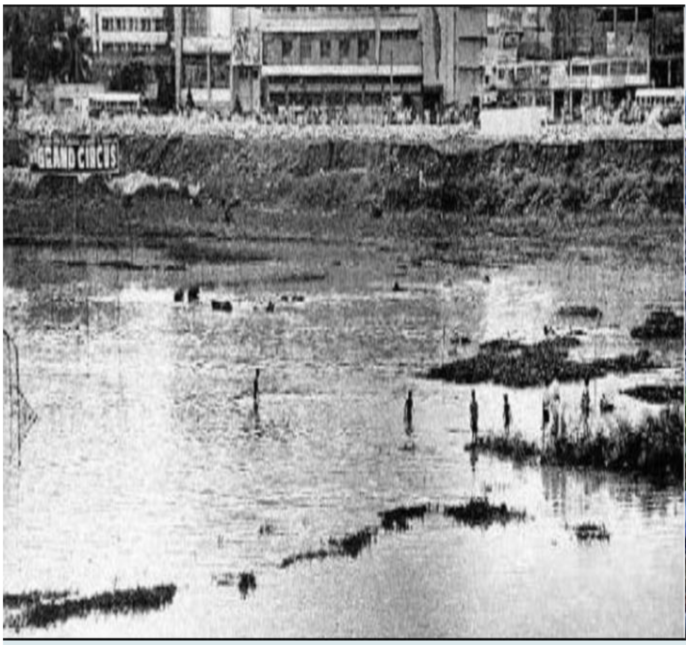

HYDROLOGICAL AND HYDROGEOLOGICAL CONSEQUENCES OF RAPID AND LARGE – SCALE URBANIZATION

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Hydrological and hydrogeological consequences of rapid and large – scale urbanization

Hydrologiska och hydrogeologiska följder av snabb och storskalig urbanisering

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Picture on front page: Dharmambudhi lake - year 1975 (Suma, 2016) and 2013 (Sastry, 2013)

Abstract

Urbanization is a process where rural population move to urban places for better job opportunities and facilities. This is a natural process and more or less unavoidable. But when this process takes place rapidly and at large -scale, the urban cities will undergo various changes that will impact the environment. Rapid and large-scale urbanization is mainly observed in developing countries of Asia and Africa.

These changes affect the hydrological and hydrogeological processes of the cities, which in turn affects the local people. In order to meet the demands of the growing cities, the land use is changed, for example the lakes are encroached, and the impervious area is increased.

This thesis aims to study the hydrological and hydrogeological consequences due to rapid and large-scale urbanization through a literature review of three cities. The catchment area of one of the three cities is further studied by computing surface runoff and amount of infiltration through the ground surface for two different years, using software such as extension tools of ArcGIS and HEC-HMS.

Shanghai, Hanoi and Bengaluru cities were chosen for the literature review. These cities were chosen because they face different consequences due to rapid and large-scale urbanization. One of the catchment areas of Bengaluru city, namely Vrishabhavathi valley, was used to estimate the surface runoff and amount of infiltration through the ground surface by numerical simulations.

In the case of Shanghai, the city mainly faces land subsidence due to over exploitation of groundwater. In the case of Hanoi, the city faces water quality degradation. Even though groundwater is exploited there is hardly any changes in the groundwater levels as the city´s aquifer is laterally recharged by the Red river that flows adjacent to the city. Flooding during monsoon, was one of the major effects faced by the Bengaluru city, as the city´s lake areas have been encroached. The lakes once acted as flood controllers.

The estimation of surface runoff and amount of infiltration through the ground surface was carried out on Vrishabhavathi catchment area in Bengaluru city. The years 1975 and 2017 were selected for past and present scenarios respectively. According to the computed simulation, the surface runoff was more important for the year 2017 whereas the amount of infiltration through the ground surface was large for the year 1975. This is due to the adverse change in the land use of Bengaluru city. Before the large-scale urbanization the lakes of this city were connected to each other and these lakes reduced the peak discharge and hence controlled the floods.

Generally, rapid and large – scale urbanization does have effects on the hydrological and hydrogeological processes. As urbanization is more or less unavoidable, care should be taken before the city is expanded. For example, measures such as artificial recharge, rainwater harvesting and flood management should be taken in order to save the city from further negative hydrological and hydrogeological effects.

If the ArcGIS/ HEC-HMS model is to be developed further to get better reliability, it is necessary to have detailed information from the measuring stations such as infiltration characteristics of the different sub-basins, time of attenuation from reach to reach, cross section of the channel, roughness of the channel, soil moisture, humidity, river discharge and other information related to the ground properties.

Keywords: Rapid and large-scale urbanization, ArcGIS, HEC-HMS, surface runoff, surface infiltration.

Acknowledgment

I am extremely grateful for the opportunity to work on this. It was both challenging and enlightening. I would like to express my sincere gratitude to my supervisor, Gerhard Barmen, for supervising my work and for continues encouragement throughout the course of the thesis. I would also like to thank Karin Larsson, for her extended support with the ArcGIS software.

I would further like to thank my family, my husband Akhilesh Ema Arunachalam, my parents K V Gopinath Gupta and Kalavathi G Gupta whose support ensured I pursue my dreams. To my in-laws and sister, thank you for the love and encouragement. Last but not the least, to the most important person of my life, my little son who supported me in his own ways to work on my thesis.

To my friends, thank you for checking on me. I am grateful to God for giving me the strength to complete this thesis project.

Contents

List of abbreviations

CN – Curve Number

DEM – Digital Elevation Model

GIS - Geographical Information System

HEC-HMS - Hydrologic Engineering Centre’s Hydrologic Modelling System

LAS – Lower Aquifer System

UAS – Upper Aquifer System

UTM – Universal Transverse Mercator

WGS -World Geodetic System

1 Introduction

Urbanization refers to a process that leads to the growth of cities due to economic development and industrialization. It can also be referred to as, movement of rural population to the urban area. About 55% of the world´s population lives in urban areas in 2018. In 1950, around 30% of the population used to live in urban areas and the share is expected to reach 68% by the year 2050. Urbanization is a global phenomenon and has a distinct level of development around the globe. Latin American and Caribbean countries have a large portion of the population already living in urban areas, whereas Asian and African countries are still rural and will urbanize faster than other regions over the coming decades. This development changes the landscape of the settlement, the living conditions and the environment (Economic & Social Affairs, 2018).

Rapid and large-scale urbanization takes place when the population moves to the cities at a faster and at a larger -scale than the expected rate of infrastructure development. This results in a positive increase in economic development of the country, but in turn it poses serious problems such as environmental degradation and, lack of infrastructure. This kind of urbanization has been going on in many developing countries for decades (Career Trend,2017).

In developing countries, the growth of the urban areas is concentrated around the urban core by replacing the adjacent land use such as agriculture and vegetation (Pauchard et al., 2006) to an urban land to meet the needs of growing population. And this change in the concentration of population and in the land use will have an impact on the hydrology and the hydrogeology of the local area.

Hydrological and hydrogeological effects might vary from place to place and these effects can be classified as local climate change, urban heat island, water table decrease or other physical and chemical changes within the water cycle. These changes alter the natural water system and cause serious effects on the environment.

1.1 Background of the thesis project

The cities that are in the phase of rapid and large-scale urbanization undergo a lot of hydrological and hydrogeological changes. These changes cause an impact on the day to day lives. In most of the cases the impacts can be found only during the monsoon period.

To meet the demands of the fast-growing cities, the land use is changed, agricultural land is converted to urban land, lakes are encroached for construction of tall apartment buildings or for commercial purpose. Due to these changes the natural river system is lost as the minor rivers might be changed to impermeable land or urban road. The surface water infiltration is reduced, and surface runoff increases leading to floods in the low-lying areas of the city and increase of the peak discharge (Manasi and Jamwal, 2016). Moreover, exploitation of groundwater with the decreased surface water infiltration leads to reduced groundwater levels.

India is a developing country and Bengaluru is one of its fast-growing cosmopolitan cities. This city was once well known for its greenery and its pleasant climate throughout the year. It was also known for its numerous lakes. The city´s lakes were interconnected by canals. They were the main source of water for the local people and the lakes also recharged the aquifers and maintained the groundwater level.

Due to the boom of Information Technology (IT) in Bengaluru, the city is undergoing rapid and large-scale urbanization. To meet the demands of the growing city, the lake areas are being encroached for commercial purposes or for the construction of high-rise apartments. As the land use of the city has changed over the decades, the city is facing hydrological and hydrogeological effects such as floods during monsoon. Due to this, low-lying areas will be flooded, and this will have effect on local people. Not only flooding, but also increased areas with impermeable land have led to reduced amount of infiltration through the ground surface.

1.2 Aim and goal of the thesis

The main aim of the thesis is to investigate the effects on groundwater due to rapid and large-scale urbanization. More specifically the objective of the study can be divided into the following parts:

- To study examples of hydrologic and hydrogeological effects due to rapid urbanization by literature review.
- To estimate the effect of rapid and large-scale urbanization by computing the surface-runoff and amount of infiltration through the ground surface for a catchment area for two different years, before and after a long period of urbanization. This should be done by using extension tools such as Hydro Tools and HEC-GeoHMS of ArcGIS and HEC-HMS software.

1.3 Limitations

- This project is based on literature, archive documents and geological maps meaning that no field investigations have been conducted.
- To meet the first aim, examples from different countries were chosen and they are based mainly on the description found in literature available through Lund University Library.
- For the second aim, the study area was delimited to the catchment area of Vrishabhavathi river. This area is part of Bengaluru city and it is also a part of a larger sub-basin of the big river Arkavathi.
- The analysis mainly focuses on the long-term changes in the amount of water infiltrated through the surface and surface runoff to study the effects of rapid and large-scale urbanization.

1.4 General methodology

A literature review for three cities was carried out throughout the course of the thesis project and a catchment area within the Indian city Bengaluru, which is one of the three cities, was used to simulate the effects using extension tools of ArcGIS and HEC-HMS software.

2 Hydrologic and hydrogeological processes in relation to rapid and large-scale urbanization.

2.1 Hydrological and hydrogeological process

Hydrology can be defined as the study of water. In the broadest sense, hydrology addresses the occurrence, distribution, movement and chemistry of all waters of the earth. Hydrogeology encompasses the interrelationships of geologic materials and processes with water.

The freshwater available for the human use is very small, more than 98% of it is ground water. Water moves from one form to other and from one place to other every time. This movement of water is referred to as water cycle (Fetter, 2014). Figure 2.1 represents the water cycle

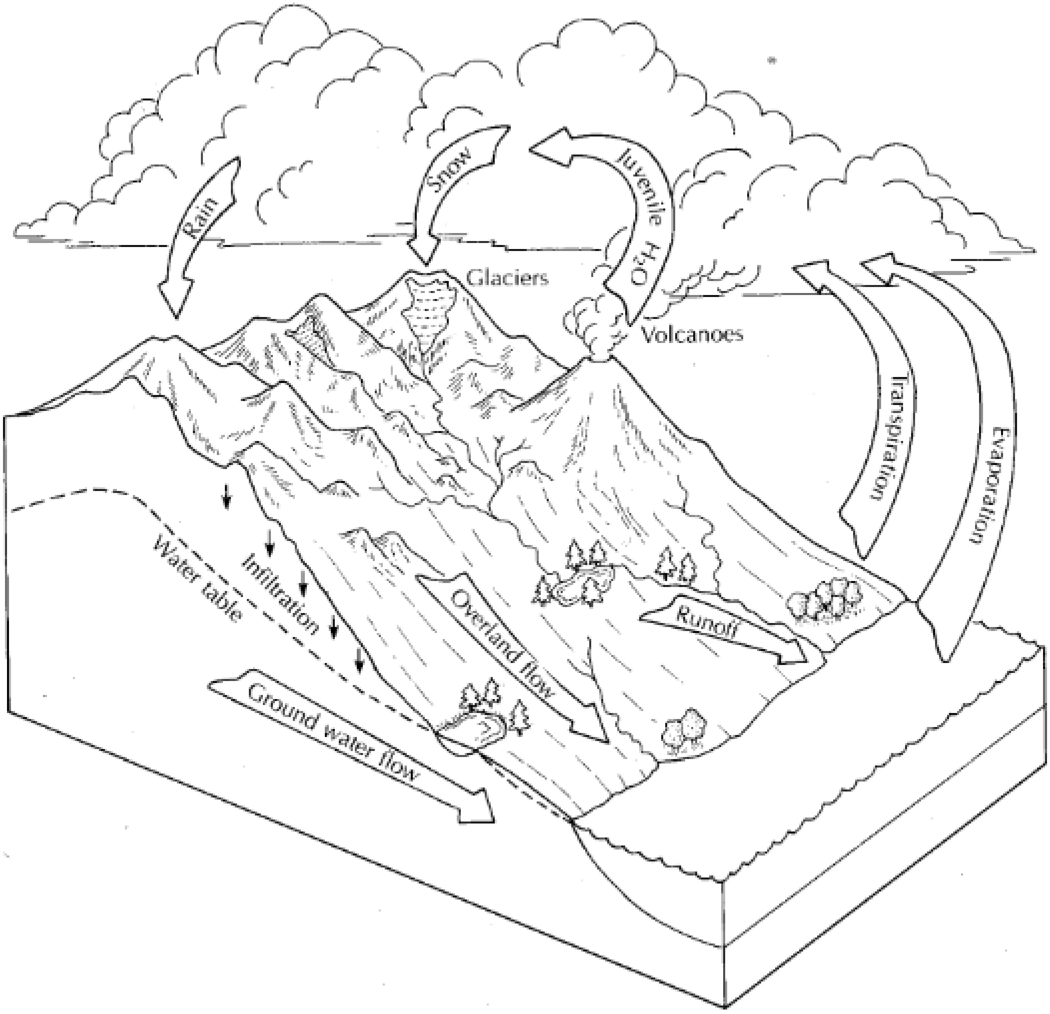


Figure 2.1: Water cycle (Fetter, 2014).

The water at the earth´s surface evaporates based on the humidity of the air, depending on the air temperature. The water evaporates in the form of water vapour. The water vapour rises, and forms clouds and condenses down back to earth´s surface as precipitation. Based on the perviousness of the soil, the precipitated water infiltrates through the earth surface or flows on the surface causing surface runoff.

Figure 2.2 shows a schematic representation of the water cycle or hydrologic cycle. The movement of liquid water is shown in solid lines and of water vapour is shown in dashed line (Fetter, 2014). The water that falls as precipitation can either infiltrate through the soil surface or can move as overland flow which is called surface runoff. This is well explained by the Horton hypothesis (Ward and Robinson, 2011).

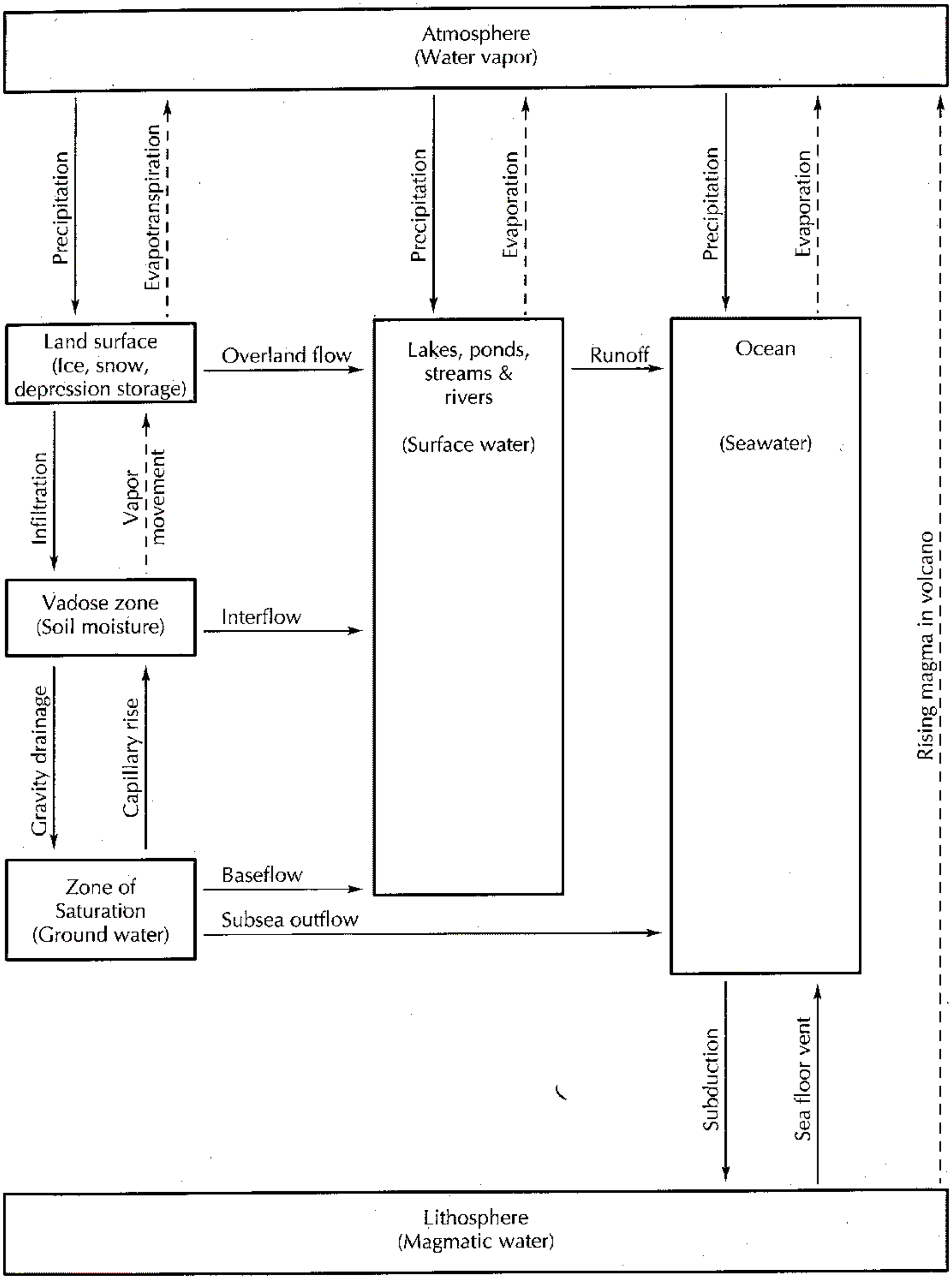


Figure 2.2: Schematic representation of the hydrologic cycle or water cycle (Fetter, 2014).

Horton proposed a simple hypothesis, that is the soil surface divides the precipitation so that a part goes rapidly as overland flow to the stream channels and another part infiltrate through the soil surface. Figure 2.3 illustrates the Horton hypothesis. The infiltrated part either evaporates back to the atmosphere or forms groundwater which may flow to the streams.

