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The impacts of land-use change on Runoff characteristics from the IWRM perspective:
A case study in Wadi Al-Mulaikhy Sub-watershed in Sana'a basin, Yemen

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Submitted by

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بِسْمِ اللَّـهِ الرَّحْمَـٰنِ الرَّحِيمِ

"أَوَلَمْ يَرَوْا أَنَّا نَسُوقُ الْمَاءَ إِلَى الْأَرْضِ الْجُرُزِ فَنُخْرِجُ بِهِ زَرْعًا تَأْكُلُ مِنْهُ أَنْعَامُهُمْ وَأَنفُسُهُمْ أَفَلَا يُبْصِرُونَ (٢٧)" السجدة

"وَمِنْ آيَاتِهِ أَنَّكَ تَرَى الْأَرْضَ خَاشِعَةً فَإِذَا أَنزَلْنَا عَلَيْهَا الْمَاءَ اهْتَزَّتْ وَرَبَتْ إِنَّ الَّذِي أَحْيَاهَا لَمُحْيِي الْمَوْتَىٰ إِنَّهُ عَلَىٰ كُلِّ شَيْءٍ قَدِيرٌ (٣٩)" ص

DEDICATION

To My Parents

To My Wife

&

My Sons and Daughter

To My Brothers

To My Sisters

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ABBREVIATION

CN	Curve Number
DEM	Digital Elevation Model
GALSUP	General Authority of Land, Survey & Urban Planning
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center- Hydrologic Modeling System
HEC-GeoHMS	Hydrologic Engineering Center-Geospatial Hydrologic Modeling System
HWSD	Harmonized World Soil Database
HBV	Hydrologiska Byrans Vattenbdansavdelning
IHDP	Improved Heuristic Dynamic Programming
Ia	Initial Abstraction
IWRM	Integrated Water Resource Management
JICA	Japan International Cooperation Agency
LCI	land Cover Institute
L-THIA	Long Term Hydrological Impact Analysis
LU	Land use
MCUM	Million Cubic Meter
NPP	Net Primary Production
NRCS	Natural Resources Conservation Service
NWRA	National Water Resources Authority
ROC	Receiver Operating Characteristic
RRM	Rainfall-Runoff Model
RS	Remote Sensing
ROC	Relative Operating Characteristics Curve
SBWMP	Sana’a Basin Water Management Project
SCS	Soil Conservation Services
SI	International System
SWAS	Sources for Sana'a Water Supply Project
SWAT	Soil and Water Assessment Tools
USGS	United States Geological Survey

USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
WEAP	Water Evaluation and Planning
WEPP	Water Erosion Prediction Project
WEC	Water and Environment Center
WH	Water Harvesting
WHS	Water Harvesting System
WRAY	Water Resources Assessment Yemen Project
YRSGISC	Yemen Remote Sensing and GIS Centre

ABSTRACT

Runoff is affected by several parameters such as soil type, and land use changes, which include vegetation cover and level of urbanization. The current study assesses the impact of land use change between 1994 and 2018, on the runoff characteristics of Wadi Al-Mulaikhy Sub-watershed in the Sana'a basin, Yemen by integrating GIS, HEC-GeoHMS extension, and HEC-HMS model. Remote sensing (RS) data, land use, soil type, and rainfall are the main input data. The study results showed that the agricultural area was reduced by 5.67%. Conversely the surface runoff for the overall study area have been increased by 1.65%. It was found that there is no significant change in runoff volume relative to land use change due to some agricultural general class changes to other classes (shrubs/brush), which have similar runoff characteristics. The second change is agricultural general class changes to urban classes (urban high density, urban medium to low density and roads) which occurred at the north of the study area near the boundary of the city of Sana'a which has an urban expansion. The changes in runoff parameters were found in the sub basin (W300, W310 and W320) which are located in the north of the study area due to the changes of agricultural general class to urban classes (urban high density, urban medium to low density and roads).

