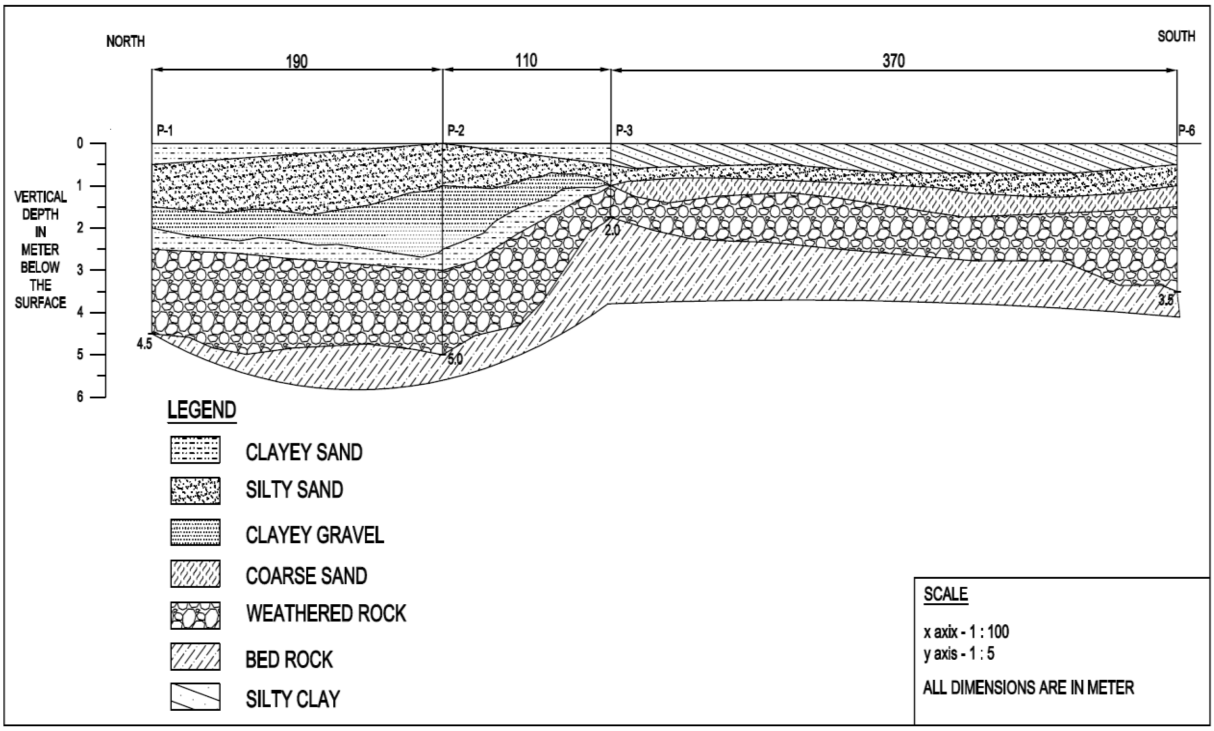


*Figure 35: Lake bed soil variation from north to south (Indian Institute of Technology, 2018b)*