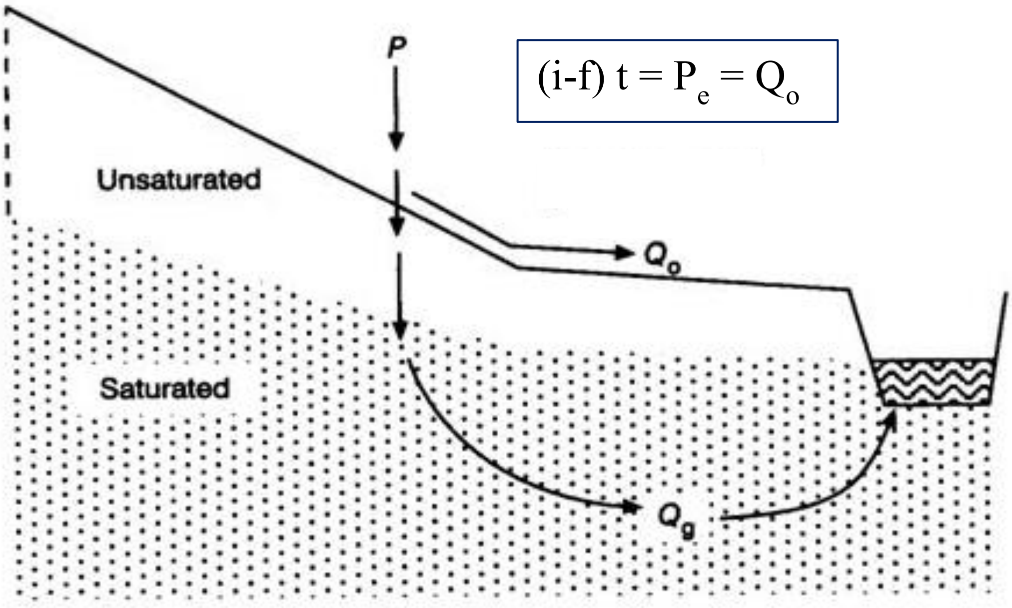


Figure 2.3: Horton hypothesis (Ward and Robinson,2011)

The rate at which the precipitation either goes as overland flow or infiltrates the surface depends on the infiltration capacity of the soil surface. According to Figure 2.3, the temporal part (t) of a rain storm at the intensity (i) that is greater than the infiltration rate (f), will give rise to an excess precipitation (P_e), which will flow over the surface as overland flow (Q_o). If the infiltration capacity is greater than the intensity of rain, then no overland flow occurs instead the soil moisture capacity is attained. Further infiltration through the ground surface will percolate to the groundwater reservoir which in turn increases the groundwater flow (Qg) to the stream channel (Ward and Robinson, 2011).

A major aspect of hydrology is movement of water in the atmosphere, on earth´s surface and also the ground. Hydrogeology could be described as a part of hydrology with focus on groundwater and the interaction between geological properties and water properties. The hydrological and hydrogeological process begins with the evaporation of water from the earth´s surface and the evaporated water condenses and falls back to earth surface as precipitation. Further the precipitated water infiltrates through the soil surface or runs on the surface to form surface runoff. The amount of infiltration of water through the soil surface depends on various factors such as:

- Permeability of soil
- Type of soil
- Moisture content of soil
- Level of groundwater table, etc.

2.2 Effects on the water system by rapid and large-scale urbanization

Urbanization can be defined as a process in which rural population moves to urban area. Urbanization replaces the permeable vegetated land surface with impervious surface area, this changes the hydrology and hydrological process of a watershed (Zhou et al., 2013). It reduces the rate of surface infiltration and increase the surface runoff, that in turn leads to increased peak discharge, that in turn leads to huge floods.

As rapid and large-scale urbanization refers to a process where the population moves into the urban areas faster than the development of infrastructure and at a larger area, this can also be defined as change of land use at a faster rate and larger area, to meet the demands of the fast-growing urban area. In the process, natural land is converted to impervious land, lakes are encroached for construction or for commercial purposes, small streams are converted to compact surface or impervious roads. Table 2.1 provides a short description of the characteristics of urbanization, large-scale urbanization and rapid urbanization.

Table 2.1: Modes of urbanization, changes in land use and their effects on the water system (USGS Water Science School, 2018)

Modes of Urbanization	**Changes in land use**	**Effects on water system**
Urbanization	• Removal of trees and vegetation • Construction of new buildings, may be with proper sewage system or with septic tanks • Start to search for new water resource or drilling a bore-hole	• Increased storm runoff and erosion due to reduced vegetation • More sediments in the streams • Floods might occur due to changes in water drainage pattern
Large-scale Urbanization	• Levelling and compaction of land for construction of houses. • Filling the lakes, ponds of farms or any other water bodies such as wetlands • Diversion of streams to meet the water demand of people • Sewage discharge into streams	• Increased land erosion and sediments washed into the streams • Increased chance of flooding and changes in the quality of water in the streams. • Local flooding • Small streams are paved • Natural land that used to infilter surface water is converted to impervious surface or roads • Less surface infiltration causes increased runoff

		• Due to increased runoff the storm sewers are full and therefore the water is let to streams, causing the small streams also to flood. • Increased sewage in streams leads to pollution of stream water.
Rapid Urbanization	• Addition of more roads, houses, commercial and industrial buildings. • Increased waste water discharge to local streams • New-water supply and distribution system needs to be built for the growing population • Small streams are changed to accommodate new building construction. • Increased number of wells to meet the demands of the people	• Increased pavement, results in less surface water infiltration that in turn reduces the groundwater table. This might lead to drying of some existing wells. • Increased run off joins the storm sewers, which then joins the streams. This runoff causes flooding • Changes in the channel of the stream leads to flooding and erosion • More sewage is discharged to the streams as it exceeds the design capacity • Usage of too many large wells leads to reduced levels of water table • Reduction of groundwater level results in sinkholes and land subsidence

Urbanization is one of the major factors that alters the hydrological and geological properties of earth´s surface. Some of the general effects caused due to urbanization are:

1. Levelling of land surface for the construction of buildings, roads, parking lots, etc. This includes filling of low lying areas such as stream channels.
2. Introduction of new sources contamination of air, surface water and groundwater.
3. Alteration of local climate. This includes the urban “heat island effect” and changes in the precipitation pattern.
4. Due to introduction of subsurface conduits, tunnels, etc., a zone of increased permeability, often by many orders of magnitude, is created.
5. Much of the landscape is converted to impervious areas
6. Natural soil becomes compact.

7. Natural vegetation gets altered. This affects the evapotranspiration, groundwater recharge rate and stream flow.
8. Groundwater recharge changes due to items 4,5,6 and 7.
9. Streamflow gets altered and rainfall leads to flash floods due to items 5 and 6.
10. Lakes and wetlands disappear or become encroached (Bhaskar et al., 2015).

This section mainly deals with theoretical and general effects. The hydrological and hydrogeological effects observed in a number of real cases are focused in Chapter 4.

3 Material and methodology

This chapter aims to present and discuss the general methodology indicated in the section 1.4. A comprehensive literature review and an estimation of the effects using one of the catchment areas of Bengaluru city for a past scenario and present scenario were carried out throughout the thesis project.

3.1 Selection criteria

Rapid urbanization is a wide topic where a lot of studies have been carried out in different fields and are still ongoing. Hence there was a need to exhaustively define the scope of the literature for the thesis to ensure the thesis study meets the project aim and goal defined in section 1.2 of the report.

The aim of thesis is to study the hydrological and hydrogeological consequences of rapid and large-scale urbanization. There are numerous methods and cases that have been used to study the consequences. In order to limit the literature review, selection criteria have been formulated. The selection criteria were chosen in such a way that the consequence scenario is different in each studied case.

As the rapid and large-scale urbanization is mainly observed in developing countries of Asia and Africa, three cities were chosen from Asia and the reasons for selecting them are stated below. One catchment area of one of the cities was chosen to estimate and simulate the hydrological and hydrogeological consequences of rapid and large-scale urbanization (see section 3.4 and onwards). As most of the literatures for many other cities were available in their native language, only three cities were chosen for the study. Another limiting aspect is time and the scope of this thesis of 30 ECTS. Therefore, the study is limited to three cities and estimation and simulation of one catchment area.

3.1.1 Shanghai, China

China ranks first in the world population and Shanghai is the largest and most densely populated city of China. This city is situated at the Chinese east coast and is experiencing rapid urbanization from the year 1945 due to industrialization and economic growth.

3.1.2 Hanoi, Vietnam

Vietnam is one of the developing countries of southeastern Asia. Hanoi is the capital city of Vietnam and the city lies next to the Red river. The city is experiencing rapid and large-scale urbanization since 1986, when the country adopted economic reforms. As the city lies next to the Red river and is supplied by aquifers in contact with the river and situated close to the city center, the groundwater table and groundwater recharge varies with the river flow and surface runoff. Hence this was one of the cities chosen for the literature study.

3.1.3 Bengaluru, India

India is another developing country of Asia and it ranks second in the world´s population. Bengaluru is capital city of one of the Indian states, Karnataka. The city is experiencing rapid and large-scale urbanization from past decades. The city was once well known for its greenery, pleasant climate all year round and numerous lakes. The numerous lakes were interconnected to each other and recharged the groundwater. Due to rapid and large-scale urbanization most of the lakes have been encroached. Hence the city was selected to study the consequence of urbanization on hydrology and hydrogeology.

3.2 Literature review

The literature review used a couple of accessible databases such as LUBsearch and Google scholar. Table 3.1 shows an overview of database of the keywords used during the literature study. A detailed description of the information obtained from the literature review is presented in Chapter 4 of the report.

Table 3.1: The table shows the main database and keywords used throughout the course of literature review. The table aims to shows how the literature study was carried on but does not present all the searches made during the entire course of the thesis.

No.	Database	Search strategy	Hits
1	LUBsearch	Effects of closing lakes on the groundwater	9
		Closing AND lakes AND groundwater	14
		Urbanization OR Urbanisation OR LUCC OR LULC AND lakes	138942
		Disappeared lakes of Shanghai	7
		hydrological effects AND urbanization	682
		hydrogeology AND urbanization	226
		urbanization AND groundwater AND Bengaluru	4
		Bangalore AND urbanization	342
2	Google scholar	rapid and large scale urbanization	389000
		disappeared lakes of Bangalore	3010

An initial search on the consequences on hydrology and hydrogeology due to rapid urbanization yielded up to 389000 hits. All the literature from the hits shown in Table 3.1 was not relevant for the thesis study. Based on the formulated selection criteria, the review was limited and yielded more relevant literature, which is presented in Chapter 4 of the report.

3.3 Selection of city for simulation

Bengaluru city was selected for the estimation and simulation of the effects as it was supposed that it would be possible to find available model input data for this city. The city is subdivided into three catchment areas, namely Vrishabhavathi valley, Hebbal Nagavara Valley and Koramangala Challaghatta Valley.

Vrishabhavathi valley was chosen for the analysis as the government of Karnataka, India, has started many rejuvenation projects to restore the lakes and rivers of this valley. The simulation was carried out for two scenarios, a past and a present scenario. This was done to study, compare and draw conclusions on the consequences of rapid and large-scale urbanization on hydrology and hydrogeology. The years chosen for the analysis were based on the available data.

3.4 Methodology of the simulation.

This section presents a procedure for the modelling and simulation of hydrological effects of the rapid and large-scale urbanization. First the background information is described for building a model. This is followed by a detailed description of how the models are used to simulate hydrological processes in this project. Then the results of the simulation are presented and discussed in Chapter 5.

3.4.1 Background information

The modelling part of the study was performed using the extension tools of ArcGIS such as Hydro Tools and HEC-GeoHMS (Geospatial Hydrologic Modeling Extension) and the simulation was carried out using Hydrologic Engineering Centre’s Hydrologic Modelling System (HEC-HMS).

ArcGIS refers to a computerized system that is "designed to capture, manage, analyse, and display all forms of geographically referenced information" (ESRI, 2018a). The modelling of the catchment area of Bengaluru city was carried out in ArcMap, a software that belongs to a collection of ArcGIS 10.3.1 programs developed by the ESRI company. Extension tools such as Arc Hydro Tools and HEC- GeoHMS were used.

Arc Hydro Tools are used to model the flow of water across a surface (ESRI, 2018b). HEC-GeoHMS program allows the user to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate sub-basins and streams, construct inputs to hydrological models and assist with report preparations. HEC-GeoHMS helps to create the hydrological inputs that can be used directly with HEC-HMS (Fleming and Doan, 2013).

HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems. The software can include many hydrologic analysis procedures such as event infiltration, unit hydrographs and hydrologic routing. It also considers the procedures necessary for continuous simulation including evapotranspiration, snowmelt and soil moisture accounting. This software can be used together with other software for studying water availability, urban drainage, river flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation (US Army Corps of Engineers, 2016).

The HEC-HMS program has the power and speed to make it possible to represent watersheds with hundreds of hydrologic elements, but this process is time consuming. Hence, ArcGIS can use the elevation data and geometric algorithms to perform the same task much faster.

ArcGIS´s extension tool HEC-Geo HMS is used to create basin and meteorological models for the use with the HEC-HMS program (US Army Corps of Engineers, 2016).

The data required for modelling was obtained form a consultancy company namely Aapha Innovations, Hyderabad, India (Table 3.2). The data was received in raster, vector and excel format. Raster format is a spatial data that defines space as an array or grid of equally sized cells arranged in rows and columns. Each cell is represented by a value such as the elevation of the cell. Vector format is a co-ordinate-based data that represent the geographic feature as points, lines and polygons. The cell size of a raster format represents the area covered on the ground of each cell. The cell size of the DEM used for the modelling is 30 x 30 m.

Not all the data required for simulation were available. Based on the availability of data, the procedure and the methodology for the simulation were adjusted. The rainfall data that were available regard the whole area of Bengaluru city. It was difficult to find the rainfall data for individual watersheds. Therefore, the rainfall was assumed to be equal for the whole area.

Table 3.2: The source and the data format used for the analysis of the catchment area

Input data	**Format**	**Cell size (m)**	**Source**
Digital Elevation Model (DEM)	Raster	30 x 30	Aapha Innovations, Hyderabad, India
Soil type	Vector	-	
Land use for the year 1975	Vector	-	
Land use for the year 2017	Vector	-	
Rainfall data for the year 1975	Excel	-	
Rainfall data for the year 2017	Excel	-	

Two different scenarios were simulated within this study. The first one was using the data from the year 1975, representing the past scenario and the second one was corresponding to the year 2017 for the present scenario. First the raw data was used to create the basin model using extension tools of ArcGIS namely Hydro Tools and HEC-GeoHMS.

3.4.2 Procedure followed for modelling

Two softwares, extension tools of ArcGIS and HEC-HMS were used for modelling. Figure 3.1 shows the working process illustrating the main parts of the procedure carried out for the simulation. The detailed procedure carried out in the ArcGIS is shown in Appendix A .

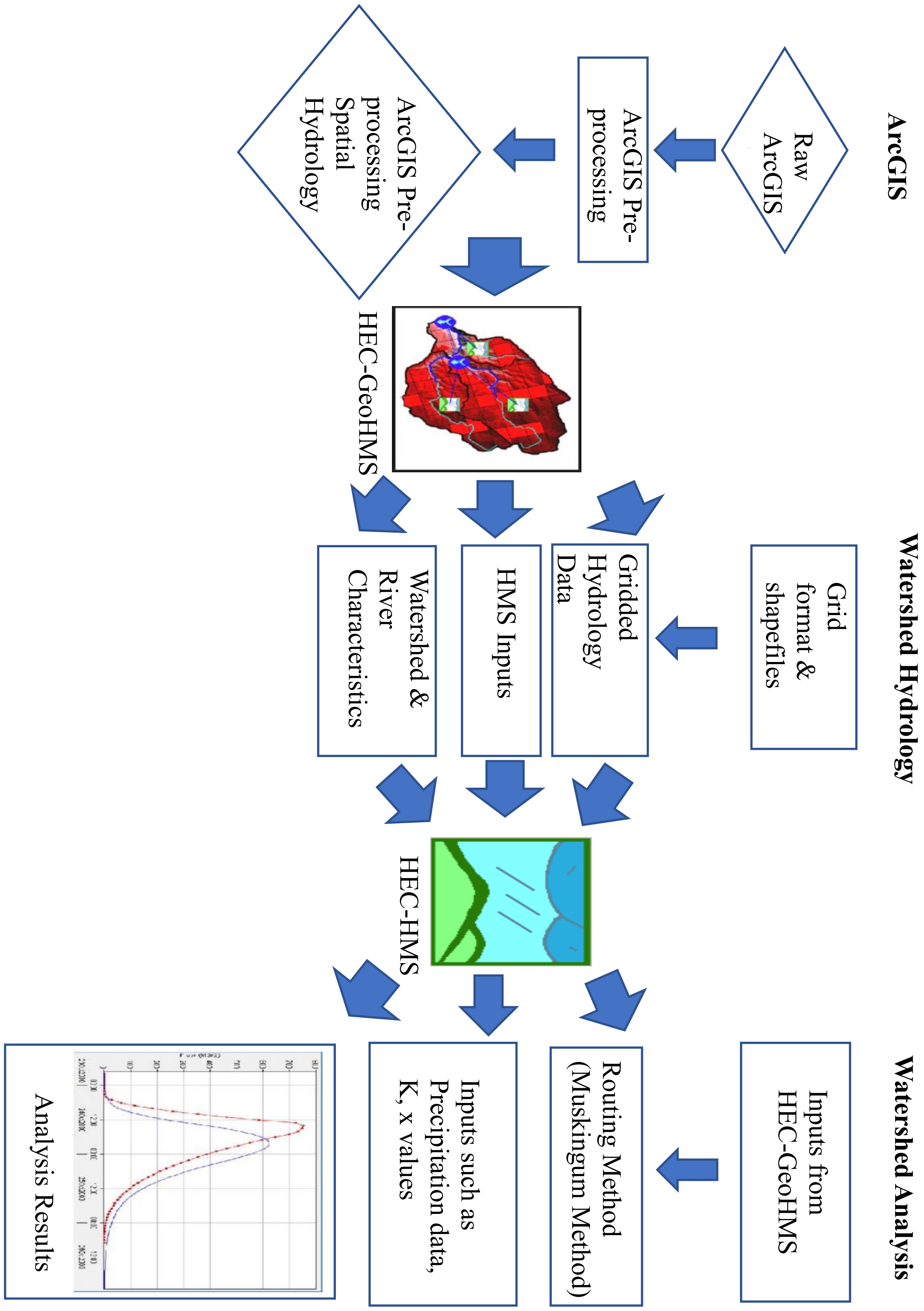


Figure 3.1: Schematic overview of the working process using ArcGIS and HEC-HMS softwares. The process starts with the ArcGIS then the extension tool of ArcGIS that is HEC-GeoHMS is used to create the watershed of the river basin and this is exported to HEC-HMS to generate the results. The model will be further explained in the following sections.