To apply the IWRM for water demand, three different scenarios were developed between 2018 and 2050 for domestic and agricultural use. The first scenario was applied for the current situation for the year 2018-2050. The annual population growth was 5.5%, annual changes in agricultural general was -0.23%, annual consumption per capita was 25.55 m^3, and annual consumption for agricultural was 4000 m^3 per hectares. The amount of water for domestic use will be increased from 0.26 MCUM in 2018 to 1.46 MCUM by 2050, and the amount of water demand for agricultural use will be decreased from 8.75 MCUM in 2018 to 8.13 MCUM in 2050.

The second scenario was calculated in case the population growth was 5.5% and increase in water consumption for agricultural used 6000 m^3 per hectares. The amount of water demand for domestic use will be increased from 0.26 MCUM in 2018 to 1.46 MCUM by the year 2050. The amount of water demand for agricultural demand will be increased from 8.75 MCUM in 2018 to 11.74 MCUM by the year 2050.

The third scenario was applied in case the annual urbanization was 4%, and the consumption of water demand for agricultural used 6000 m^3 per hectares. The amount of water demand for domestic use will be increased from 0.26 MCUM in 2018 to 1.46 MCUM by 2050. The amount of water demand for agricultural use will be decreased from 8.75 MCUM in 2018 to 3.34 MCUM by 2050.

Key Words: Runoff, Land use Change, GIS, HEC-HMS, Agriculture, Water demand, Wadi Al-Mulaikhy.

CHAPTER 1 INTRODUCTION

1.1 Preface

Water is the most essential natural resource for living species. Since the available amount of water is limited, scarce, and not spatially distributed in relation to the population needs, proper management of water resources is essential to satisfy the current demands as well as to maintain sustainability (Geremew, 2013).

Water availability in Sana'a City, capital of Yemen, is one of the scarcest in the world. The region has no perennial surface water runoff, and is practically dependent on the use of groundwater. Over-exploitation is causing the groundwater table to deplete at an alarming rate and Sana'a Basin, with a water table drawdown of about 3 meters per annum, is amongst the worst affected areas in the country (Al-Derwish, 2014).

Change in runoff characteristics which induced by urbanization, is important for understanding the effects of land use change on earth surface hydrological processes. With urban land development, the impervious land surfaces expand rapidly, and the capability of rainfall detention declines sharply and runoff coefficient increases. Usually urbanized land leads to a decrease in surface roughness; hard road and drainage system can greatly shorten the time of runoff confluences (Shi et al., 2007).

Constructing suitable water harvesting structures or applying changes in land management can reduce surface runoff, conserve water, and increase infiltration rate. Appropriate sites and structures of water harvesting (WH) help in flood control in lower catchment, avoid excessive runoff, improving soil moisture availability and increase the water table(Singh et al., 2009).

Remote Sensing (RS) and Geographic Information System (GIS) provide effective tools for land use planning and modeling. Land use change is an indicator of human interaction with nature. Therfore, it is necessary to discover and monitor land use changes in order to either protect the environment or ensure sustainable development (Mousazadeh et al., 2015). The use of RS techniques for hydrological modelling has gained momentum to estimate surface runoff in both gauged and ungauged watersheds (Ibrahim-Bathis and Ahmed, 2016).

Hydrological modeling is a common used tool to estimate the basin's hydrological response due to precipitation. It allows to predict the hydrologic response to various watershed managements and to have a better understanding of the impacts of these practices (Choudhari et al., 2014).

Several studies have been conducted using the HEC-HMS model in different regions under different soil and climatic conditions. The model was found accurate in spatially and temporally predicting watershed response in event based and continuous simulation as well as simulating various scenarios in flood forecasting and early warnings (Choudhari et al., 2014).