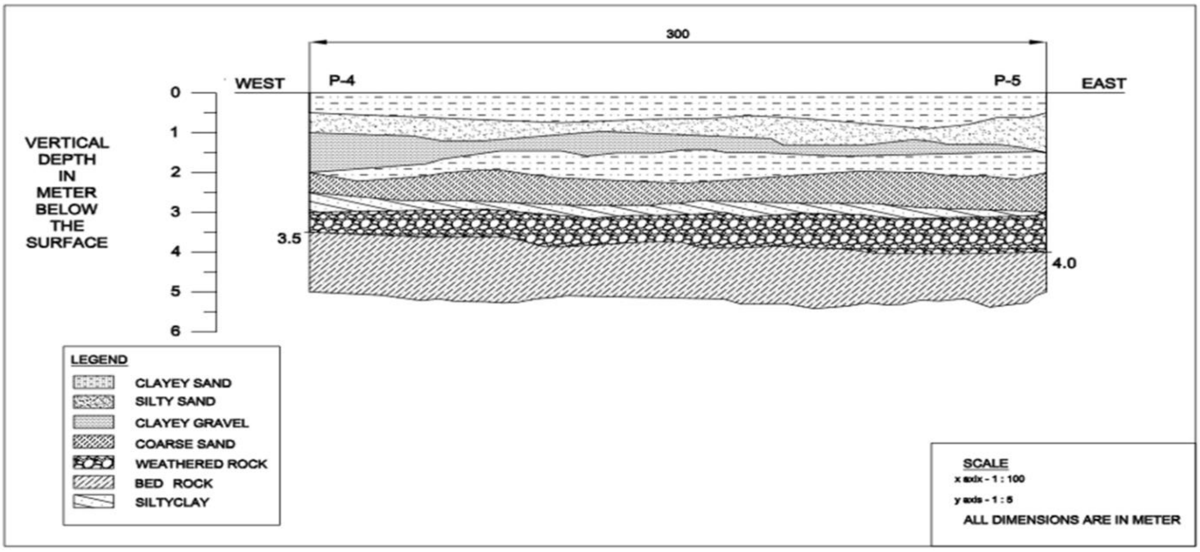


*Figure 36: Lake bed soil variation from west to east (Indian Institute of Technology, 2018b)*

# Appendix IX: Derivation of lake bed hydraulic conductivity after dredging

Deriving from appendix IV dredging up to 1 meter would mean that silty sand, coarse sand or clayey gravel layers can be reached. Their hydraulic conductivities can be found in Table 17. The lower value is 1.5 mm/hr. As a maximum of approximately 10% of the lake bed is going to be dredged to 1 meter (Figure 33), the upper value was taken as 15.5 was taken as intermediate value.

*Table 17: Hydraulic conductivities of different soil types (Rossman, 2015)*

| Soil type in lake bed | Soil type used from manual | Hydraulic conductivity (mm/hr) |
|---|---|---|
| Silty sand | Silt loam | 6.6 |
| Coarse sand | Sand | 120.4 |
| Clayey gravel | Sandy clay loam | 1.5 |

# Appendix X: Detailed data on impact LIDs

*Table 18: Detailed results for the impact on the water balance of cisterns, percolation pits and the combination of them*

| LID | Year | Households implemented (%) | Infiltration catchment area | (Mm3) | Average storage | (Mm3) | Maximum outflow | (m3/s) | Total Outflow | (Mm3) |
|---|---|---|---|---|---|---|---|---|---|---|
| Current situation | Dry | - | 0.508 | | 0.278 | | 3.93 | | 5.659 | |
| | Average | - | 0.865 | | 0.279 | | 4.86 | | 7.126 | |
| | Wet | - | 0.843 | | 0.280 | | 5.85 | | 9.366 | |
| Rain Barrels | Dry | 5% | 0.504 | -0.82% | 0.278 | 0.00% | 3.93 | 0.00% | 5.658 | -0.02% |
| | | 15% | 0.504 | -0.92% | 0.278 | 0.00% | 3.93 | -0.03% | 5.656 | -0.06% |
| | | 25% | 0.503 | -1.02% | 0.278 | 0.00% | 3.93 | -0.03% | 5.653 | -0.10% |
| | Average | 5% | 0.865 | -0.04% | 0.279 | 0.00% | 4.86 | 0.00% | 7.124 | -0.03% |
| | | 15% | 0.864 | -0.11% | 0.279 | 0.00% | 4.86 | 0.00% | 7.120 | -0.08% |
| | | 25% | 0.863 | -0.25% | 0.279 | 0.00% | 4.86 | 0.00% | 7.117 | -0.13% |
| | Wet | 5% | 0.843 | -0.03% | 0.280 | 0.00% | 5.85 | 0.00% | 9.364 | -0.02% |
| | | 15% | 0.842 | -0.14% | 0.280 | 0.00% | 5.85 | 0.00% | 9.361 | -0.06% |
| | | 25% | 0.841 | -0.24% | 0.280 | 0.00% | 5.85 | 0.00% | 9.357 | -0.09% |
| Percolation Pit | Dry | 5% | 0.536 | 5.37% | 0.278 | 0.00% | 3.92 | -0.23% | 5.646 | -0.23% |
| | | 15% | 0.585 | 15.04% | 0.278 | -0.01% | 3.92 | -0.20% | 5.622 | -0.65% |
| | | 25% | 0.631 | 24.20% | 0.278 | -0.02% | 3.92 | -0.25% | 5.594 | -1.14% |
| | Average | 5% | 0.899 | 3.95% | 0.279 | 0.00% | 4.83 | -0.64% | 7.108 | -0.25% |
| | | 15% | 0.968 | 11.87% | 0.279 | -0.01% | 4.83 | -0.64% | 7.074 | -0.73% |
| | | 25% | 1.030 | 19.08% | 0.279 | -0.02% | 4.83 | -0.62% | 7.044 | -1.15% |
| | Wet | 5% | 0.880 | 4.42% | 0.280 | 0.00% | 5.84 | -0.17% | 9.352 | -0.15% |
| | | 15% | 0.951 | 12.75% | 0.280 | -0.01% | 5.84 | -0.17% | 9.327 | -0.42% |
| | | 25% | 1.016 | 20.49% | 0.280 | -0.01% | 5.84 | -0.19% | 9.303 | -0.68% |
| Combination | Dry | 5% | 0.535 | 5.29% | 0.278 | 0.00% | 3.92 | -0.23% | 5.645 | -0.25% |
| | | 15% | 0.583 | 14.77% | 0.278 | -0.01% | 3.92 | -0.23% | 5.619 | -0.70% |
| | | 25% | 0.629 | 23.72% | 0.278 | -0.02% | 3.92 | -0.28% | 5.586 | -1.28% |
| | Average | 5% | 0.899 | 3.89% | 0.279 | -0.01% | 4.83 | -0.64% | 7.106 | -0.28% |
| | | 15% | 0.966 | 11.62% | 0.279 | -0.01% | 4.83 | -0.64% | 7.069 | -0.80% |
| | | 25% | 1.026 | 18.56% | 0.279 | -0.02% | 4.83 | -0.64% | 7.037 | -1.25% |
| | Wet | 5% | 0.880 | 4.36% | 0.280 | 0.00% | 5.84 | -0.17% | 9.350 | -0.17% |
| | | 15% | 0.949 | 12.51% | 0.280 | -0.01% | 5.84 | -0.17% | 9.322 | -0.47% |
| | | 25% | 1.012 | 20.05% | 0.280 | -0.01% | 5.84 | -0.19% | 9.295 | -0.76% |