3.4.2.1 Procedure in ArcGIS

The raw DEM obtained from Aapha Innovations was used in ArcGIS and a coordinate system, namely WGS 1984 UTM 43N, was assigned as Bengaluru city lies between UTM zone 43N and 44N. The data were processed further using Hydro Tools.

The first step is to process the terrain. Hence DEM was used to identify the surface drainage pattern. This step helps to delineate the watershed and to generate the stream networks. (Merwade, 2012). The DEM of Bengaluru city with the raster cell size of 30m x 30m was used for the processing. Figure 3.2 shows the major river networks and major watersheds of the Bengaluru city.

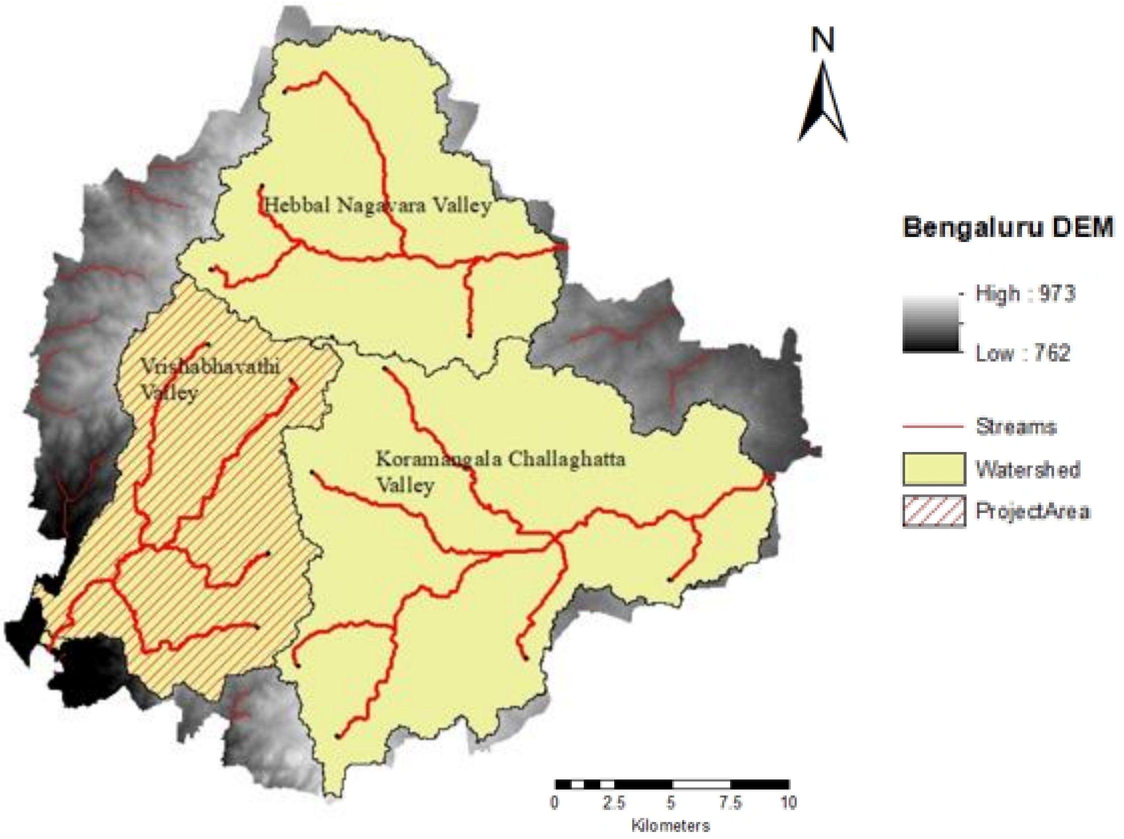


Figure 3.2: Major rivers and watersheds of Bengaluru city.

Bengaluru city has three major watershed regions namely Hebbal Nagavara Valley, Vrishabhavathi Valley and Koramangala Challaghatta Valley. As the area of the Bengaluru city is huge, it was difficult to carry out the simulation for the whole area of Bengaluru city. Hence one of the watersheds had to be chosen for the estimation. As the government of Karnataka state have announced for rejuvenation projects for Vrishabhavathi Valley, the same was chosen for the simulation.

Once the terrain was processed, the next step was to create a slope grid for Vrishabhavathi Valley. This grid represents the rate of change of elevation for each DEM cell. Figure 3.3

illustrates the slope grid and it was based on the percentage rise of the DEM within cells. After the creation of the slope grid, HEC-GeoHMS tools were used for further modelling.

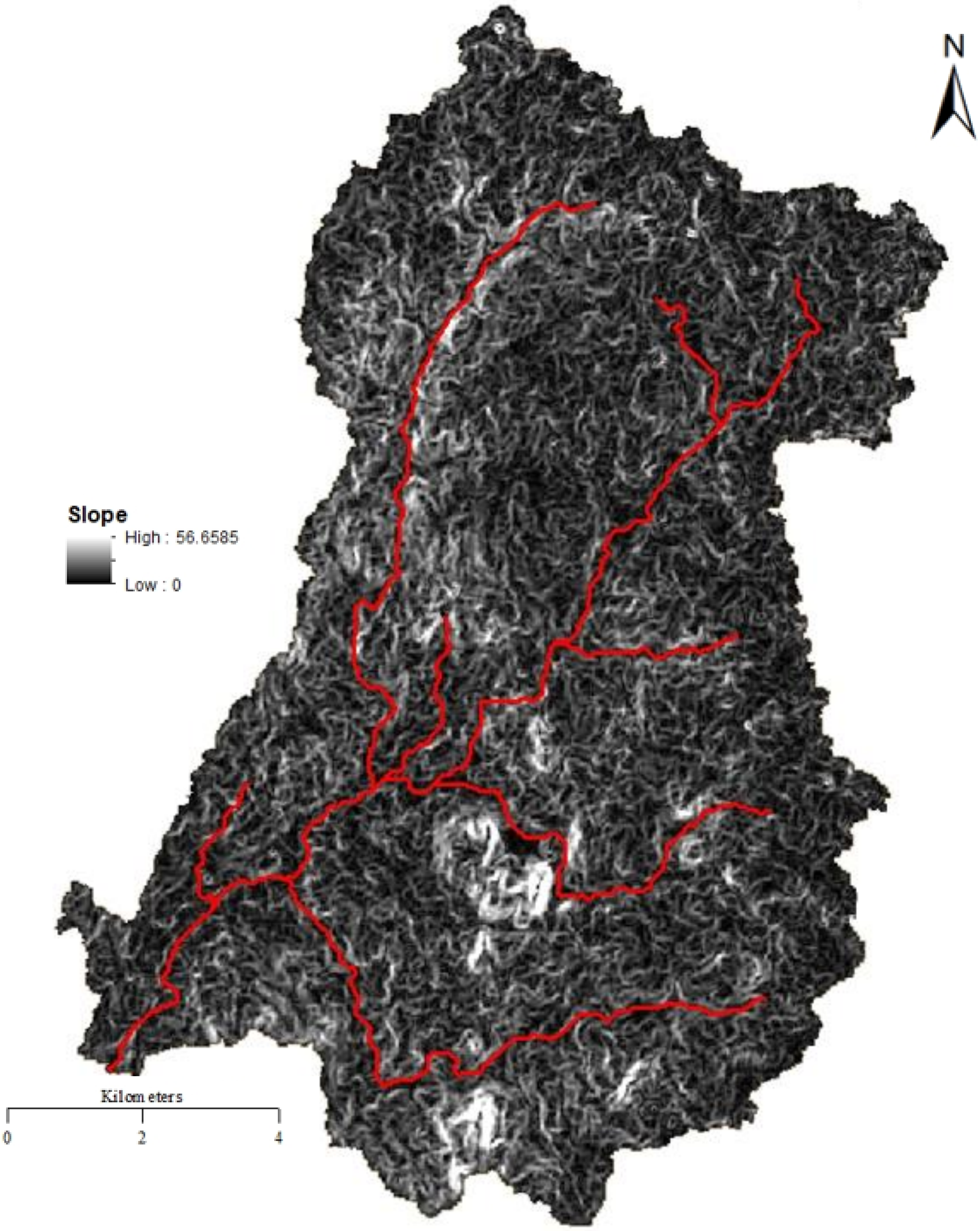


Figure 3.3: Variation of the slope within the catchment of river Vrishabhavathi. The lighter colour indicates a steeper slope. The unit of slope is in percentage rise of the DEM.

HEC-GeoHMS creates the background map files, basin model files, meteorological model files and grid cell parameters files which can be used by HEC-HMS. The basin model file contains sub-basin areas and hydrological parameters, which are estimated using the DEM (Fleming and Doan, 2013).

Further using the HEC-GeoHMS the basin is delineated to sub-basins to make the simulation easy. Figure 3.4 shows the Vrishabhavathi river basin which is delineated to 57 sub-basins. The sub-basins and the river reach of each sub-basin were named using HEC-GeoHMS tools. Sub-basin characteristics such as river length, river slope, basin slope and sub-basin elevation are extracted.

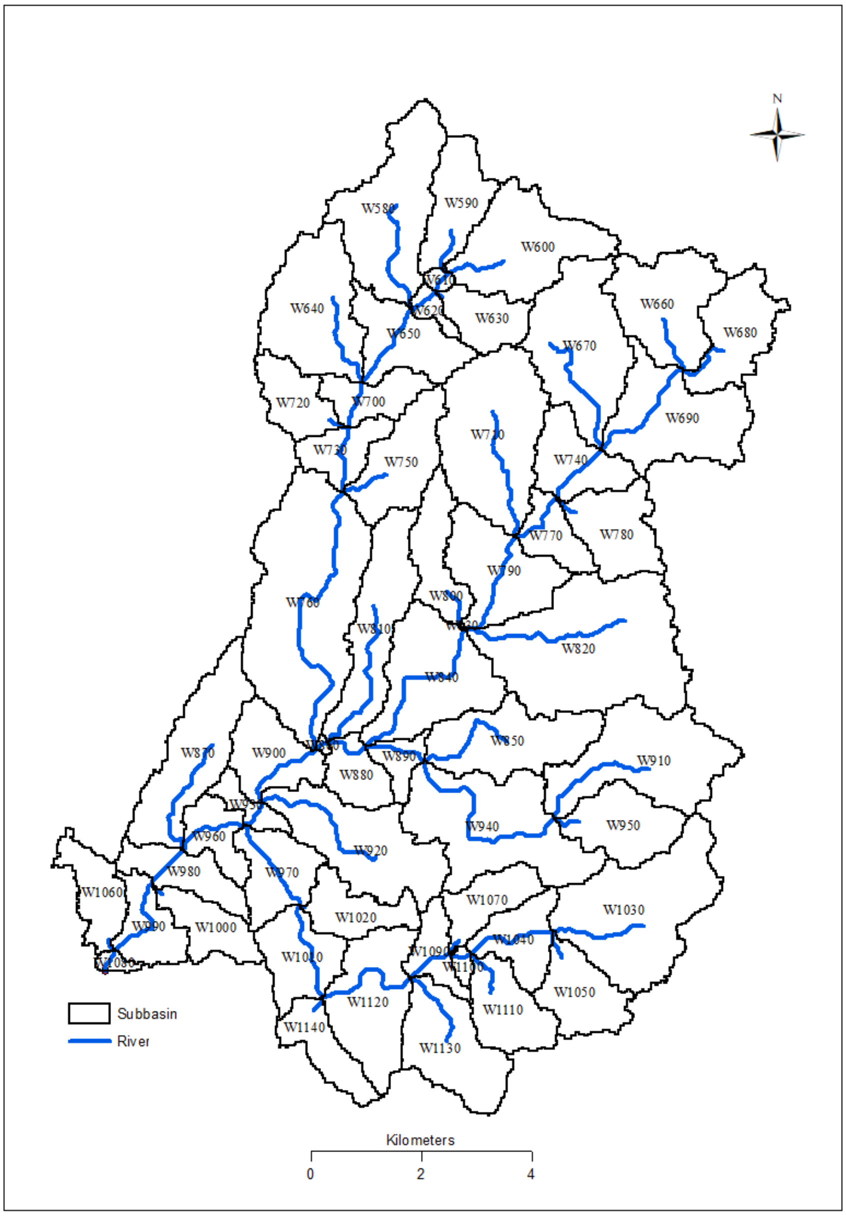


Figure 3.4: Vrishabhavathi river basin delineated to 57 sub-basins. The names of the sub-basin are assigned by the software.

The extension tool has provision for computing hydrological parameters such as curve number (CN). Curve number is an empirical parameter used in hydrology for predicting direct runoff or ground surface infiltration from rainfall. This parameter is based on the soil and land use data. The soil data obtained from the Aapha Innovations were dived into five groups namely clay, silt, silty clay, silty clay loam and silty loam. This was further divided into four hydrological soil groups A, B, C, D mainly based on the percentage of clay.

The land use data was divided into barren land, vegetation, urban and built up, and water body. As CN values depends on the soil and land use, a table called CN Lookup table was created to assign values for the combinations (*Table 3.3*). For the calculation of CN number, the Soil Conservation Service (SCS) method was used (USDA, 1986). Appendix B shows the details of the hydrological soil groups classification and the procedure used to calculate the CN values. According to the Table 3.3, higher CN value means the surface is more impervious and a lower CN value indicates that the surface is less impervious.

Table 3.3: The CN Lookup table. Values used for combinations of land use and soil group.

Land use	Classification group no.	Hydrological soil groups			
		A	B	C	D
Water body	1	100	100	100	100
Urban and built up	2	89	92	94	95
Vegetation	3	49	69	79	84
Barren Land	4	77	86	91	94

Figure 3.5 represents the CN grid for the year 1975 and the CN grid for the year 2017 is shown in Appendix B.

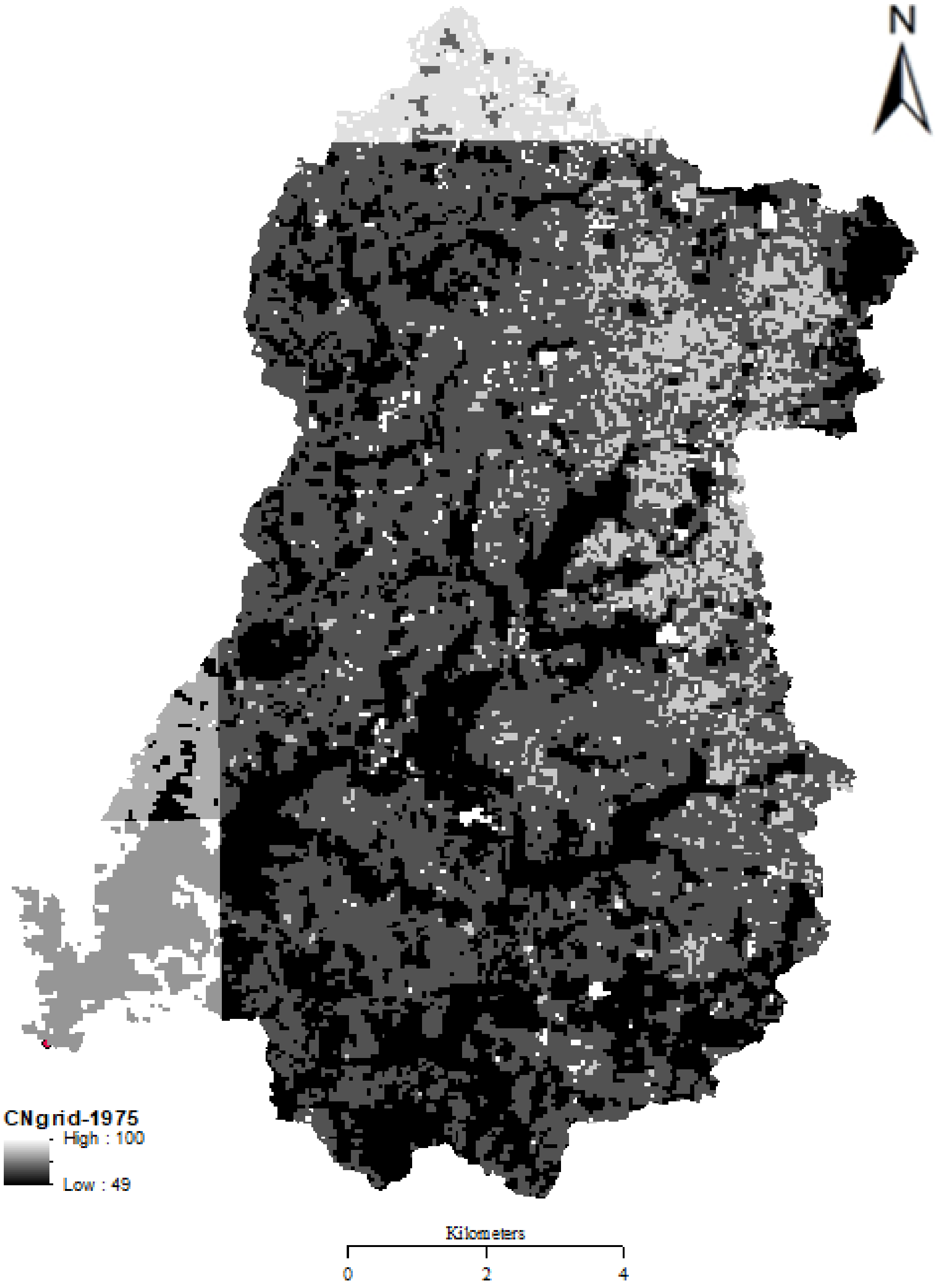


Figure 3.5: CN grid of the year 1975.

The CN values were then assigned to each of the sub-basins and the model was prepared to export to HEC-HMS software. Figure 3.6 illustrates the model that was created using Hydro Tools and HEC- GeoHMS, extension tools of ArcGIS.