1.2 Problem Statement

Over the last decades, urban and rural areas of Sana'a basin faced a remarkable development and accelerated population growth. Geographic location, high frequency of heavy rainfall events and the increase of impervious surfaces in the city associated with rapid urban development lead to less infiltration, more changes in surface runoff and increased risks of flash floods. Environment and groundwater degradation including; urbanization, changes in land-use (LU), and land management practices have a major impact on natural resources including water, soil, etc.

Modeling of land use information can be used to develop solutions for natural resources management in Sana, a basin such as the negative impact of soil and groundwater recharge. Many wells become dry and this create conflicts among different water users. To have efficient and sustainable water management, there is an essential need to study land use change in Sana'a Basin, in order to have the change in irrigation system and surface runoff.

1.3 Study Objectives

The main objective of this study is to assesses the impact of land use change on runoff characteristics in Wadi Al Mulaikhy sub-watershed in Sana'a basin between the years 1994 and 2018.

The main objective is achieved through the following secondary.

- Produce land use maps of Wadi Al Mulaikhy sub-watershed in Sana'a basin between the years 1994 and 2018.
- Assess the change in the land use and runoff volume between 1994 and 2018.
- Assess the change in water demands uses between 2018 and 2050 under different management scenarios.

1.4 Study area

The study area is located in Wadi Al Mulaikhy in the southern part of Sana'a Basin as shown in Figure 1-1). The total area of the wadi is (63.00) km^2. The wadi is located in the upstream of Sana'a Basin and it has one major stream that extends from south to north. Its coordinate is between (1687890 to 1675760 N) longitude and (407908 to 418001 E) latitude. The average monthly temperature ranges between 15° and 25° based on the National Water Resource Authority (NWRA) records. The annual rainfall was 249 mm (JICA, 2007).