*Table 19: Detailed results for the impact of dredging the lake on the water balance*

| | Year | Hydraulic conductivity (mm/hr) | Seepage volume (Mm3) | | Average storage (Mm3) | | Maximum outflow (m3/s) | | Total Outflow (Mm3) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Dredging | Dry | 0.5 | 1.497 | 0% | 0.419 | 51% | 4.00 | 2% | 5.534 | -2% |
| | | 1.5 | 3.825 | 156% | 0.255 | -8% | 3.90 | -1% | 3.218 | -43% |
| | | 5 | 7.401 | 394% | 0.071 | -75% | 1.50 | -62% | 0.152 | -97% |
| | | 15 | 7.734 | 417% | 0.018 | -94% | 0.00 | -100% | 0.000 | -100% |
| | Average | 0.5 | 1.462 | 0% | 0.429 | 54% | 5.03 | 3% | 7.001 | -2% |
| | | 1.5 | 4.094 | 180% | 0.278 | 0% | 4.92 | 1% | 4.360 | -39% |
| | | 5 | 8.481 | 480% | 0.103 | -63% | 2.76 | -43% | 0.360 | -95% |
| | | 15 | 9.163 | 527% | 0.022 | -92% | 0.00 | -100% | 0.000 | -100% |
| | Wet | 0.5 | 1.440 | 0% | 0.431 | 54% | 6.05 | 3% | 9.244 | -1% |
| | | 1.5 | 4.080 | 183% | 0.323 | 15% | 5.94 | 1% | 6.589 | -30% |
| | | 5 | 10.081 | 600% | 0.160 | -43% | 3.66 | -37% | 1.059 | -89% |
| | | 15 | 11.401 | 692% | 0.031 | -89% | 0.00 | -100% | 0.000 | -100% |

# Appendix XI: Impact cisterns on water supply households

*Table 20: The water supply from a cistern compared with the dry seasonal, wet seasonal and yearly water demand of households*