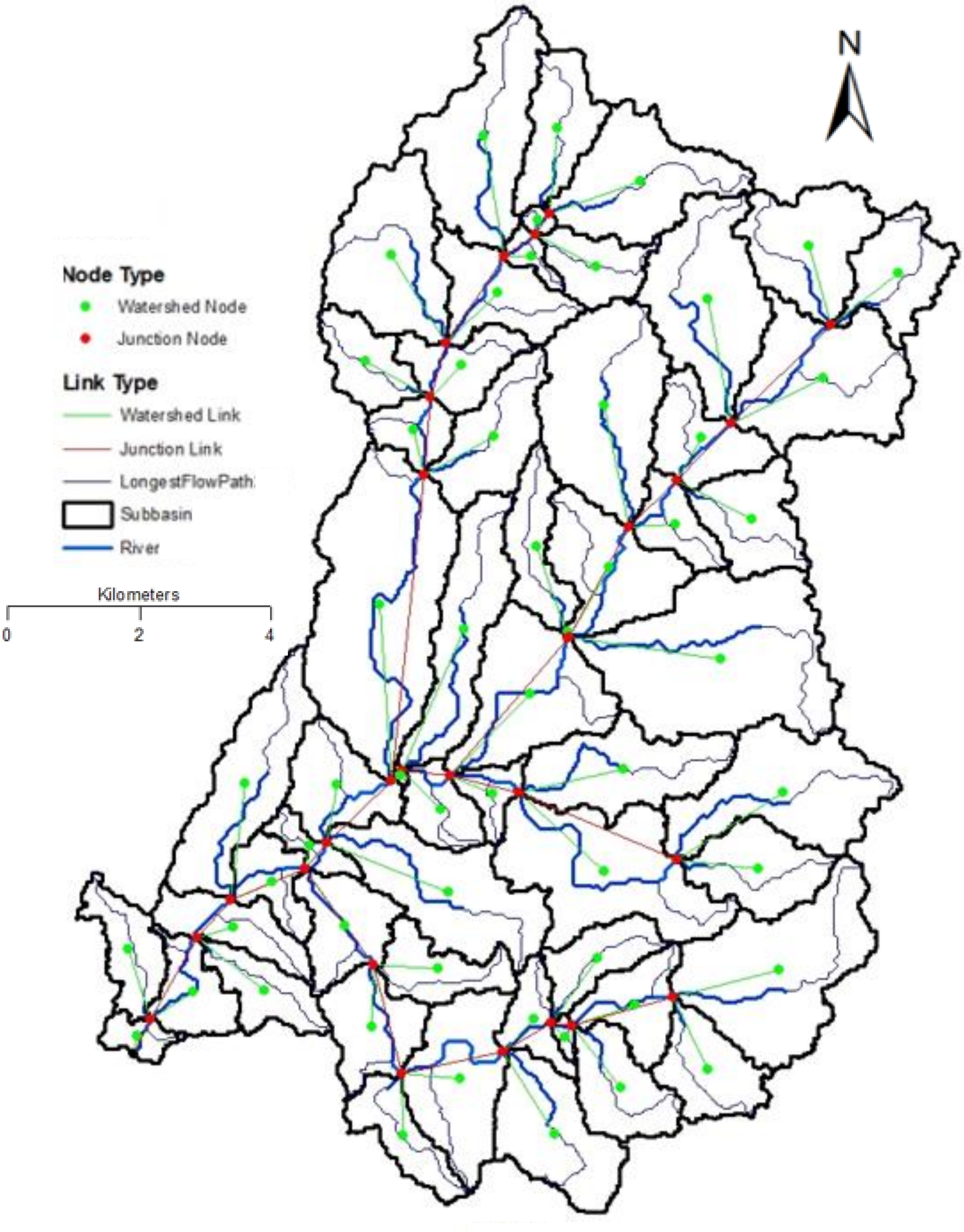


Figure 3.6: Illustration of the HEC-HMS model generated using Arc Hydro Tools and HEC-GeoHMS.

The above steps were repeated to create similar model for the year 2017.

3.4.2.2 Procedure in HEC-HMS

The model generated using extension tools of ArcGIS was imported to the HEC-HMS software. Data such as discharge of river, rainfall and duration of the simulation were added. As the rainfall data was available only for three months June, July and August, and most of the annual rainfall occurs during this part of the year, the simulation was carried out only for these months.

HEC-HMS offers different methods for the selection of each parameter (Appendix C). Based on the availability of the data the following methods were adopted and a few assumptions were made for the simulations.

- Loss method - SCS curve method
- Transform Method - SCS Unit Hydrograph Transform
- Baseflow Method - None
- Routing method - Muskingum Routing

The Muskingum routing method uses a simple conservation of mass approach to route the stream flow, hence this method was chosen. The Muskingum K and Muskingum X are the major parameters.

Muskingum K is the travel time through the reach. It can be estimated from the knowledge of the cross-section properties and flow properties.

Muskingum X is the weighting between inflow and outflow influence; it ranges from 0.0 to 5.0, where 0.0 means maximum attenuation and 5.0 means no attenuation. The X values for the streams require an intermediate value (Scharffenberg and Fleming, 2010).

The calculation of Muskingum K and Muskingum X is as shown in Appendix D.

The estimations for the year 1975 and 2017 that is past and present scenario respectively were carried out separately.

3.4.2.3 Assumptions

The river that flows through the Vrishabhavathi valley was once a main source of drinking water, but it was later converted to waste water river. There are no records maintained from the drinking water and waste water board, hence availability of the data about the river was difficult. Due to this, a few assumptions for the analysis were made as mentioned below:

- As the measuring gauge information is not available, the river is considered as ungauged to carry out the calculations.
- Vrishabhavathi river is a sub branch of river Arkavathi which is one of the major branches of the River Cauvery. The average discharge of the river Cauvery is 677 m^3/s (21.36 $km^3/year$) (Kumar et al., 2005). As Vrishabhavathi river is one of the small branches of river Cauvery, the average discharge was assumed to be $30m^3/s$. Appendix D shows the catchment area of river Cauvery, Arkavathi and Vrishabhavathi.

3.4.2.4 Simulations using the same rainfall data

The amount of rainfall for the monsoon seasons of the years 1975 and 2017 are shown in Figure 3.7. Due to the variation in the amount of rainfall between the years, it is difficult to estimate the effect of urbanization by computing the surface-runoff and amount of infiltration through the ground surface using the actual rainfall of 1975 and 2017. Hence rainfall data of the year 2017 was used for both the scenarios, while the land use of respective years were used for the simulations.

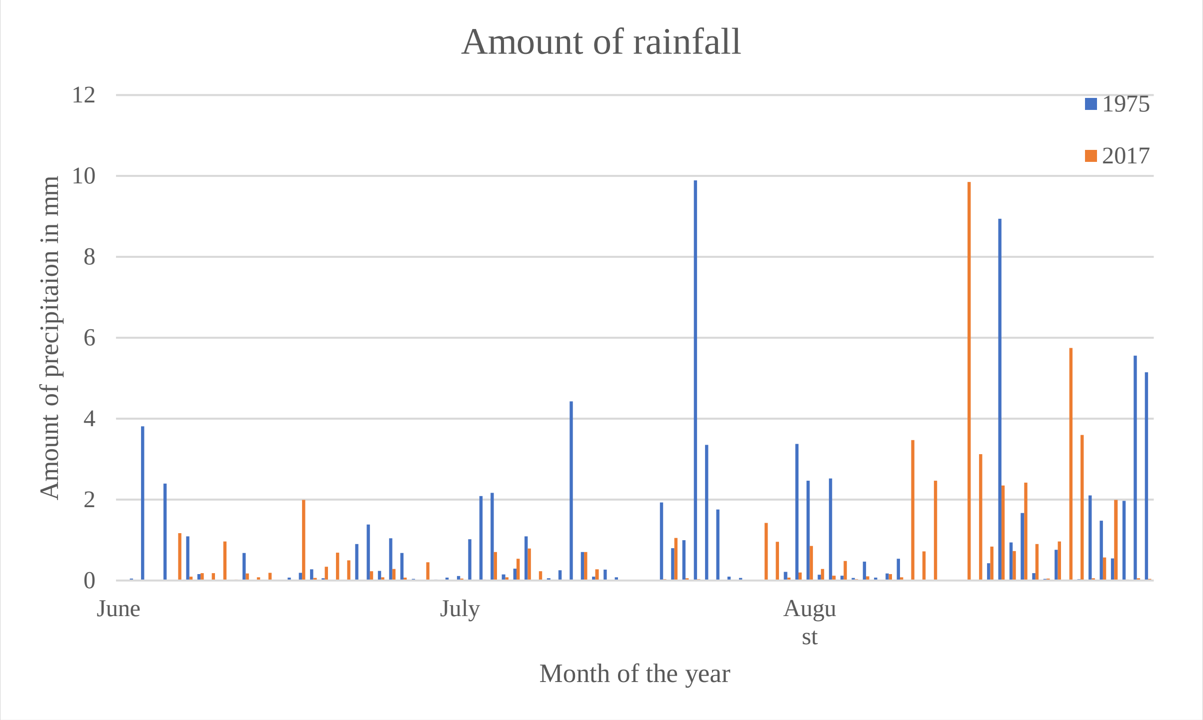


Figure 3.7: The above graphs represents the amount of precipitation for the rainy part of the year 1975 (blue) and for the year 2017(orange).

3.4.2.5 Presentation of results from selected sub-basins

The Vrishabhavathi river basin was dived into 57 sub-basins. It is difficult to present and discuss the results from all the sub-basins, hence only few sub-basins where the urbanization has a striking difference such as the vegetation is completely changed to built up area were chosen to discuss the effects. Hence only few sub-basins near the outlet were chosen as these sub-basins have striking difference in the land use and these sub-basins are low-lying area of the Vrishabhavathi river basin (see Figure 3.8).

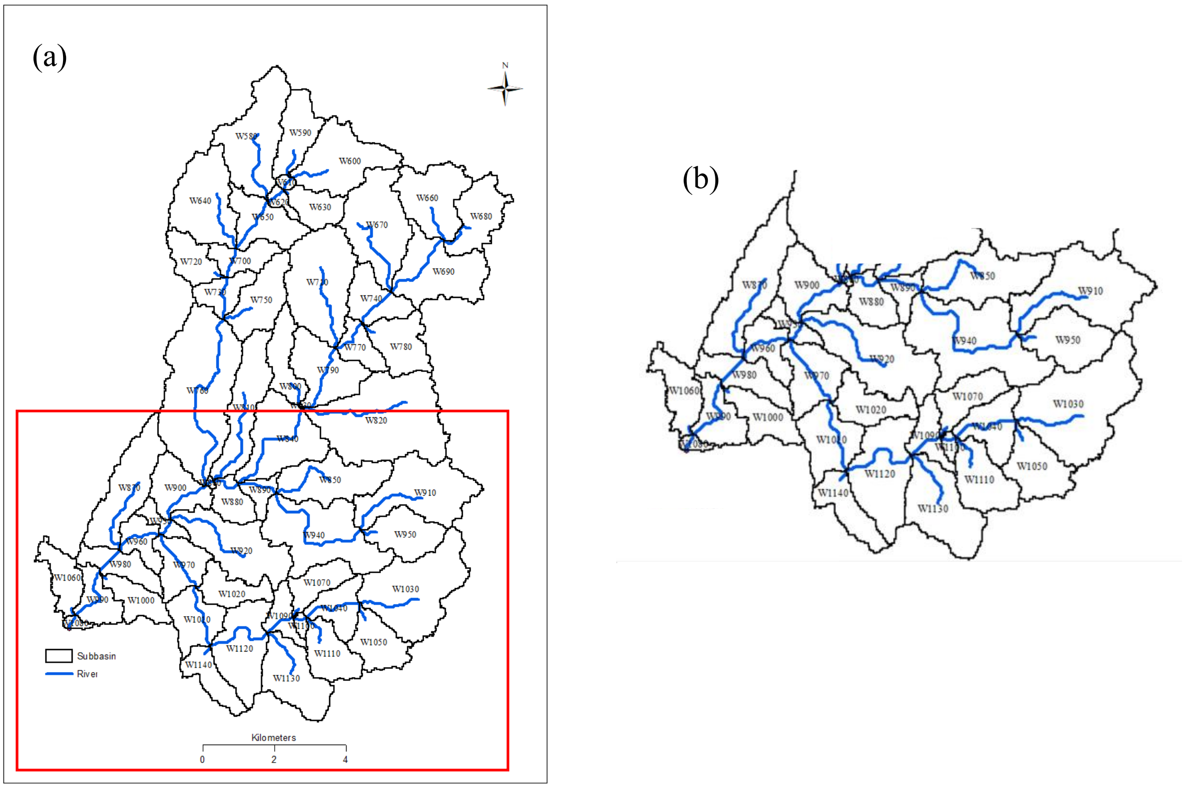


Figure 3.8: (a) Illustrates the complete Vrishabhavathi valley. Red box represents the area of the valley chosen for the discussion of the simulation results (b) sub-basins chosen from the red box for the discussion of the simulation results.

3.4.2.6 Sensitivity analysis

To check the sensitivity of the software, simulation was carried by altering the values used for the CN lookup table of the year 1975. The altered values used for the simulation is shown in Appendix E

All the results of the simulations are presented and discussed in Chapter 5 of this report.

4 Hydrological and hydrogeological consequences of rapid and large–scale urbanization based on a literature review

Hydrological and hydrogeological processes together can be referred to as the water cycle. When the natural water cycle is altered, its process and its properties also get altered. This chapter describes the hydrological and hydrogeological consequences due to rapid and large-scale urbanization through literature study of three cities.

4.1 Shanghai, China

China is one of the developing countries and over the past 30 years the country is experiencing urbanization. As per the year 2015, China´s urbanization rate had reached 56%. The rate of urbanization is greater towards eastern China when compared to western China (Yang, 2013).

Shanghai is the largest and most densely populated city of China (Lu et al., 2016). The city lies towards the east coast and Figure 4.1 shows the location of Shanghai city in China. The city has an area of about 6340.5 km^2 and according to the 2010 census the population was 14.12 millions. The city experiences four seasons and is influenced by the humid subtropical monsoon circulation. The annual mean temperature is around 15.8°C and the annual mean precipitation is 1149mm (Cui and Shi, 2012).

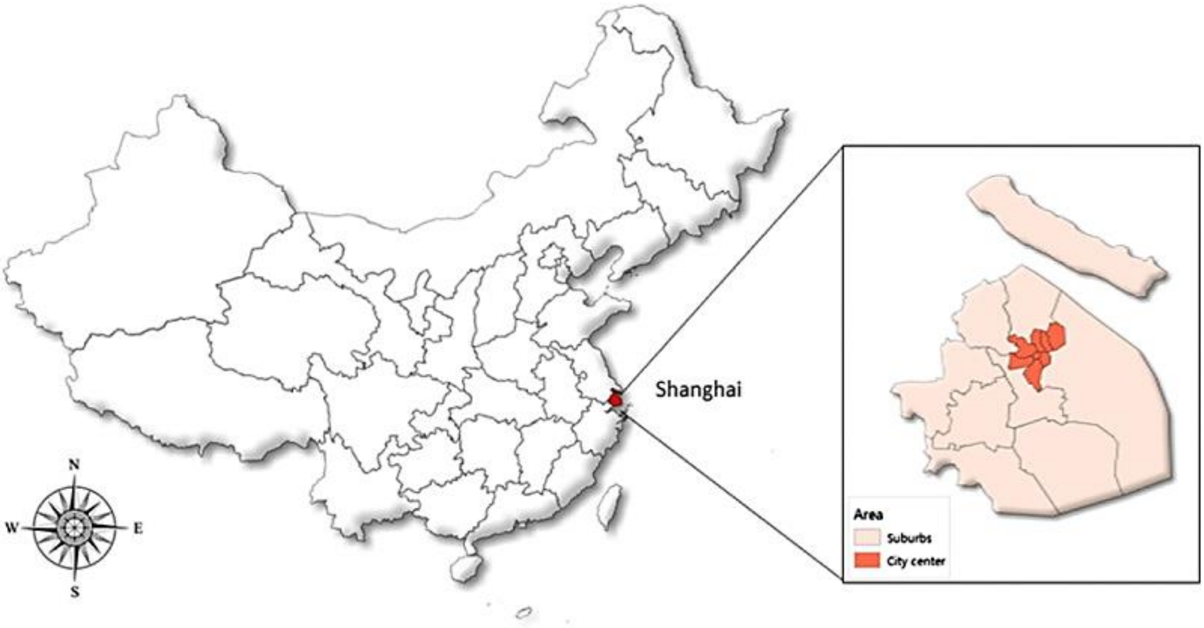


Figure 4.1: Location of Shanghai City, China (Lu et al., 2016)

The main reason for the city´s urbanization is due to industrialization and economic growth. The city is the industrial centre of China and has over 1000 factories and industries in the city centre (Yin et al., 2005). Shanghai has experienced rapid urbanization from year 1945 to 2010 and the population has increased from 5.03 millions in 1949 to 14.12 millions of persons in

2010. The population density has increased from 1734 persons per kilometre square to 3632 persons per kilometre square between the years 1970 and 2010 (Cui and Shi, 2012).

Due to the rapid development, the city has experienced huge changes in the land use over the past three decades (Cui and Shi, 2012). Figure 4.2 shows the land use changes of the city for the years 1994, 2000 and 2006. It can be observed that the green land and agricultural land is converted to residential land and public facilities. In the year 1994, the residential land was less when compared to the year 2006. This is due to the urbanization: more and more construction has taken place to accommodate and meet the demands of the growing city.

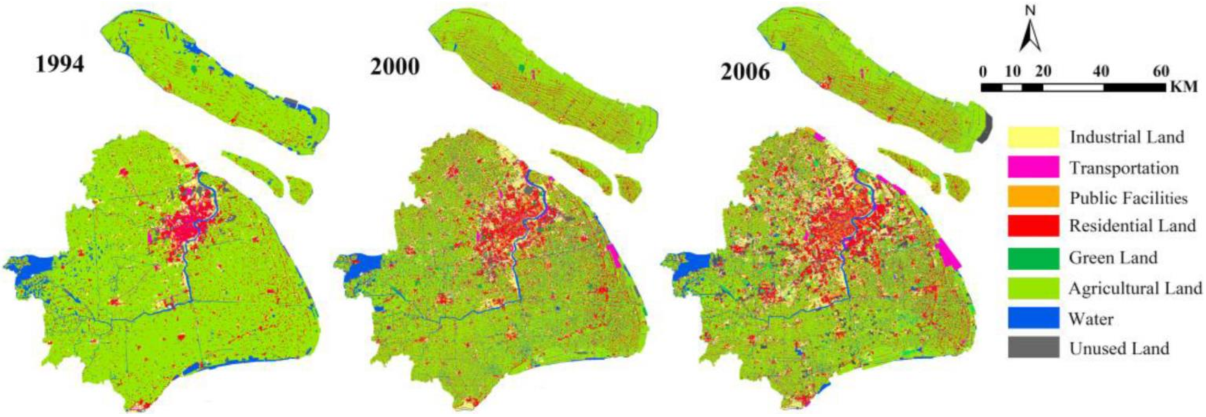


Figure 4.2:Land use of Shanghai city for the years 1994, 2000 and 2006 (Zhang et al., 2016).

The geomorphology of Shanghai is divided into four types i.e., the western lacustrine plain, the central Huangpu River plain, the eastern coastal plain and the estuarine delta. Most parts of Shanghai are a soft deltaic deposit with some isolated outcrops of bedrock. Most of the bedrocks lies under Quaternary and Tertiary sediments at a depth of about 300m (Lu et al., 2016).