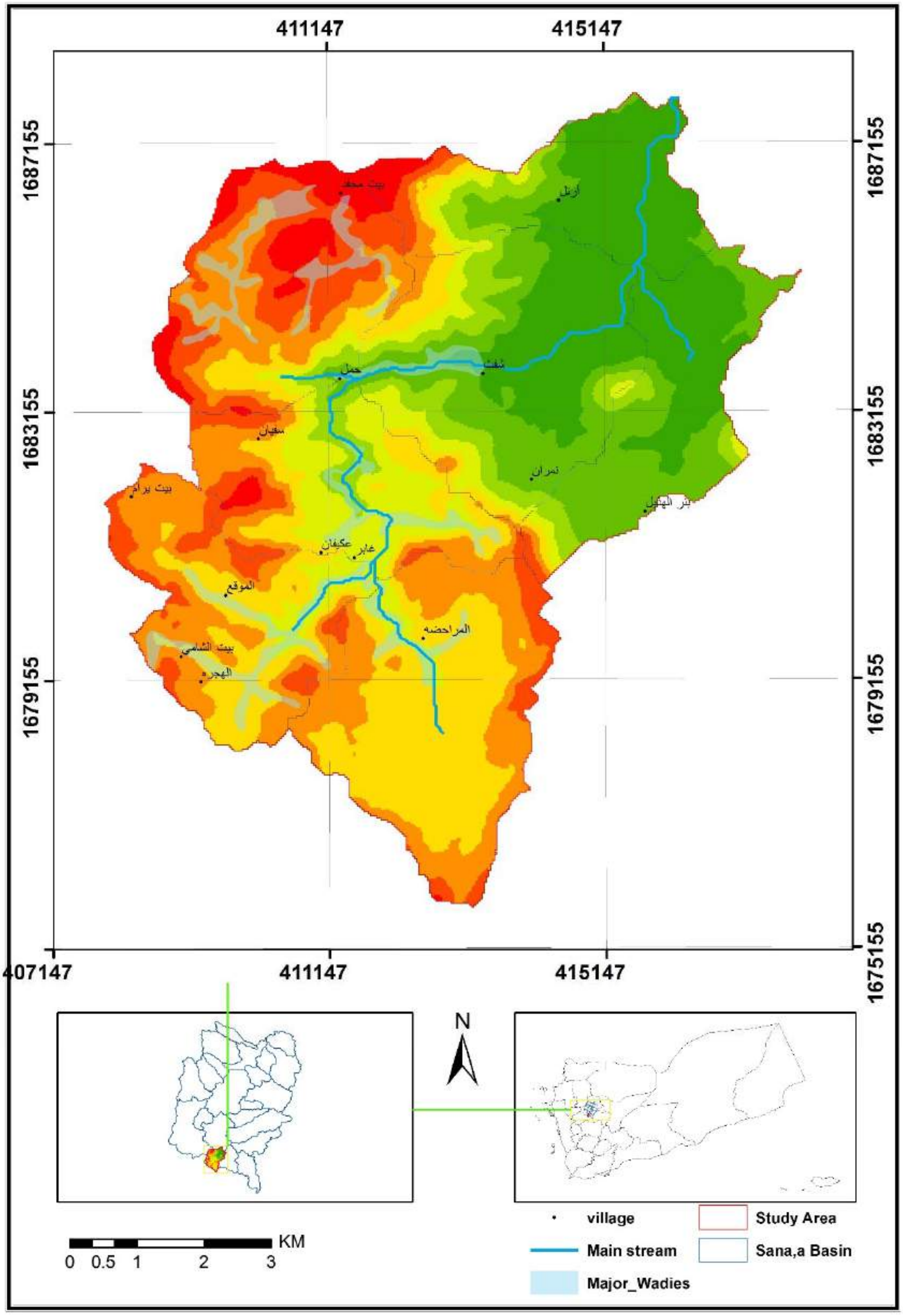

Figure 1-1 : Location map of the Wadi Al Mulaikhy sub-watershed in Sana'a Basin, Yemen

1.5 Previous studies

Many studies have been conducted about runoff in Sana'a Basin. They included but were not limited to study the impact of land use change on runoff volume in Wadi Al Mulaikhy sub-watershed. They used two types of methods to estimate the runoff volume. The first one has calculated runoff by using a runoff coefficient, obtained by hydrological observation of main wadis in Yemen. The average of runoff coefficient was 0.55 for wadis based on the observed flow volume from primary watershed conducted by Water Resources Assessment Yemen Project (WRAY-35)(WRAY-35., 1995). Sources for Sana'a Water Supply Project (SWAS)Technical report No.9 also calculated a runoff coefficient of 0.049, if the direct runoff was taken into account, and 0.061 if the total runoff was referred(JICA, 2007) . In addition, a report about the calculation of annual runoff depends on the runoff coefficient suggested by WRAY -35 1995 and rainfall applied in Sana'a Basin Water Management Project (SBWMP) (Noman, 2007). The Annual runoff in Wadi Al Mulaikhy sub-watershed was 956000 m^3 (JICA, 2007). The second method has calculated the runoff by using SCS-CN method that is the empirical model prepared by the U.S Soil Conservation Services(SCS). The first one constructed rainfall-runoff model by using SCS method obtained the mean total outflow of the Sana'a Basin was 27 MCM/year(TS-HWC, 1992). Another report about the feasibility study of 13 dam rehabilitation adopted the SCS method to estimate the runoff volume only where the proposed dam site is located. The runoff coefficient which obtained ranges from 0.049 to 0.17(SBWMP, 2010). Also, a study concerning rainfall-runoff analysis for 22 sub-basins in Sana'a Basin using SCS-CN method was conducted. They found out the runoff coefficient ranges from 0.22 to 0.122(Noman, 2007).