| Year | Scenario | Period | Water need ($10^3$ $m^3$) | Water supply from cistern ($10^3$ $m^3$) | Percentage supplied |
|---|---|---|---|---|---|
| Dry | 5% | Jan-Jun | 32.9 | 0.4 | 1% |
| | | Jul-Dec | 34.0 | 2.9 | 8% |
| | | Full year | 66.9 | 3.3 | 5% |
| | 15% | Jan-Jun | 98.7 | 1.2 | 1% |
| | | Jul-Dec | 102.0 | 9.4 | 9% |
| | | Full year | 200.7 | 10.6 | 5% |
| | 25% | Jan-Jun | 164.5 | 1.8 | 1% |
| | | Jul-Dec | 170.0 | 14.8 | 9% |
| | | Full year | 334.6 | 16.7 | 5% |
| Average | 5% | Jan-Jun | 32.9 | 0.9 | 3% |
| | | Jul-Dec | 34.0 | 4.1 | 12% |
| | | Full year | 66.9 | 5.0 | 7% |
| | 15% | Jan-Jun | 98.7 | 3.0 | 3% |
| | | Jul-Dec | 102.0 | 13.3 | 13% |
| | | Full year | 200.7 | 16.2 | 8% |
| | 25% | Jan-Jun | 164.5 | 4.6 | 3% |
| | | Jul-Dec | 170.0 | 20.9 | 12% |
| | | Full year | 334.6 | 25.5 | 8% |
| Wet | 5% | Jan-Jun | 32.9 | 1.2 | 4% |
| | | Jul-Dec | 34.0 | 4.4 | 13% |
| | | Full year | 66.9 | 5.6 | 8% |
| | 15% | Jan-Jun | 98.7 | 4.1 | 4% |
| | | Jul-Dec | 102.0 | 14.4 | 14% |
| | | Full year | 200.7 | 18.4 | 9% |
| | 25% | Jan-Jun | 164.5 | 6.4 | 4% |
| | | Jul-Dec | 170.0 | 22.7 | 13% |
| | | Full year | 334.6 | 29.1 | 9% |

## Appendix XII: Increase in lake seepage for different hydraulic conductivities

*Table 21: Seepage volumes for different hydraulic conductivities and their relative increase*

| Year | Hydraulic conductivity (mm/hr) | Seepage ($Mm^3$) | Difference |
|---|---|---|---|
| Dry | 0.5 | 1.50 | 0% |
| | 1.5 | 3.83 | 156% |
| | 5 | 7.40 | 394% |
| | 15 | 7.73 | 417% |
| Average | 0.5 | 1.46 | 0% |
| | 1.5 | 4.09 | 180% |
| | 5 | 8.48 | 480% |
| | 15 | 9.16 | 527% |
| Wet | 0.5 | 1.44 | 0% |
| | 1.5 | 4.08 | 183% |
| | 5 | 10.08 | 600% |
| | 15 | 11.40 | 692% |

# Appendix XIII: Overview input data

*Table 22: Overview of all input data*

| Data source | Source | Description |
|---|---|---|
| Rainfall data | Self-Recording Rain Gage of (Indian Meteorological Department, 1969-2016) | Hourly rainfall data from 1969 to 2016 at Meenambakkam (7 km from site) |
| Temperature data | (Indian Meteorological Department, 1969-2016) | Daily minimum and maximum temperature at 12.5 , 79.5 (85 km from site) |
| Digital Elevation Map (DEM) | (Digital Globe Quickbird Imagery, n.d.) | Raster map of elevation for every 10 x 10 meters. |
| Land use Map | (National Remote Sensing Centre, 2004) | Raster map of land use for every 50 x 50 meters. |
| Soil map | (Tamil Nadu Agricultural University, 2004) | Polygon map of hydrologic soil group |
| Bed level contour map Sembakkam lake | (Indian Institute of Technology, 2018d) | Contour map of the elevation of the bed level of Sembakkam lake |
| Capacity lakes | (Tank Memoir, n.d.) | Capacity of Sembakkam lake and the upstream lakes |
| Dry weather discharge | (Indian Institute of Technology, 2018d) | Discharge of six inlets of Sembakkam lake, measured in an arbitrary way |
| Dry weather inflow | (Indian Institute of Technology, 2018d) | Discharge of Sembakkam lake, measured in an arbitrary way |
| Measurements drainage network | Field visit | Measurement of dimensions at 18 representative locations in Sembakkam catchment area |
| Remaining parameters sub-watersheds and drainage network | (Bisht et al., 2016; Kumar et al., 2019; Li et al., 2014; Li et al., 2016; Rossman, 2015; Tsai et al., 2017; Vemula et al., 2019) | Parameters such as imperviousness and Manning-n coefficient |
| Dimensions LID | (Narasimhan, 2019) | Common dimensions for a percolation pit and cistern |