The Quaternary deposits mainly consist of a Holocene phreatic aquifer group and five artesian aquifers. These artesian aquifers are separated by six aquitards (Xu et al., 2009). Figure 4.3 shows the hydrogeological profile of the city.

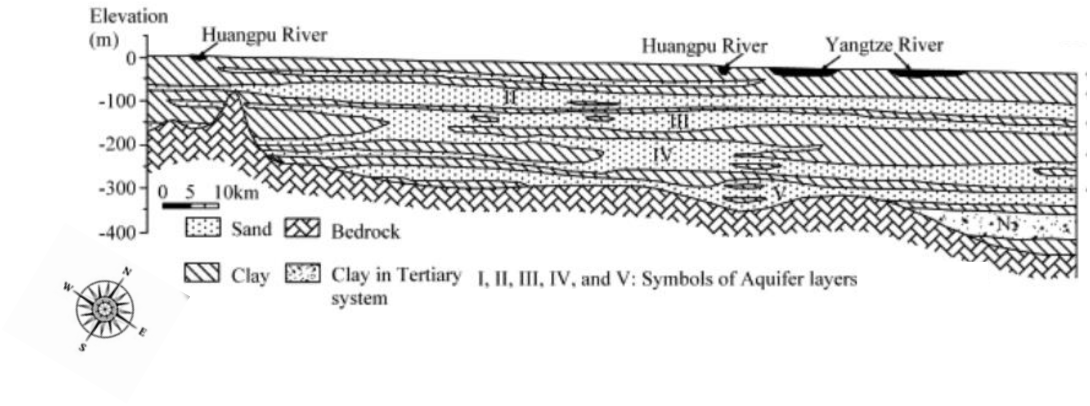


Figure 4.3: Hydrogeological profile of Shanghai (Xu et al., 2009).

Some of the aquifers contain clay lens structures that are well consolidated and are rich in clay. Lagoons and marine sediments are less consolidated and are rich in organic material. Both the well consolidated and less consolidated layers have low hydraulic conductivity and can be referred to as aquitards. Infiltration from precipitation is the major source of recharge for the unconfined aquifers and the vertical and lateral seepage from the surface water is the secondary source of infiltration. The confined aquifers are recharged mainly by the seepage from the river channel of Yangtze River (Xu et al., 2012).

The main source of water for the city is from the Huangpu river and groundwater. Due to the poor quality of the unconfined aquifer and the 1st confined aquifer, pumping is relatively small in these aquifers. However, the major part of groundwater extraction is from the 2nd and 3rd confined layers (shallow aquifers) and also from the 4th and 5th confined aquifers (deep aquifers).

4.1.1 Hydrological and hydrogeological consequences

Rapid urbanization has caused a lot of changes to the land use of the city. It has led to reduction of cultivated land and increased built up area and paved roads (Cui and Shi, 2012).

The growing city needs to accommodate the increasing population, this in turn has an effect on global, regional and local weather and climate because of land use changes and that in turn is related to the other physical processes such as changes in the exchanges between land surfaces and the atmosphere. Urbanization has a major impact on the regional near-surface air temperatures and wind fields. This also influences the air quality (Cui and Shi, 2012).

According to Cui and Shi (2012), land use changes have an impact on the temperature. An increased impervious land also leads to a higher temperature in the urban areas compared to the surrounding areas. This leads to a phenomenon called heat island. Heat island also called Urban Heat Island (UHI) is an urban area that is significantly warmer than the surrounding area due to human activities.

According to Ren et al., (2003), rapid urbanization has led to a decreased water quality One of the main reasons for the decreased water quality is the low capacity of sewage treatment that has led to the industrial and residential waste being discharged directly to the river.

Due to large built up area, the load on the soil increases. The growing city has led to construction of underground structures such as tunnels and foundation pits. The groundwater levels have decreased in the long-term due to the leakage of the tunnel linings, cut off of groundwater flow due to under-ground structures in the aquifers and reduced replenishment of groundwater from suburban regions. All these factors influence land subsidence in the city. Also increased extraction of groundwater has led to sea water intrusion in the coastal area (Xu et al., 2009).

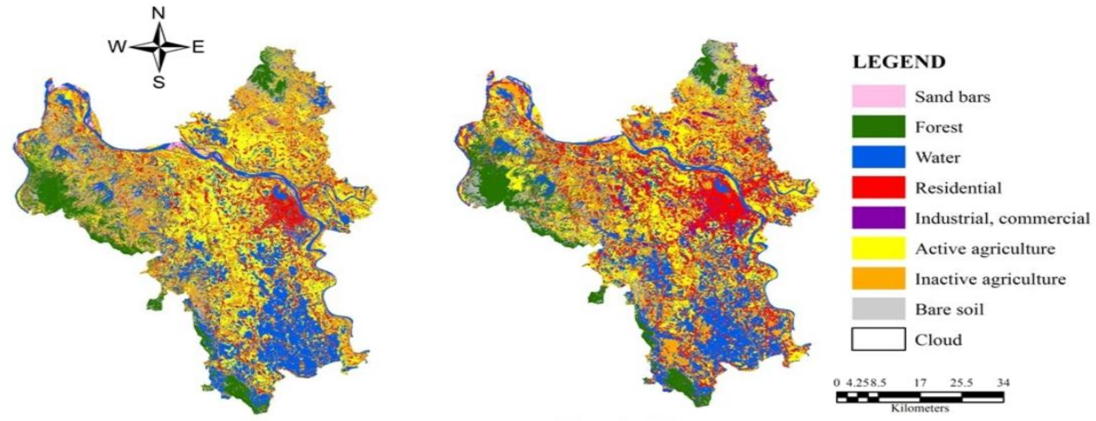
4.2 Hanoi, Vietnam

Vietnam is situated in southeastern Asia and the country has rapidly been urbanized since it adopted economic reforms in 1986 (Nong et al., 2018). Hanoi is the second largest city and the capital of Vietnam (Nguyen and Anh, 2016). The city is located in the upper part of the Red river delta and Figure 4.4 shows the location of the city. This city experiences the maximum rate of urbanization in Vietnam (Thuy and Duy, 2014).

Groundwater is the primary source of domestic water in Hanoi city. As the area has been urbanized rapidly and in a large-scale, the city´s water demand has increased and is expected to increase more in the coming years. To meet the growing demands of the city, supply of surface water was developed in the year 2008. Groundwater is still a prominent source in the suburban and rural areas surrounding the urban centre of Hanoi. The city experiences a humid, subtropical climate and receives in average 1680 mm of annual precipitation. The precipitation mainly occurs during the rainy season, that is from May to September (Kuroda et al., 2017).

Figure 4.4: Location of Hanoi city, Vietnam (Vietnam Briefing, 2013., Pulliat,2015., edited by author).

As the city experiences rapid and large-scale urbanization, land use has changed over the years to accommodate the growing city. Figure 4.5 shows the land use change in the Hanoi city. There is an increase in the residential area in the year 2014 when compared to the year 2003. This indicates increase in the built up area, which means that the natural soil is compacted to make conditions favourable for the construction purposes.



Year 2003

Year 2014

Figure 4.5: Land use of Hanoi city for the year 2003 and 2014 (Kuroda et al., 2017).

The city is characterized by a fluvial system including rivers and levee belts, floodplain and fluvial terraces. The river delta is made up of Quaternary sediments of alluvial and marine origin (Kuroda et al., 2017). The Quaternary deposits consist of sand, gravel and cobbles imbedded with fine layers of clay, silt and sand (Trafford et al., 1996).

The geological layers below the city consist of unconsolidated sediments of alluvial and marine origin and their total thickness is around 50-90 m. These sediments contain large volumes of water and thus there are aquifers within them (Trafford et al., 1996). The Quaternary formations are classified into two aquifer systems (Kuroda et al., 2017), namely the Upper Aquifer System (UAS) and the Lower Aquifer System (LAS). The UAS is separated from the LAS by semi-permeable clay layers or aquitards. Due to the presence of a meandering river the thickness of the aquifers varies. The UAS is typically around 20-40 m deep in most of the places. The UAS acts as a leaky layer or semi confining layer to the underlying aquifer system. The LAS is also called the Hanoi Aquifer and it consists of highly permeable sand and gravel aquifers. The LAS lies above a sandstone of Neogene age and the latter is unconsolidated at its contact with the LAS (Trafford et al., 1996). A schematic cross-section of the aquifer system is shown in Figure 4.6.

A large amount of recharge of LAS is received from the Red river especially where the semi confining layer is thin or relatively permeable or absent. The LAS is also recharged from the other surface water courses. Prior to the 20th century recharge of both UAS and LAS occurred in response to the levels of the river (Trafford et al., 1996).

Aquifers or the groundwater that are near the river and the central urban area, are laterally recharged by the Red river. However, the aquifers of the city that are located far away from the river are recharged from other surface water bodies (Kuroda et al., 2017).

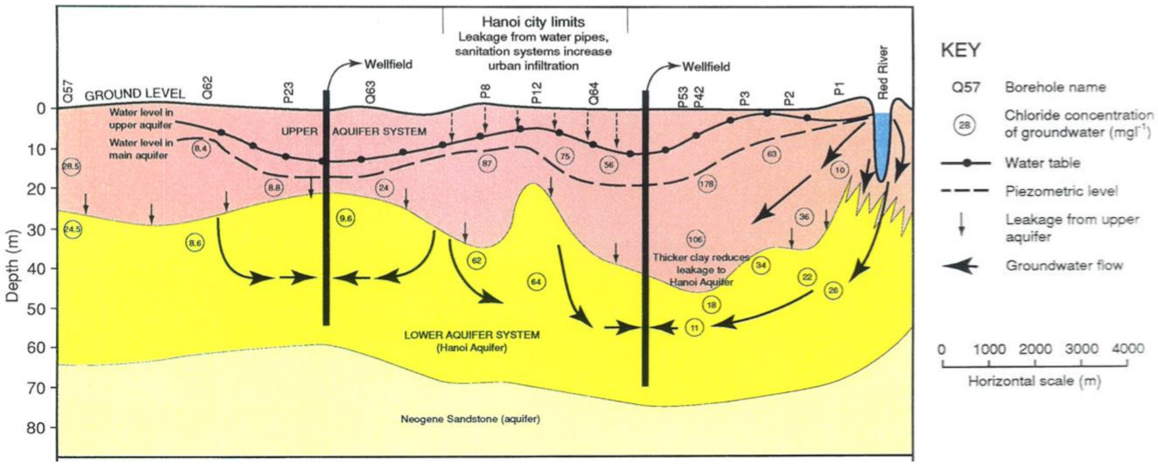


Figure 4.6: Geological cross-section of the aquifer system beneath Hanoi showing the variation of the Upper Aquifer System (UAS) and the Lower Aquifer System (LAS) (Trafford et al., 1996).

The population received water either from surface water or shallow wells as the groundwater exploitation of the LAS was limited prior to independence in 1954. Since the 1960´s groundwater supply of the city has increased. Due to the exploitation of groundwater to meet the demand of the city, the groundwater levels of the LAS have declined. The reduced levels in the LAS are mainly observed around and close to Hanoi city. Due to the rate of urbanization faced by the city, the recharge process has been altered and that has also affected the groundwater levels (Trafford et al., 1996).

4.2.1 Hydrological and hydrogeological consequences

Rapid and large-scale urbanization of Hanoi has led to the encroachment of lakes, wetlands and other surface water bodies. In addition to this the land use has changed, barren land and irrigational land have been converted to built up areas.

As the city lies next to the Red river, the aquifers in this area are recharged laterally by the river. Hence, groundwater variation is hardly observed in this region. But before urbanization, the groundwater dynamics and recharge system were different, and the recharge of the groundwater was mainly vertical from the local surface water bodies and the lateral recharge was seasonal. However, according to Kuroda et al., (2017) in the areas located around five km away from the river, local surface water bodies are still the main source of recharge and lateral recharge from the river acts as a minor source for the groundwater.

The city has only some small septic tanks that are installed for the wastewater of private houses, Hanoi has no sewerage system i.e. almost all industrial and private wastewater are directly conveyed into the Red River which leads to water quality degradation (Fischer et al., 2011).

In case of Hanoi city, the land use changes effects the surface runoff rates but the groundwater levels might not be affected at present. But according to various studies, if the rate of urbanization increases in the same pace, the city will experience decreased groundwater levels and this in turn will lead to land subsidence (Kuroda et al., 2017).

4.3 Bengaluru, India

India ranks second in world´s population and is a developing country of south Asia. The main reason for urbanization in India is due to liberalization of its economy after the 1990´s. This gave rise to a development of the private sector (United Nations University, 2013). Bengaluru is the capital city of Indian state Karnataka.

This city was once a small village with the population of 0.7 million in 1951, but now it is one of the fast-growing cities of India and it is the main hub of business and technological investments (Indiaonlinepages.com, 2017). Figure 4.7 shows the location of Bengaluru city. The city covers an area of 720 km^2 (Sekhar et al.,2017) and the population of the city was over 12.3 millions in 2017. Among the Indian cities, Bengaluru city ranks third in the population growth (Indiaonlinepages.com, 2017).

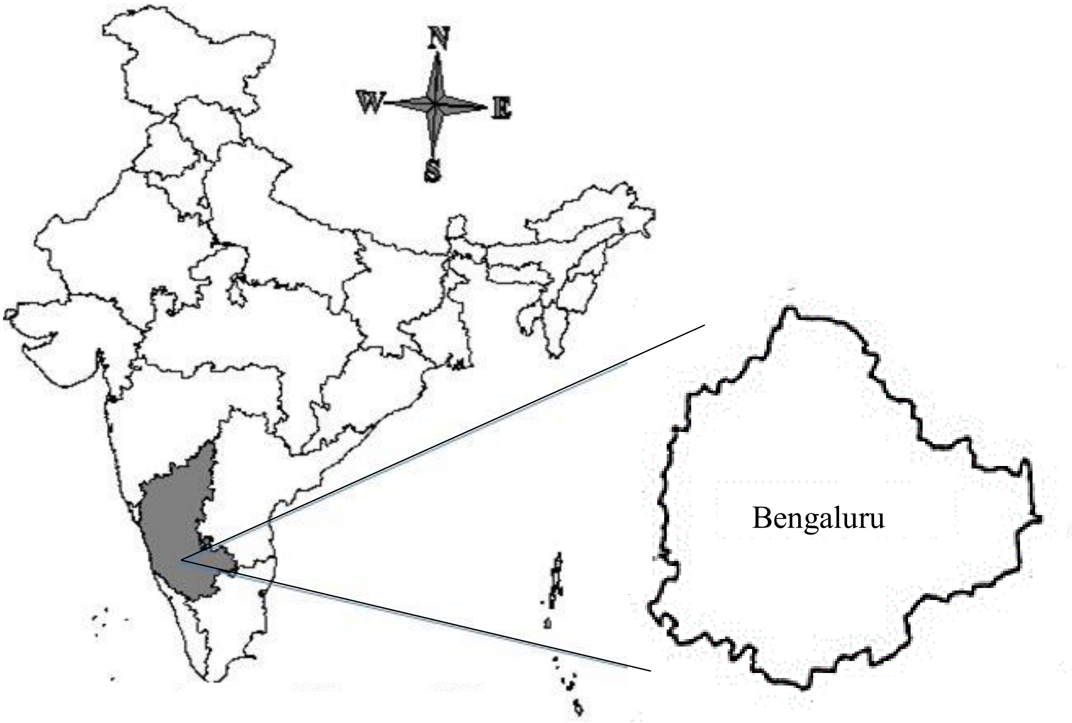


Figure 4.7: Location of Bengaluru city, India (TV et al., 2012)

The climate is semi-arid with rainfall of about 820mm and the month of September receives the peak rainfall. Around 60% of the rainfall occurs from the south-west monsoon from June to September. The northwest monsoon also brings rain from October to December. January to May is considered as dry period, although conventional thunderstorms occur from March through May. January and February hardly receive any rain (Sekhar et al.,2017).

The city lies mainly at an elevation of 900 to 970 m above mean sea level (Figure 4.8) with river Arkavathi draining to the west and South Pennar to the east (Sekhar et al., 2017). The east flowing rivers join together outside Bengaluru city.

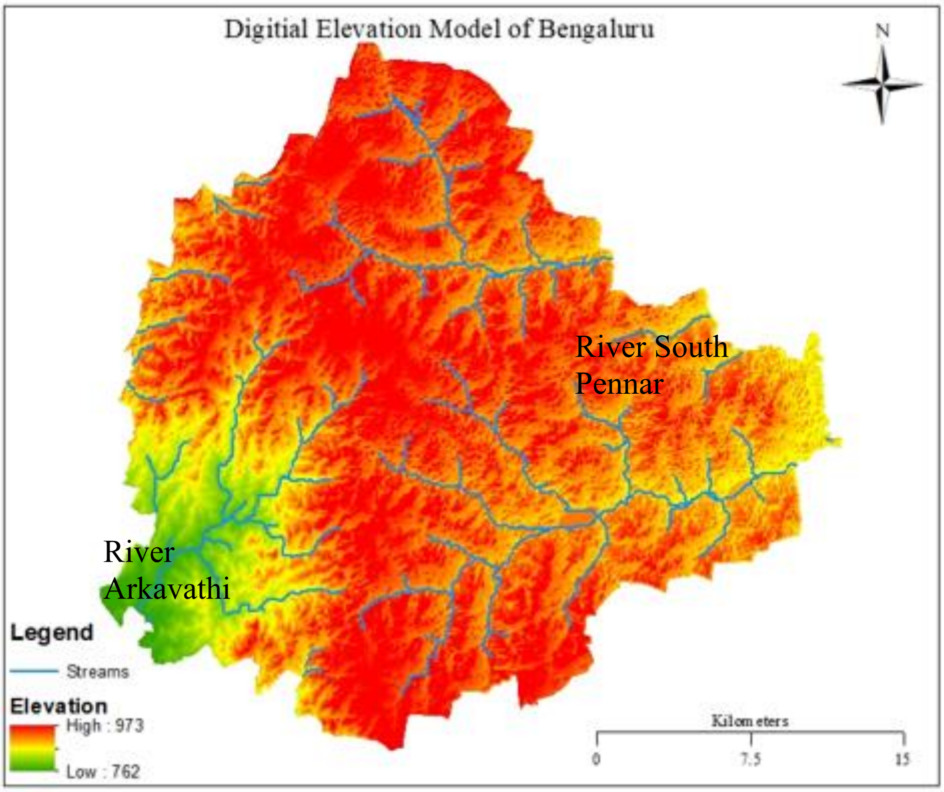


Figure 4.8: Digital Elevation of Bengaluru City.