From regional perspective there have been abundant researches on the impact of land use change on runoff. Some of them used lumped models and the others used distributed and semi-distributed models to estimate the runoff characteristics, and each of these models has their own merits and demerits. Mistry et al., 2017 calculated the surface runoff by using SCS-CN method for the PURNA SUB-BASIN in India. They found that SCS-CN method can be used for the planning and management of the watershed in the study area. Köylü and Geymen, 2016 used SCS-CN method to assess the impact of land use change on runoff by using Landsat TM satellite images and they found that SCS-CN method is a convenient method to understand and display the relation between land use change and runoff, and it will support city administrators in a similar project. Nachshon et al., 2016 used the SCS-CN model to estimate the surface runoff to study land cover properties and rainwater harvesting in the urban environment because it has been widely applied to estimate storm runoff depth for every patch within a watershed based on runoff CN. Ajmal et al., 2015 utilized the SCS-CN and its inspired modified models for runoff estimation in the South Koreas watersheds. they found that there are still some rooms for the original SCS-CN model to be modified and replaced by other relationships for more reliable and significant runoff estimation. Tiwari et al., 2014 used SCS-CN method to compute the surface runoff volume for a given rainfall event from the small agricultural, forest, and urban watershed depend on Landsat ETM with spatial resolution 30 m. The study found that SCS-CN method is capable of simulating runoff patterns and runoff volume successfully in semi-arid regions. Ramakrishnan et al., 2009 found that SCS-CN method is simple, well acclaimed and produces better results. Shi et al., 2007 applied the SCS-CN method to investigate the effect of urbanization on surface runoff and peak discharge by using Landsat satellite images and they found that the SCS-CN model could be applied in the regions where the hydrological data are limited.

Other studies have been conducted using semi-distributed models. (Maisa'a et al., 2017) predicted CN for the Zarqa River Basin in Jordan by using HEC-1 model and Rainfall-

Runoff Model (RMM) model and they found that HEC-1 model and RMM are useful tools for watershed restoration also they used SCS-CN to produce CN runoff. Zare et al., 2016 used Long Term Hydrological Impact Analysis (L-THIA) GIS model to calculate the high and volume of runoff as well as the contribution of each land use type for producing runoff in a watershed under intense development pressure in the north of Iran and they found that the model is suitable to simulate future land use change through the use of a Receiver Operating Characteristic (ROC) also they used CN method to calculate the direct runoff. Sajikumar and Remya, 2015 studied the impact of land cover and land use change on runoff characteristics by using SWAT model and global land use, and they found the global land use data is not sufficient for getting good results in the runoff simulation from the SWAT model and local data is required for getting reasonably good results. Ngo et al., 2015 assessed runoff discharge and sediment yield from Da River Basin in the northwest of Vietnam by using SWAT model and the result indicated that SWAT generally performs well in simulating runoff and the SWAT model also uses SCS-CN method to estimate the surface runoff. Maalim et al., 2013 used water erosion prediction project (WEPP) model to simulate the hydrology and sediment dynamics in several land use and their results showed the limitation of the model to capture runoff of urbanized area. Hundecha and Bárdossy, 2004 used Hydrologiska Byrans Vattenbdansavdelning (HBV) model to assess the effect of land use changes on the runoff of a river catchment, and they found the study is limited to estimate the effect of land use changes at the lower and upper mesoscale sub-catchment.

CHAPTER 2 THEORETICAL BACKGROUND

This chapter will present and identify relevant used concepts and models including definition of land use change, integrated water resource management (IWRM), modeling procedures, ArcMap for GIS related tasks, HEC-HMS for hydrologic modeling, and HEC-GeoHMS was the interface between GIS and, HEC-HMS modeling. A brief literature review about the applicability and limitations of the applied models will be discussed as well.

2.1 IWRM Definitions

IWRM is a participatory planning and implementation process, based on sound science that brings stakeholders together to determine how to meet the long-term needs of society for water and coastal resources while preserving essential ecological services and economic benefits. IWRM helps to protect the global environment, to promote economic growth and sustainable agricultural development, promote democratic participation in governance, and improve human health (Sanjaq, 2009).