# Appendix XIV: Land use map with satellite image background

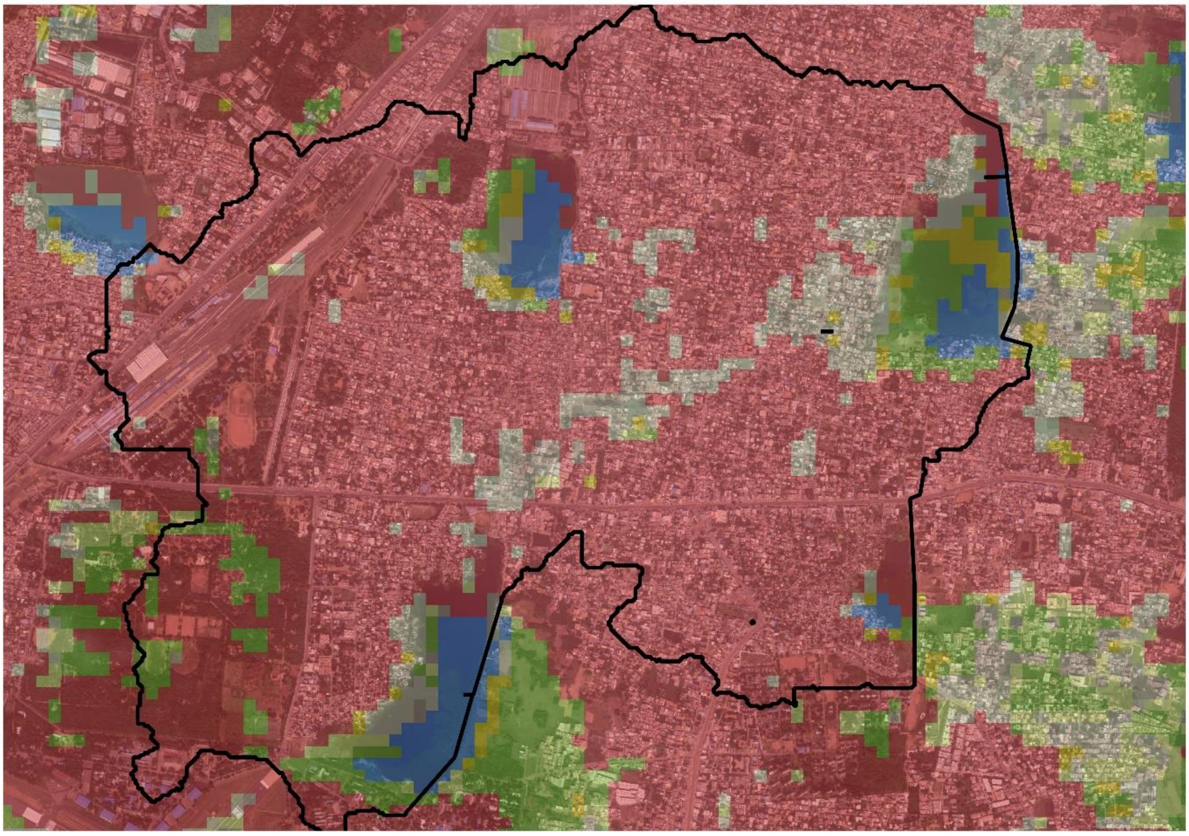

*Figure 37: Land use map against the background of a satellite image. Red area is build up area, Sembakkam catchment indicated within the black line (own figure based on (Google Maps, 2019))*

## Appendix XV: Photos of conduits at measurement locations

The locations of the measurement points are displayed in Figure 38. Pictures of these locations are presented in Figure 39 to Figure 57.