The city was once well known for its pleasant climate throughout the year and for its numerous lakes. Due to the rapid and large-scale urbanization, the lake areas are encroached for construction or for commercial purposes and sometimes illegally. In the early stages of the formation of Bengaluru city, some of the artificial lakes were built to store the water, check floods, and for recharging and maintaining the water table. The lakes also acted as sediment traps, prevented clogging up of natural valleys and regulated run off that in turn reduced the erosion (Central Ground Water Board, 2011). Most of the lakes around the city were interconnected to fulfil the water requirements of the city. This not only fulfilled the water requirements of the city, but also recharged the groundwater. As the city grew, the area with impervious surface layer increased, for example natural soil was turned into built up areas. In addition, some of the lakes were filled with sewage water and thus polluted. Example of lakes that were polluted or converted to built up areas are as listed below and Figure 4.9 shows the locations of these lakes:

- Kempambudhi lake was filled with sewage water
- Dharmambudhi lakes were converted to Central bus terminus of the city
- Sampangi Lake was converted to open ground and later into the Kanteerava stadium
- Karanji lake was converted to Gandhi Bazaar market.
- Kemapura Agrahara was transformed into residential locality (Nagendra, 2016).

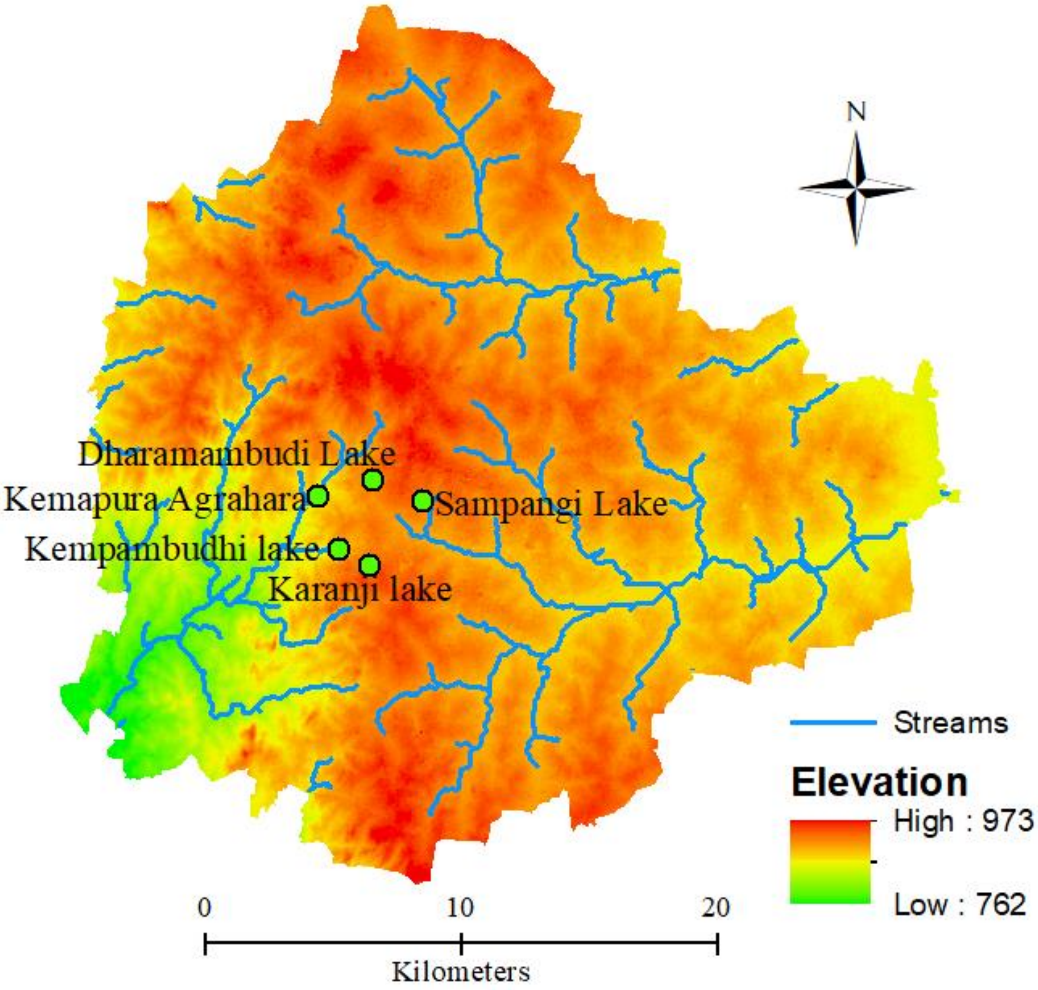


Figure 4.9: Location of a few lakes that were converted to built up area.

Due to the rapid and large-scale urbanization, the city´s land use has changed adversely. Figure 4.10 shows the land use of Bengaluru city for the years 1975 and 2017. From the figure it can be observed that the vegetation is almost replaced with urban & built up areas. In the year 2017, the land use in centre of the city is mainly barren land, this can be explained due to the progress of large-scale construction of central metro station in this particular part of the city.

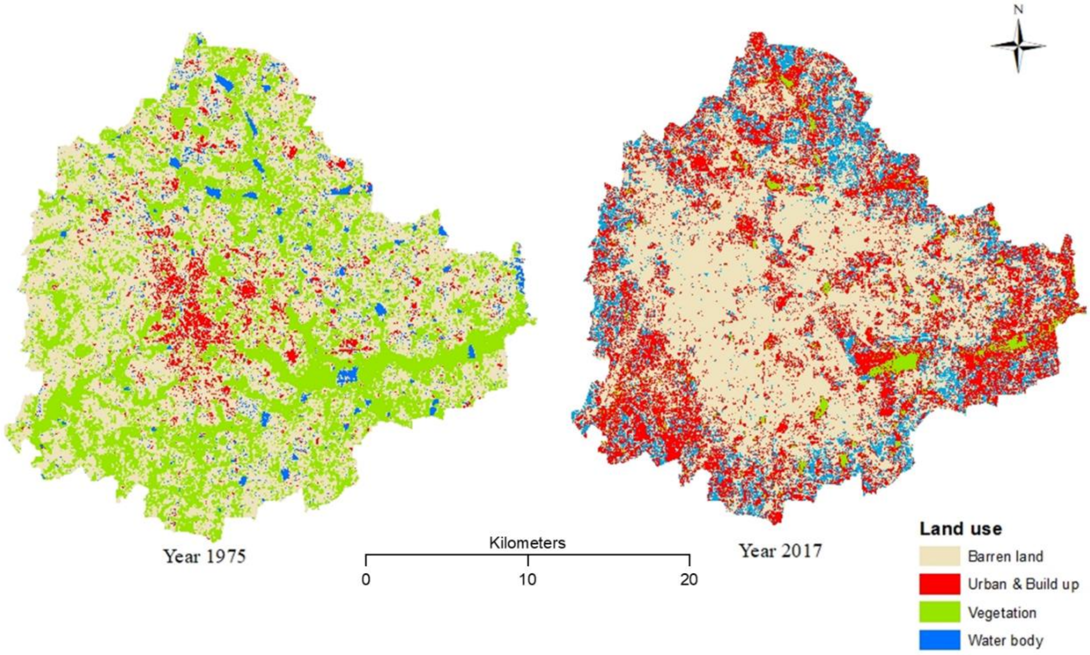


Figure 4.10: Land use of Bengaluru city for the years 1975 and 2017.

The geomorphological landforms can be divided into rocky upland, plateau and flat topped hills at a general elevation of 950 m above sea level. The major part of the city is sloping towards south and south east forming pediplains scattered with hills all along the western part. The majority of the city is formed by the pediplains and underlain by granites and gneisses. The pediplains are dissected by the streams flowing in the southern direction (Central Ground Water Board, 2013).

The city´s soil can be classified into red loamy soil and lateritic soil. Red loamy soil and sandy soil occurs on hilly to undulating land slope on top of granite and gneiss. The soil is light textured and have good infiltration rate naturally. Laterite soil occurs on undulating terrain forming plain to gently sloping topography (Central Ground Water Board, 2013) .

The major aquifer system in Bengaluru is found in granite and gneiss. Groundwater occurs under phreatic conditions in the weathered rocks and under semi-confined conditions in the joints and fractures of granite and gneiss. The occurrence and behaviour of groundwater in Bengaluru is described under three zone according to the exploration studies carried out by the Central Ground Water Board (2011). The three zones are classified as the shallow zone, the moderately deep zone and the deep zone.

The water supply scenario of Bengaluru city can also be divided into three subareas. The first and inner most subarea is fully covered with pipe water supply from the rivers Cauvery and Arkavathi. The second and intermediate subarea is partially supplied with surface water. The third and outer-most subarea comprises 111 villages and is situated in the green belt area (the area which can be used only for purposes of agriculture, horticulture etc., and large-scale activities are not permitted) (Central Ground Water Board, 2011).

The core area of Bengaluru city that is the innermost area has the shallowest groundwater levels in the range of less than 2-5m below ground in post monsoon season and 3-10m in pre-monsoon. Meanwhile the depth to the groundwater in the outer zone is 8-15m in post monsoon and 10->20m below ground level in pre-monsoon season (Central Ground Water Board, 2011).

Water levels, in the outer boundaries of the city have direct relationship with urbanization of the area. This is due to construction of new colonies or layouts and water to these new areas have been provided through boreholes, hence putting pressure on the groundwater resources. With increased construction activities, recharge has been reduced and as a result there is a fast lowering of the water table (Central Ground Water Board, 2011).

4.3.1 Hydrological and hydrogeological consequences

Bengaluru city does not have its own water resource except the aquifers . The lakes around the city were gravity fed and excess water was redirected to the low altitude lakes through canals, and the natural elevation of the city indicates that water can percolate on its own down the slopes. These lakes served as climate stabilizers over the years. As the lakes have been converted to built up areas, giving rise to an increase in impervious land, there is hardly any space for the water to percolate through the surface and recharge the groundwater (Manasi and Jamwal, 2016).

Unplanned urbanization has altered the natural drainage system of the catchment area resulting in an increased volume and rate of surface runoff. Due to the altered drainage system, the current drainage system does not have the capacity to handle the increased volume of water. Encroachment of the lakes, wetlands and flood plains have led to loss of natural flood storage (Manasi and Jamwal, 2016).

Bengaluru city is designed with a storm water drainage system to handle up to 30 mm of rainfall in an hour. But when there is heavy downpour, due to the natural gradient of the city and lack of open space, the low-lying areas of the city will be flooded. Rapid urbanization and hydraulic insufficiency of the drainage system are the major causes for urban flooding in Bengaluru city.

Increased areas of impervious layers and encroachment of lake areas have affected the local climatic conditions. Extreme rainfall events and rise in temperature are observed. The city also experiences the urban heat island effect (Manasi and Jamwal, 2016).

There is an increased pressure on the basic amenities such as drinking water, housing, sewerage, etc., from the urban people. There is also increased pressure on the necessary infrastructure and transport requirement of the growing population. This puts the natural resources (high consumption of sand, wood, minerals, etc.) and urban ecology (increased air pollution, water consumption, groundwater depletion, etc.) at risk (Manasi and Jamwal, 2016).

Rapid and unplanned urbanization has its impact on the water resources of the city, especially the groundwater with the increased exploitation by boreholes and wells dug up in all possible terrains. Due to the over-exploitation of groundwater resource, the water levels have reduced and the only solution to increase the groundwater resource is through rainwater harvesting and artificial recharge (Central Ground Water Board, 2013).

Due to rapid and haphazard urbanization, the sewage waste is directed or led to the lakes. The sewage system of new colonies or layouts are not connected to the main sewers. The effluence from such natural drains leading to the lakes, deteriorate the quality of water. It is also observed that, in the western parts of the city, all sewage is let into Vrishabhavathi river valley and most of the lakes are also polluted from sewage source (Central Ground Water Board, 2013).

5 Results and discussion

This chapter presents and discuss the results obtained from the findings of the literature review and the simulations carried out as a part of the thesis study.

The initial literature review produced number of hits regarding the consequences of rapid and large-scale urbanization, *see Table 3.1.* Most of the literature found did not meet the selection criteria formulated in section 3.1 of this report.

The cities selected for the literature review and the simulation carried out, are presented and discussed in the subsequent sections of this chapter.

5.1 Selection of the cities and the reviews from each city

Not all the literature gathered was relevant for this study. The literatures were checked for its relevance with the aim of this thesis and was narrowed down to be relevant to the study regarding the selected cities.

The selected cities were Shanghai – China, Hanoi – Vietnam and Bengaluru – India. All the three selected cities are from Asian countries. There are many other cities that are in phase of rapid and large-scale urbanization but as the literature for most of the other cities were mainly available in their native language and to limit the study only above mentioned cites were selected and the reason for the selection of these cities are mentioned in section 3.1 of this report.

The three cities have certain consequence in similar such as increased surface runoff and reduced amount of infiltration due to the change in land use over the year and water quality degradation. But other than these, the cities also faced other consequence which is discussed in the subsequent sections. It is difficult to compare the consequence faced by each city as, the changes faced by the cities, the local conditions and other factors are not similar in all the cases.

5.1.1 Consequences faced by Shanghai – China

The city is densely populated and there is an increase in impervious layer over the years due to change in land use. Hence, this has led to local climate change and a phenomenon called heat island. Further due to rapid and large-scale urbanization, the capacity of the waste water treatment plants is not sufficient to meet the growing demands, hence the untreated waste water is directed towards the river leading to water quality degradation. Also due to the underground construction such as tunnels and foundation pits have led to decreased groundwater levels in the long-term and this has led to land subsidence in the city.

5.1.2 Consequences faced by Hanoi – Vietnam

In case of Hanoi, as the Red river is the primary source of lateral recharge for the aquifers, there is hardly any changes in the groundwater levels. But before urbanization the groundwater recharge was mainly vertical from the local surface water bodies and the lateral recharge was seasonal. As the city experiences land use changes over the years, surface water bodies such as lakes and wetlands are encroached, and this has led to increased surface runoff.

The city does not have proper wastewater treatment plants, the sewage water from the houses and industries are directly led to the Red river. This has caused water quality degradation in Hanoi.

5.1.3 Consequences faced by Bengaluru – India

Bengaluru was well known for its pleasant climate throughout the year and numerous lakes. Due to rapid and large-scale urbanization there is striking change in the land use. Lakes have been encroached and there is hardly any place for the water to percolate through the surface and recharge the groundwater. The natural drainage system is altered, and the current drainage system does not have the capacity to handle the increased volume of water.

Due to the lack of open space and natural gradient of the city, the low-lying areas of the city experiences floods during heavy downpour. Due to the changes in the land use, the city experience local climate change and a phenomenon called heat island.

5.2 Results and discussion of hydrological simulations

From the literature review of the three cities, increased surface-runoff and reduced amount of infiltration through the ground surface due to land use change were the major and most common effects of rapid and large-scale urbanization. With reference to this the hydrological modelling and simulations were carried out to study the changes of these features over the years.

Vrishabhavathi river basin was chosen for simulation of the surface-runoff and amount of infiltration through the ground surface for the years 1975 and 2017, which represents past and present scenarios. The procedure of simulation is described and explained in section 3.4.

5.2.1 Amount of infiltration through the ground surface

Figure 5.1 shows the amount of infiltration for the years 1975 and 2017 for the selected sub-basins of Figure 3.8. The graph was created using the values from the HEC-HMS simulation. As each sub-basin has different area, it was difficult to cumulate the values from the subbasins and plot the graph. Hence, the average infiltration in mm was calculated for each year and sub-basin. From the graph it can be observed that the year 1975 has more infiltration through the ground surface. This can be explained as the year 1975 had more rainfall and pervious layer such as vegetation land was more when compared to the year 2017. The urban & built up area was mainly concentrated in the city centre in the year 1975. However, as the amount of rainfall was higher in 1975 than in 2017 (see Figure 3.7), a comparison like this of amount of infiltration through the ground surface is not fully relevant.

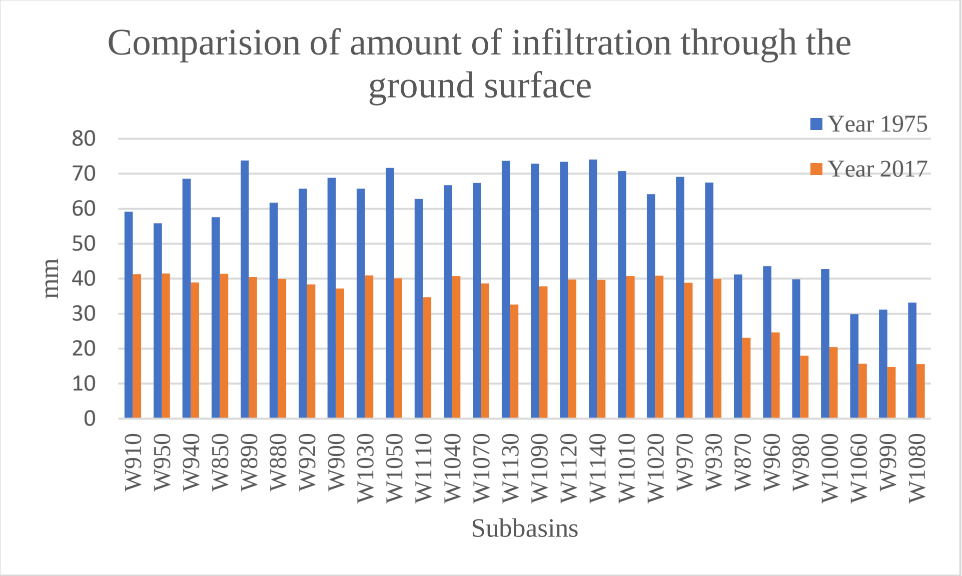


Figure 5.1: Comparison of amount of infiltration through the ground surface between different sub-basins for the years 1975 and 2017.

5.2.2 Surface runoff

Surface runoff refers to the amount of water that flows on the surface. Figure 5.2 shows that surface runoff is more in the year 1975 compared to 2017. Even though the surface runoff is more, the year 1975 also had higher rainfall and amount of infiltration through the ground surface when compared to the year 2017.