Figure 2-1) shows how the IWRM is a participatory and coordinated process, it brings all water users together to emphasize social and economic well-being and equity and it is protecting the environment by trying to achieve an equitable allocation of water resources.

According to Global Water Partnership (2000) IWRM is defined as a process, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Committee, 2000).

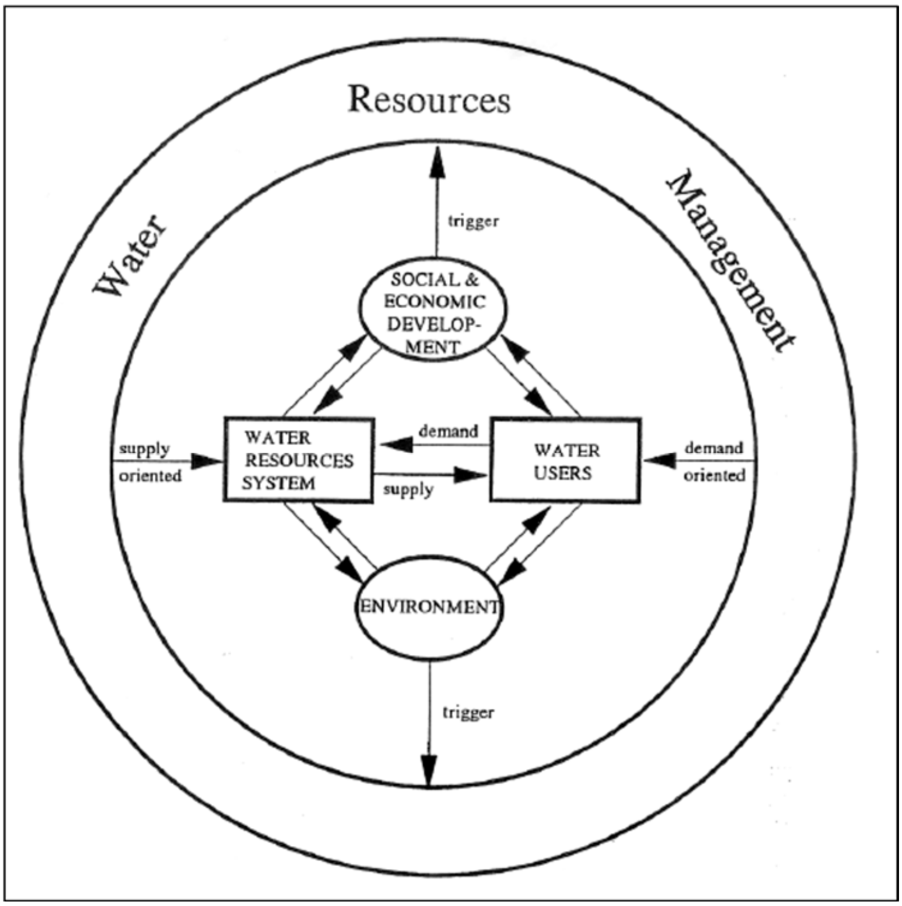

Figure 2-1: Schematic representation of IWRM(Committee, 2000)

2.2 Concepts of Land Use Change

Land use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation – the purpose for which the land is used (Turner et al., 1995). Land use itself is the human employment of a land-cover type, the means by which human activity appropriates the results of net primary production (NPP) as determined by a complex of socio-economic factors (Skole, 1994). Finally, FAO 1995 states that land use concerns the function or purpose for which the land is used by the local human population and can be defined as the human activities which are directly related to land, making use of its resources or having an impact on them (Sombroek and Sims, 1995).The description of the land use at a given level and space for a given area, usually involves specifying the combination of land use types, the particular configuration of these land use types, area and use intensity associated with each type of land tenure (Bourne, 1982, Skole, 1994). Land use change is commonly grouped into two broad categories: conversion and modification (Turner and Meyer, 1994). Conversion refers to a change in use from category to another (e.g. from forest to grassland). Modification, on the other hand, represents a change within one land use (e.g. from rained cultivated area to irrigated cultivated area) due to changes in its physical or functional attributes. These changes in land use and land cover systems have important environmental consequences due to their effects on soil and water, biodiversity, and microclimate. (Lambin et al., 2003).