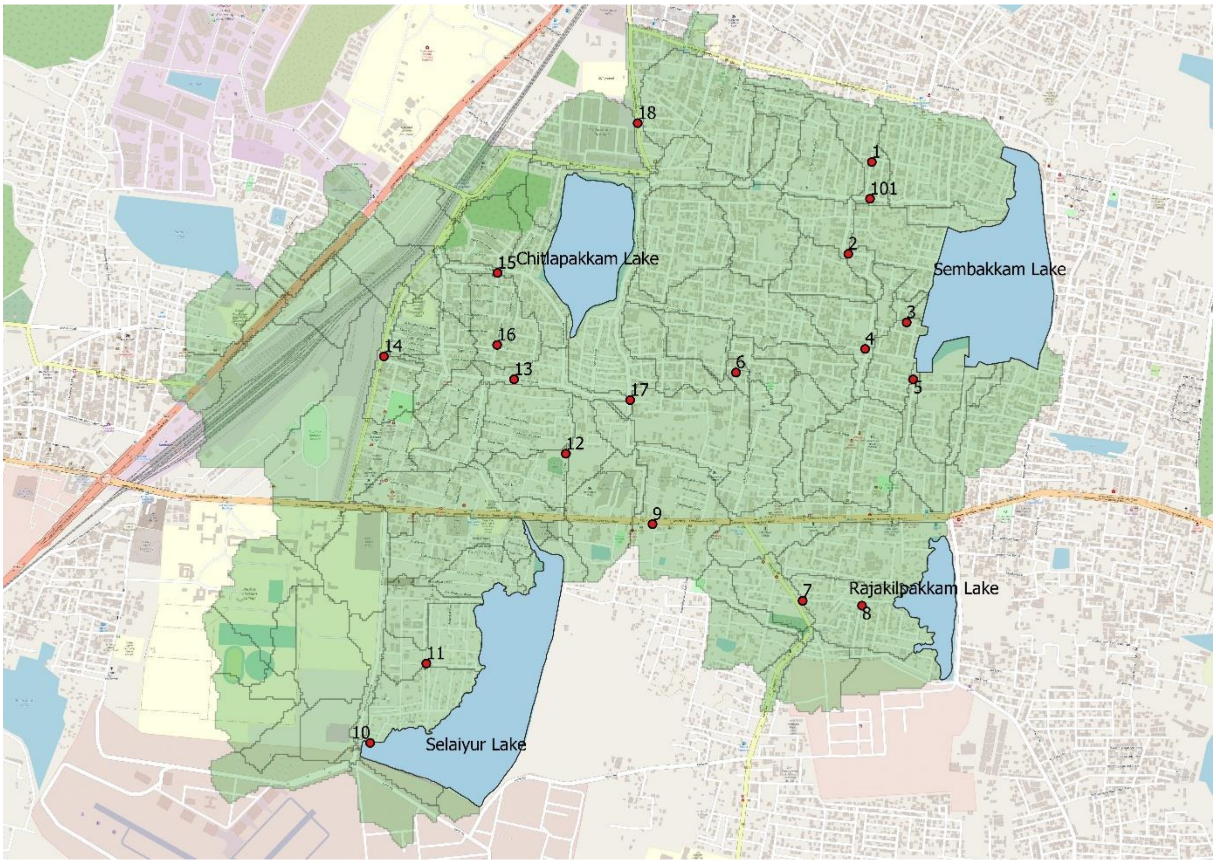


*Figure 38: Location of measurement points (own figure based on (Open Street Maps, 2019)*

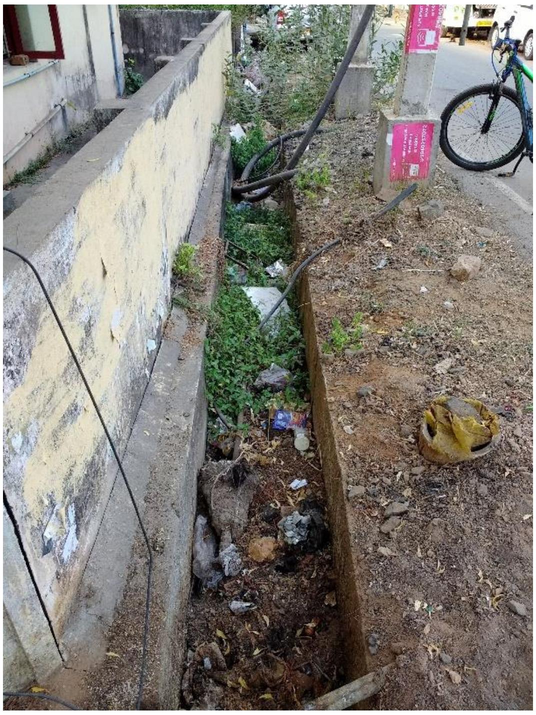

*Figure 39: location 1*

*Figure 40: location 101*

*Figure 41: location 2*

*Figure 42: location 3*

*Figure 43: location 4*

*Figure 44: location 5*


*Figure 45: location 6*


*Figure 46: location 7*


*Figure 47: location 8*


*Figure 48: location 9*

*Figure 49: location 10*

*Figure 50: location 11*

*Figure 51: Location 12*

*Figure 52: location 13*

*Figure 53: location 14*

*Figure 54: location 15*

*Figure 55: location 16*

*Figure 56: location 17*

*Figure 57: location 18*