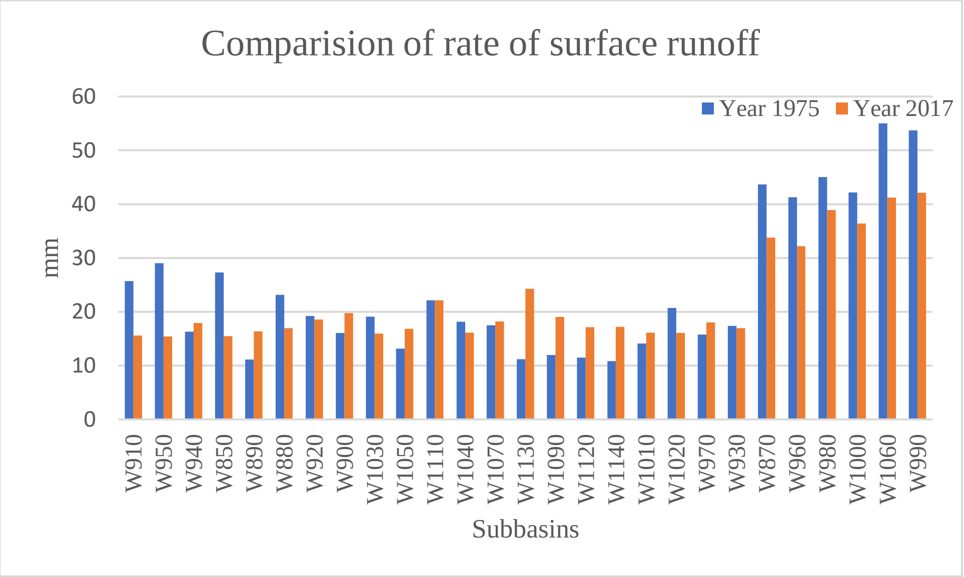


Figure 5.2: Comparison of surface runoff between different sub-basins for the year 1975 and 2017.

Hence, a comparison like this is not fully relevant as the rainfall is not the same for both the years (see also section 5.1).

5.2.3 Simulation using the same rainfall data for both the years

As the rainfall is not the same for the two years, it is difficult to study and compare the results and relate them to the rapid urbanization. Hence the year 2017 rainfall data was used for both the years to carry out the simulation and compare the amount of infiltration through the ground surface and surface runoff. All other differences between the two years, as change in land use and land cover were used in the simulation.

Figure 5.3 shows the amount of infiltration through the ground surface in mm using the year 2017 rainfall data for both the years. Even though, the same rainfall was used for the two years the amount of infiltration through the ground surface is bigger in 1975.

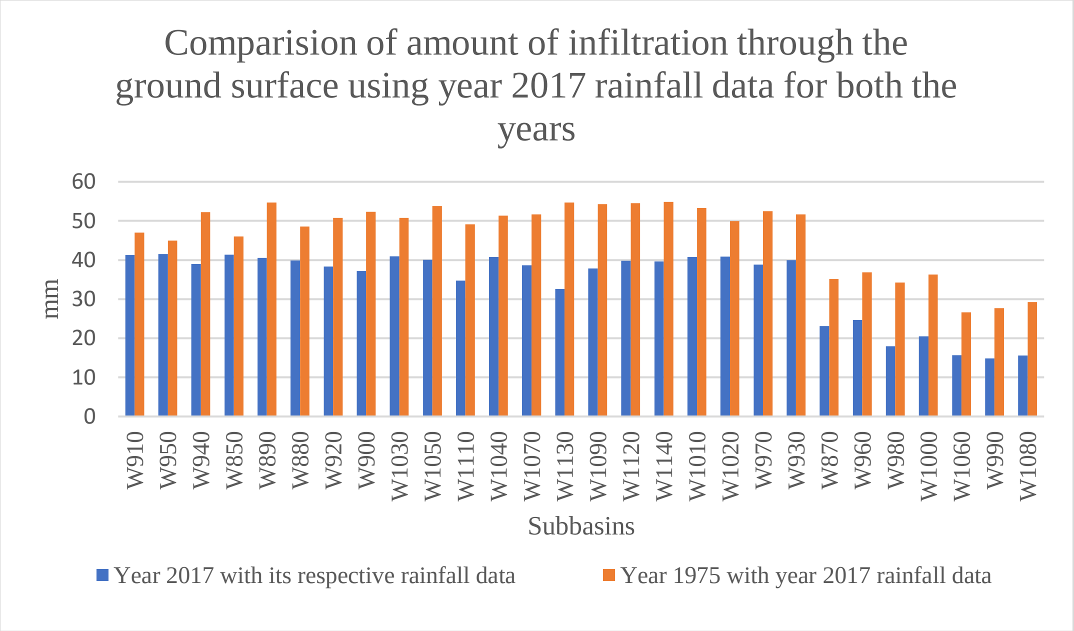


Figure 5.3: Comparison of amount of infiltration through the ground surface using the rainfall data of the year 2017 for both the years.

The year 1975 had relatively more pervious area when compared to the year 2017 and this is the reason for the higher simulated amount of infiltration in 1975.

Figure 5.4 presents the surface runoff for both the years using same rainfall data. The year 2017 has more surface runoff when compared to the year 1975. This is due to the change in the land use over the years has increased the impervious layers leading to increased surface runoff in the year 2017.

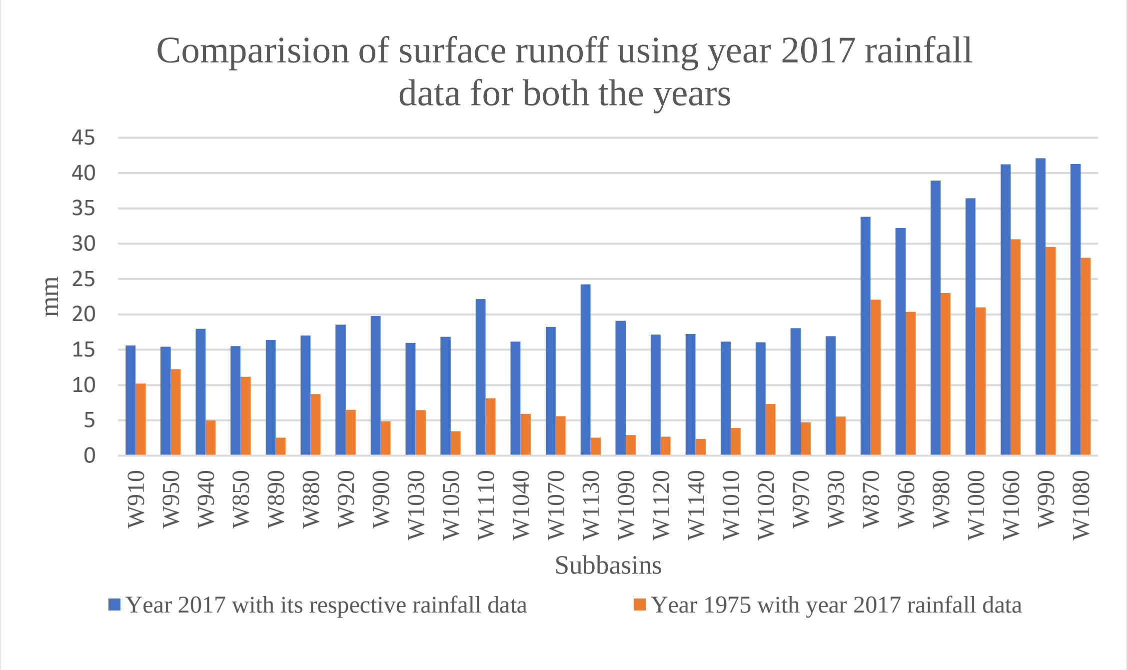


Figure 5.4: Comparison of surface runoff using the rainfall data of the year 2017 for both the years.

Hence from the results obtained from the simulation it is demonstrated that urbanization do have effects on the amount of infiltration through the ground surface and surface runoff. The major factors that contribute to these effects are change in land use, that is increased impervious layers over the years leads to these changes. From Figure 5.4 it can also be observed that there is a change in the surface runoff pattern. The peaks in the blue line are representing the sub-basins that are situated close to the outlet (sub-basins W870, W960, W980, W1000, W1060, W990, W1080). Hence these peaks indicate that there is an increased risk for flooding in these sub-basins after a long period of large-scale urbanization.

Hence the results from the simulation confirms that there is reduced amount of infiltration through the ground surface and increased surface runoff and also it is in line with the consequences studied in the literature review of this thesis.

5.2.4 Sensitivity analysis

To check the sensitivity of the software, an analysis was also carried out by altering the values used for the CN lookup table. Figure 5.5 shows the results from one of the basins regarding amount of infiltration through the ground surface. The blue line present the same CN values as used in the main simulation (Table 3.3) and the orange lines represents the results with the altered CN values. Appendix E shows the altered CN values.

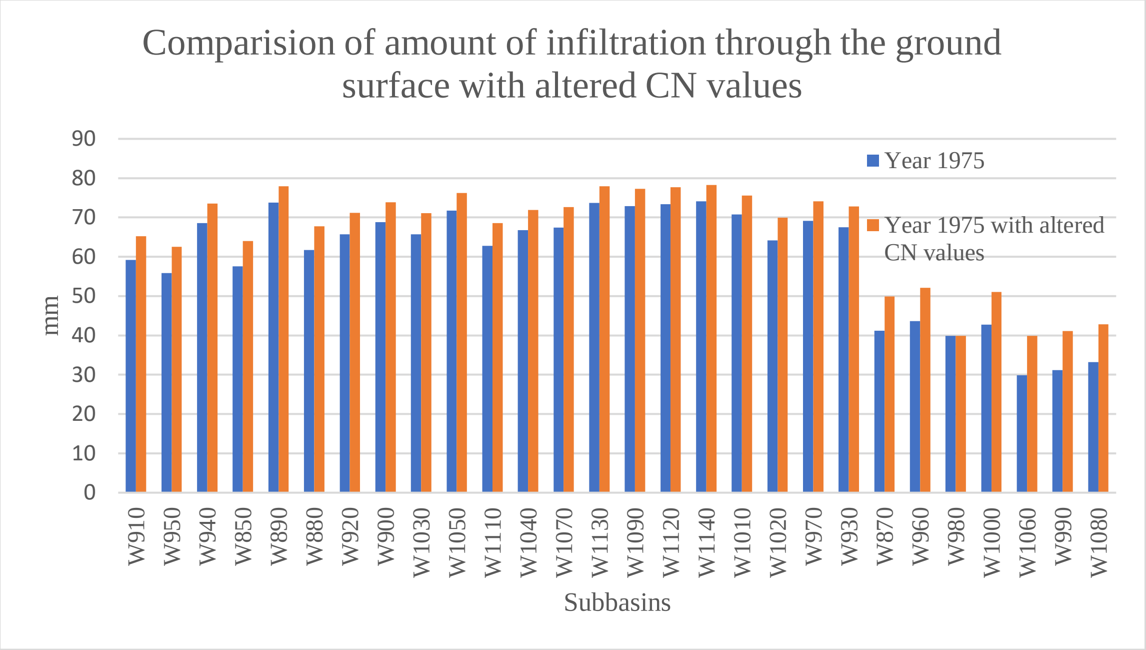


Figure 5.5: Comparison of results from the altered CN values.

From the graph it can be observed that the amount of infiltration is different in the two cases. This proves that the software and the simulation results are sensitive to the values used and are representing the hydrological processes in an expected way.

6 Conclusion and recommendations

It is concluded from the literature review that rapid and large-scale urbanization is one of the factors that alters and effects hydrological and hydrogeological processes. These effects have an impact on the local environment in the long-term. Severe hydrological and hydrogeological consequences due to rapid urbanization have been identified from the studied cities namely Shanghai- China, Hanoi- Vietnam and Bengaluru- India. The three cities have certain consequence in similar such as increased surface runoff and reduced amount of infiltration due to the change in land use over the years and water quality degradation.

The results from the simulation are in line with the literature review and confirms that rapid and large-scale urbanization have effects on groundwater. Due to the reduced amount of surface infiltration and increased surface runoff the groundwater table is reduced.

Few measures could be taken to decreases the negative effects of urbanization. Some of the measures that can be taken to save the city might be construction of permeable roads, artificial recharge, rainwater harvesting, flood management and watershed management. Further, there should be awareness created among the local people about urbanization and its consequences on the hydrological and hydrogeological processes.

6.1 Future model development

In order to develop the ArcGIS/HEC-HMS model, it is recommended to include detailed information of the watershed. Such information may include soil moisture, humidity, details from the measurement gauges, cross sections of the channel, roughness of the channels, base flow, discharge of the river basin and other characteristics of different sub-basins. Including this information will make the model more reliable and realistic. More sophisticated softwares could also be used which include the groundwater and aquifer conditions. It would also be interesting to collect information about the problems faced by the local people.

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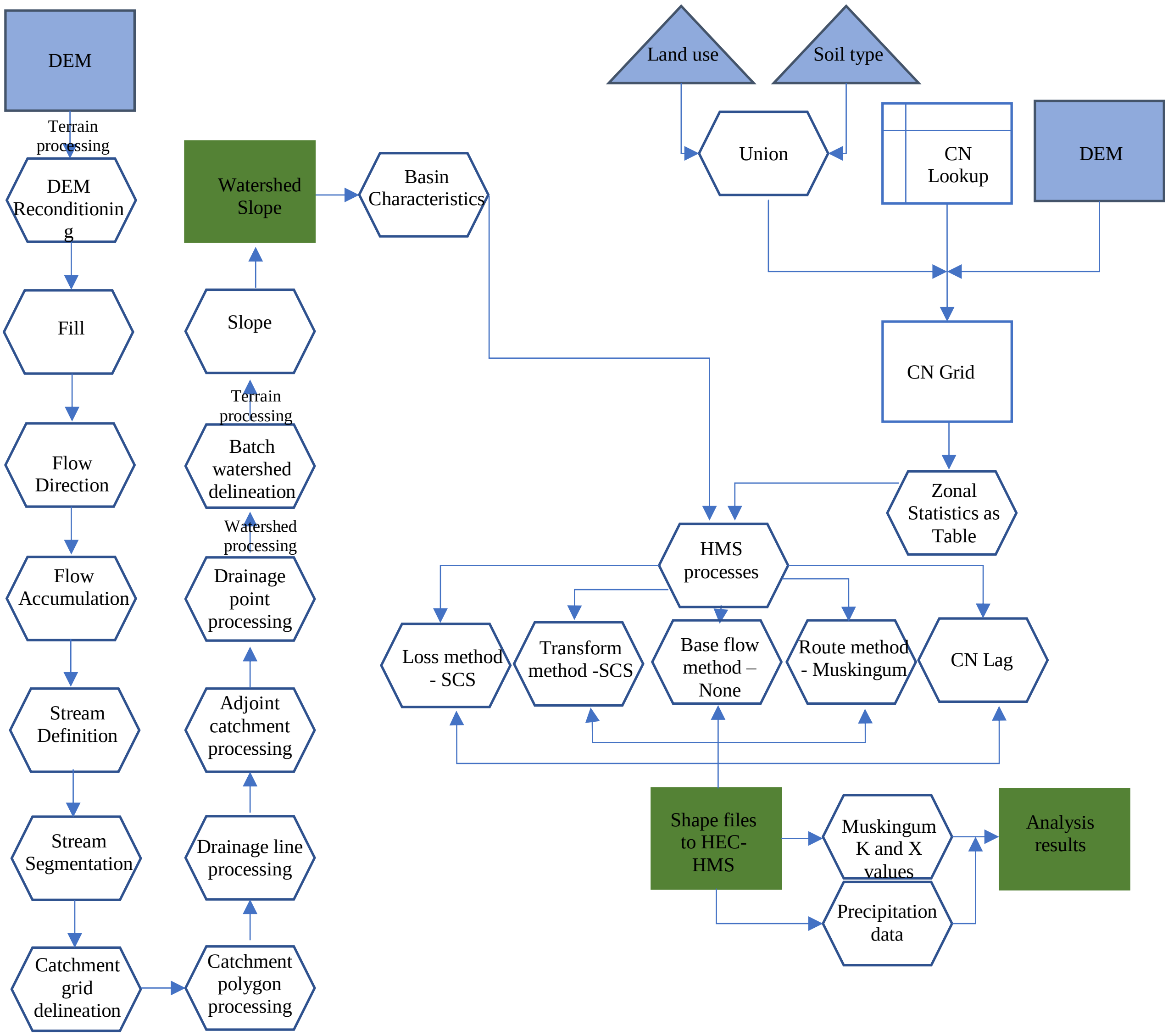
8 Appendices

Appendix A: Flow chart of ArcGIS



Above: The flow chart of the steps followed in ArcGIS is as shown above. The input data is shown in blue, the operations followed in white and processed data is shown as green colour. The flow chart was produced by the author.

Appendix B: Hydrological classification of soil and CN values

Table B1: Hydrological classification of soil

Groups	Percentage of clay	Other soils	Texture	Soils under these groups
A	Less than 10%	More than 90% of sand and gravel	Gravel or sand texture	• loamy sand • sandy loam • loam • silt loam
B	10%-20%	50% - 90% sand	Loamy sand or sand loam texture	• loam • silt loam • silt • sandy clay loam
C	20% - 40%	Less than 50% sand	• Loam • silt loam • sandy clay loam • clay loam • silty clay loam textures	• clay • silty clay • sandy clay
D	More than 40%	Less than 50% sand	Clayey textures	• clay

CN values:

The runoff curve number is based on the area´s hydrologic soil group, land use and hydrological conditions. The SCS runoff equation is given as Equation 1

Equation 1: $Q = \frac{(P-I_a)^2}{(P-I_a)+S}$

Where

Q = Runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (in) and

I_a = initial abstraction (in)

And I_a is given by Equation 2

Equation 2: $I_a = 0.2S$

By removing I_a as an independent parameter, this approximation allows use of a combination of S and P to produce a unique runoff amount. Substituting Equation 2 into Equation 1gives Equation 3

Equation 3: $Q = \frac{(P-0.2S)^2}{(P+0.8S)}$

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100 and S is related to CN by Equation 4

Equation 4: $S = \frac{1000}{CN} - 10$

Equation 3 and Equation 4 are solved from the figures given below.

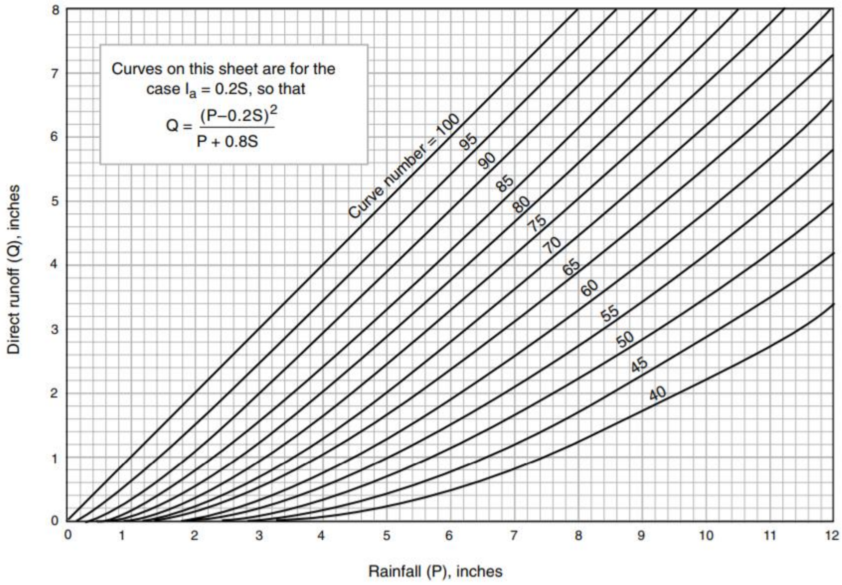


Figure B1: Solution of runoff equation

Table B2: Runoff depth for selected CN´s and rainfall amounts.