The land use type can affect both infiltration and the amount of runoff by following the fall in precipitation (Haites et al., 1995, Geremew, 2013). Surface runoff and groundwater flow are the two components of the stream flow. Surface runoff is mostly contributed directly from rainfall, while groundwater flow is contributed from infiltrated water. However, the source of stream flow is mostly from surface runoff during the wet months, whereas during the dry months the stream flows from the groundwater.

Increase in cropland and decrease in forest, results increase in stream flow due to the crop soil moisture demand. Crops require less soil moisture than forests; therefore, the rainfall satisfies the shortage of soil moisture in agricultural lands more quickly than in forests there by generating more runoff when the area under agricultural land is extensive. Hence, this leads to increase in stream flow. In addition, deforestation also has its own impact on hydrological processes, resulting in lower precipitation and faster runoff after precipitation (Legesse et al., 2003).

In general, the knowledge of the impact of land use changes on the natural resources, such as water resources, depends on an understanding of the past land use practices, current land use patterns, and projection of future land use and land cover, depending on the size and the distribution of the population, economic development, technology, and other factors (Hadgu, 2008).

2.2.1 Land use Change: Bio-Physical and Socio-Economic Factors

The bio-physical factors include characteristics and processes of the natural environment such as weather and climate variations, topography, landform, and geomorphic processes, plant succession, volcanic eruptions, soil types and processes, drainage patterns, availability of natural resources. The socio-economic factors include demographic, economic, social, political and institutional factors and processes such as industrial structure and change, population and population change, technology and technological change, the market, the family, various public sector bodies and the related policies and rules, values, community organization and norms, property regime (Briassoulis, 2000).

2.2.2 Land use Change: Environmental and Socio-Economic Impacts

The impacts of land use change are usually distinguished according to the spatial level on which they manifest themselves into global, regional and local impacts. Note that the terms global, regional and local do not have a precise physical meaning in studies of land use change especially as regards the regional and local levels.

Land use changes have a multitude of environmental impacts at the lower spatial levels in urban, suburban, rural and open space areas which have been widely documented. Especially important are the land use changes (land conversion) that occur in the periphery of large urban concentrations that are subject to urbanization and industrialization pressures and frequently result in losses of prime agricultural lands and tree cover. Their environmental impacts include changes in the hydrological balance of the region, increased risk of floods and landslides, air pollution, water pollution, etc. Other local impacts of land use change include soil erosion, soil and groundwater contamination and salinization, sedimentation, extinction of indigenous species, coastal erosion and pollution, marine and aquatic pollution of local water bodies.

In addition to the environmental impacts, the socio-economic impacts of land use change are equally significant and give rise to serious concerns at all spatial levels. Global level socio-economic impacts concern issues of food security, water scarcity, population displacement and, more generally, the issue of human security and vulnerability to natural and technological hazards. International organizations and non-governmental organizations such as FAO, the World Bank, the improved heuristic dynamic programming (IHDP), etc., undertake systematic assessments to support policy and decision making at all spatial levels on the above issues.

At the regional level, the socio-economic impacts of land use changes are more variegated reflecting the variety of regional settings where these changes occur. However, these changes also stem from the same processes discussed above and evolve around such issues as availability of land for regional food production, changes (reduction) in land productivity and, consequently, (lower) profitability and changes in industrial structure, employment/ unemployment, poverty, population change and migration, and quality of life issues such as health and amenity.