	Runoff depth for curve number of—												
Rainfall	40	45	50	55	60	65	70	75	80	85	90	95	98
	inches												
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.17	0.32	0.56	0.79
1.2	.00	.00	.00	.00	.00	.00	.03	.07	.15	.27	.46	.74	.99
1.4	.00	.00	.00	.00	.00	.02	.06	.13	.24	.39	.61	.92	1.18
1.6	.00	.00	.00	.00	.01	.05	.11	.20	.34	.52	.76	1.11	1.38
1.8	.00	.00	.00	.00	.03	.09	.17	.29	.44	.65	.93	1.29	1.58
2.0	.00	.00	.00	.02	.06	.14	.24	.38	.56	.80	1.09	1.48	1.77
2.5	.00	.00	.02	.08	.17	.30	.46	.65	.89	1.18	1.53	1.96	2.27
3.0	.00	.02	.09	.19	.33	.51	.71	.96	1.25	1.59	1.98	2.45	2.77
3.5	.02	.08	.20	.35	.53	.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	.06	.18	.33	.53	.76	1.03	1.33	1.67	2.04	2.46	2.92	3.43	3.77
4.5	.14	.30	.50	.74	1.02	1.33	1.67	2.05	2.46	2.91	3.40	3.92	4.26
5.0	.24	.44	.69	.98	1.30	1.65	2.04	2.45	2.89	3.37	3.88	4.42	4.76
6.0	.50	.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	4.30	4.85	5.41	5.76
7.0	.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.25	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.32	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

Further detailed selection of CN values including the soil type are available through Technical release 55 (TR55) by United States Department of Agriculture (USDA 1986).

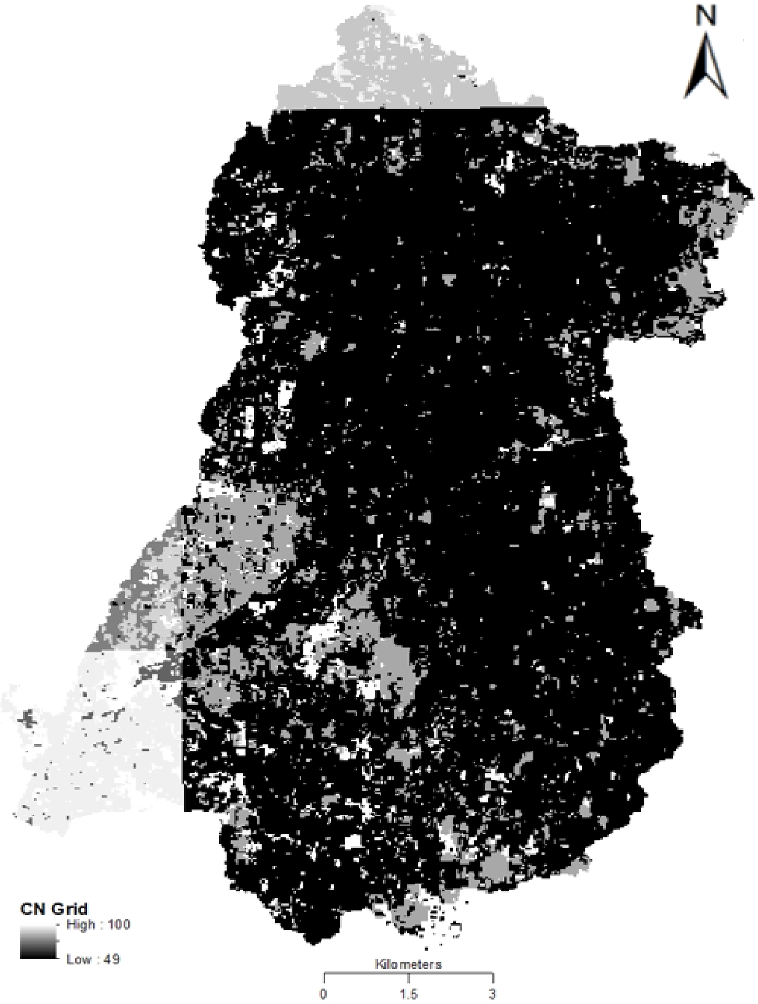


Figure B3: Illustrates the CN grid for the year 2017.

Appendix C: Different methods in HEC-HMS

Loss method:

A sub basin conceptually represents infiltration, surface runoff and subsurface processes interacting together. Some of the loss methods are:

- Deficit and Constant loss
- Exponential loss
- Green and Ampt loss
- Gridded Deficit Constant Loss
- Gridded Green and Ampt loss
- Gridded SCS Curve Number loss
- Gridded Soil Moisture Accounting
- Initial and Constant loss
- **SCS Curve number loss**
- Smith Parlange loss
- Soil Moisture Accounting loss

SCS Curve Method loss was chosen for the analysis. This method intends to calculate the total infiltration during a storm. The incremental precipitation during a storm is calculated by the program by recalculating the infiltration volume at the end of each time interval. A composite curve number which includes different soil groups and land use combinations in the subbasin should be used.

Transform method:

The actual surface runoff calculations are performed by a transform method within the sub-basin. Eight transform methods are provided as mentioned below:

- Clark Unit Hydrograph Transform
- Kinematic Wave Transform
- ModClark Transform
- **SCS Unit Hydrograph Transform**
- Snyder Unit Hydrograph Transform
- User-Specified S-Graph Transform
- User-Specified Unit Hydrograph Transform

SCS Unit Hydrograph Transform method was chosen for the analysis.

Baseflow method:

The actual subsurface calculations are performed by a baseflow method. Six different method are provided, they are:

- Bounded Recession Baseflow
- Constant Monthly Baseflow

- Linear Reservoir Baseflow
- Nonlinear Boussinesq Baseflow
- Recession Baseflow
- **None**

The baseflow method “None” was chosen for the analysis. By choosing this the sub-basin will not compute the baseflow and the outflow will only include direct runoff from the transform method. This method was chosen due to the limitations of the availability of data.

Routing method:

A reach is an element with one or more inflow and only one outflow. Seven different routing methods are provided by HEC-HMS. Each method requires different levels of details and each method is not equally adapted to a particular stream.

- Kinematic Wave Routing
- Lag Routing
- Modified Puls Routing
- **Muskingum Routing**
- Muskingum- Cunge routing
- Staddle Stagger Routing
- None

Muskingum Routing method was chosen for the analysis due the limitation of the availability of the data.

Appendix D: Calculation of Muskingum parameters

Calculation of Muskingum K:

According to Song et al., (2011) The calculation of Muskingum parameters for an ungagged basin is as follows:

For an ungauged basin, the travel time K can be estimated by Equation 5

Equation 5: $K = L \div 3600Vc$

Where, L = reach length

Vc = flood wave celerity (speed of the wave)

Vc can be calculated by Equation 6

Equation 6: $Vc = dQ \div dA$

Where, A = area of flow at a cross section

dQ = differential value of the outflow

dA = differential value of the flow area

Q can be obtained from the Mannings formula, Equation 7

Equation 7: $Vav = \frac{Q}{A} = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$

Where, Vav = Average velocity

n = Manning´s roughness coefficient

R = hydraulic radius = $flow\ area \div wetted\ perimeter$

S = slope

The relation between flood wave celerity and velocity can be obtained from the following Equation 8

Equation 8: $Vc = \frac{5}{3}\left(1 - \frac{4}{5}\frac{A}{BP\, sin\propto}\right)Vav = \leftthreetimes\, Vav$

Where, B = water surface width

$\propto$ = angle formed by dykes over the horizontal plane

$\leftthreetimes$ = wave celerity coefficient of the channel cross section

$\leftthreetimes$ =5/3, 4/3, 13/9 for rectangular channel, triangular channel and parabolic channel respectively.

For stable river channels wetted perimeter can be estimated by Equation 9

Equation 9: $P = c\sqrt{Q_o}$

Where, c = coefficient, ranges between 4.71 – 4.78

Q_o = reference discharge

Reference discharge is as shown in Equation 10

Equation 10: $Q_o = Q_b + 0.5\,(Q_P - Q_b)$

Where, Q_b = minimum discharge

Q_p = peak discharge

Hydraulic radius can be calculated using Equation 11

Equation 11: $R = \left(\frac{Q_o n}{P\sqrt{S}}\right)^{\frac{3}{5}}$

The channel is assumed to be rectangular for the analysis. Therefore parameter K for rectangular channel is as Equation 12

Equation 12: $K = \frac{0.6\, n^{0.6} L c^{0.4}}{3600\, {Q_o}^{0.2} S^{0.3}}$

Calculation of Muskingum X:

Muskingum X can be estimated using Equation 13

Equation 13: $X = \frac{1}{2} - \frac{D}{V_c L}$

Where, D = Diffusion Coefficient

Equation (9) can also be expressed as Equation 14

Equation 14: $X = \frac{1}{2} - \frac{Q_o}{2SPV_c L}$

Therefore, for a rectangular channel X can be calculated using Equation 15

Equation 15: $X = \frac{1}{2} - \frac{0.3{Q_o}^{0.3} n^{0.6}}{S^{1.3} c^{0.8} L}$ (Song et al., 2011)

Table D1 shows the values used for the calculations of Muskingum K and Muskingum X

Table D1: Values used for the calculation of Muskingum K and Muskingum X

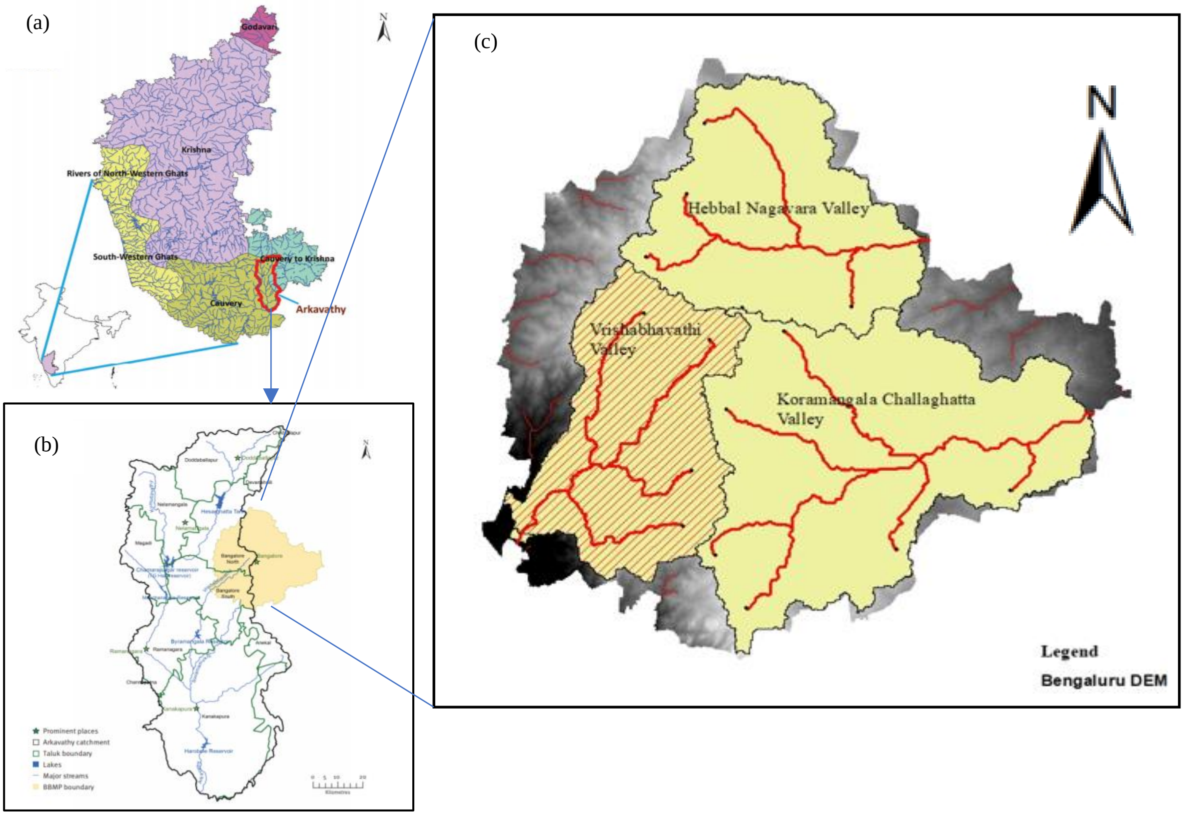
Parameter	**Value**
Discharge (Q)	30 m^3/s
Manning´s roughness coefficient	0.003
Coefficient (c)	4.75
Cross-section of channel	Rectangle

Table D2 shows the values of K and X for each sub-basin, which was calculated using the above equations and values.

Table D2: Calculation of Muskingum K and Muskingum X

River Name	River Length (m)	Slope (m/m)	Muskingum K (hour)	Muskingum X
R10	1011.60	0.0129	0.018	0.498
R20	1197.27	0.0226	0.018	0.499
R30	396.81	0.0126	0.020	0.495
R40	195.77	0.0409	0.002	0.498
R50	2408.83	0.0120	0.044	0.499
R60	601.59	0.0083	0.020	0.494
R70	1035.99	0.0058	0.023	0.494
R80	893.83	0.0201	0.014	0.499
R90	1936.65	0.0170	0.032	0.499
R100	1710.31	0.0053	0.040	0.496
R110	417.47	0.0287	0.006	0.498
R120	958.00	0.0052	0.022	0.493
R130	2762.14	0.0076	0.058	0.498
R140	2445.51	0.0086	0.049	0.499
R150	1309.12	0.0076	0.027	0.497
R160	924.60	0.0249	0.014	0.499
R170	1277.45	0.0110	0.024	0.498
R180	486.46	0.0082	0.010	0.492
R190	2707.89	0.0126	0.049	0.499
R200	1237.04	0.0040	0.031	0.492
R210	2215.24	0.0108	0.042	0.499
R220	800.45	0.0162	0.013	0.498
R230	43.50	0.0040	0.020	0.279
R240	3352.99	0.0152	0.057	0.499
R250	3298.93	0.0115	0.061	0.499
R260	3432.98	0.0084	0.069	0.499
R270	6014.28	0.0060	0.135	0.499
R280	217.52	0.0400	0.020	0.498
R290	932.51	0.0097	0.018	0.497
R300	1183.89	0.0059	0.027	0.495
R310	2260.29	0.0212	0.035	0.500
R320	1733.61	0.0040	0.044	0.495
R330	2458.70	0.0118	0.045	0.499
R340	594.13	0.0034	0.016	0.480
R350	535.24	0.0093	0.010	0.494
R360	4065.34	0.0133	0.072	0.500

R370	2575.38	0.0097	0.050	0.499
R380	1403.59	0.0043	0.035	0.494
R390	2968.91	0.0115	0.055	0.499
R400	844.60	0.0024	0.025	0.478
R410	282.78	0.0040	0.007	0.466
R420	1976.61	0.0061	0.044	0.497
R430	120.41	0.0040	0.003	0.420
R440	1930.28	0.0176	0.031	0.499
R450	238.18	0.0040	0.006	0.460
R460	1943.66	0.0015	0.065	0.483
R470	349.58	0.0143	0.006	0.495
R480	1792.94	0.0067	0.039	0.497
R490	540.52	0.0148	0.009	0.497
R500	345.85	0.0202	0.020	0.497
R510	916.68	0.0011	0.034	0.443
R520	646.64	0.0040	0.016	0.485
R530	1016.88	0.0089	0.020	0.497
R540	1984.98	0.0091	0.039	0.498
R550	2236.35	0.0049	0.053	0.497
R560	313.54	0.0040	0.008	0.469
R570	1613.20	0.0155	0.027	0.499



Arkavathi river basin

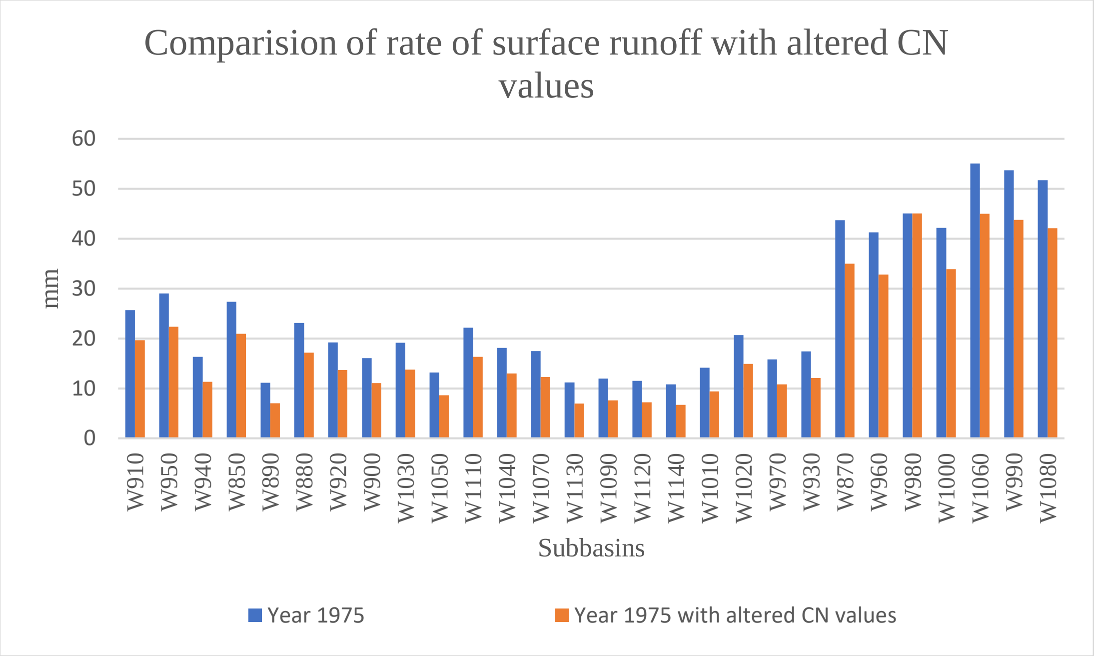
Above: (a) shows the location and the catchment area (green colour) of river Cauvery. (b) shows the catchment area of river Arkavathi. (c) Shows the catchment area of Vrishabhavathi river which is a part of Arkavathi river basin.

Appendix E: Altered CN values

Table represents the altered CN values used for the CN lookup table. The values were chosen arbitrarily.

Table E: Altered CN values based on hydrological soil group and Land use

Land use	Classification group no.	Hydrological soil groups			
		A	B	C	D
Water body	1	100	100	100	100
Urban and built up	2	86	87	89	90
Vegetation	3	44	64	74	79
Barren Land	4	72	81	86	89



Above: Comparison of results from the altered CN values.