At the local level, the socio-economic impacts of land use changes comprise similar concerns, but are limited to the localities where these changes occur. The issue of the conversion of agricultural land to urban and other uses (e.g. tourism) has received special publicity and concern. In addition to the environmental impacts mentioned above, there are also serious socio-economic impacts. In the case of tourism development on previously agricultural land, a less visible but extremely important socio-economic impact is the increased dependency of the tourist region on not locally produced farm products and the increased pressures for agricultural output grown in and bought from other areas. Local level socio-economic, like the environmental impacts, may act cumulatively and cause larger than local impacts in the longer term (Hadgu, 2008).

2.3 Hydrological Models

Hydrological models are mathematical descriptions of components of the hydrologic cycle. They have been developed for many different reasons and therefore have many different forms. However, hydrological models are generally designed to meet one of two main objectives. One of the objectives of watershed hydrological modeling is to better understand the hydrological processes of a watershed and how changes in the watershed can explain these phenomena. The other objective is for hydrologic prediction(Geremew, 2013, Tadele and Förch, 2007).

Based on the description of the process, hydrological models can be classified into three main categories (Cunderlik, 2004).

1. **Lumped models**: Parameters of lumped hydrologic models do not vary spatially within the basin, and therefore the basin response is evaluated only at the outlet, without explicit consideration of the response of each sub-basin. Parameters often do not represent the physical characteristics of hydrological processes and usually involve certain degree of empiricism. These models are not usually applicable to event-scale processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models.
2. **Distributed models**: Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modeling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to assess the influence of this distribution on simulated precipitation-runoff behavior. Distributed models generally require large

amount of (often unavailable) data. However, the governing physical processes are modeled in detail, and if properly applied, they can provide the highest degree of accuracy.

3. **Semi-distributed models**: Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin into a number of smaller sub-basins. The main advantage of these models is that their structure is more physical than the structure of lumped models, and they are less demanding on input data than fully distributed models like Soil and Water Assessment Tools (SWAT) (Arnold et al., 1993, Geremew, 2013), HEC-HMS are considered as semi-distributed models (Engineers, 2000, Geremew, 2013).

There are different criteria that can be used to select the appropriate hydrological model for a specific problem. These criteria are always dependent project, since each project has its own specific needs and requirements. In addition, certain criteria depend on the user. Among the different project selection criteria, there are four common and fundamental criteria that must always be answered(Cunderlik, 2003, Geremew, 2013).

- Expected outcomes of the model that are important to the project and therefore to be estimated by the model (Does the model predict the variables required by the project such as long-term sequence of flow?).
- Hydrologic processes that need to be modeled to estimate the desired outputs adequately (Is the model capable of simulating single-event or continuous processes?).
- Availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?).
- Price (Does the investment appear to be worthwhile for the objectives of the project?).

The reasons for selecting HEC-HMS model for this study are;

- It is semi-distributed model, which mean the spatial geographic variations of characteristics and process are considered explicitly.
- It is an empirical model built up on observation of input and output, without seeking to represent explicitly the process conversion.
- It is fitted parameter model, includes parameters that cannot be measured. Instead, the parameters must be found by fitting the model with observed values of the input and the output.
- Model structure is more physically-based than the structure of lumped models.
- Model input data requirements are less than fully distributed models.
- It is continuous and an event model simulates single storm and long period.
- The model is partially allowed to vary in space by dividing the basin into a number of smaller sub-basins.

2.4 Rainfall-Runoff Model: HEC-HMS Description

2.4.1 Fundamentals

HEC-HMS is an open source software for the modeling of the rainfall-runoff process developed by the U.S. Army Corps of Engineering´s Hydrologic Engineering Center (USACE). The software includes a graphical user interface for data model management and analysis. It is important to mention that the Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) itself is not a real hydrological model, but rather a software that allows the user to perform hydrological modeling which is based on a wide selection of common mathematical models used in hydrology. In HEC-HMS, the rainfall-runoff process in a watershed is represented in a simplified manner as shown in Figure 2-2).

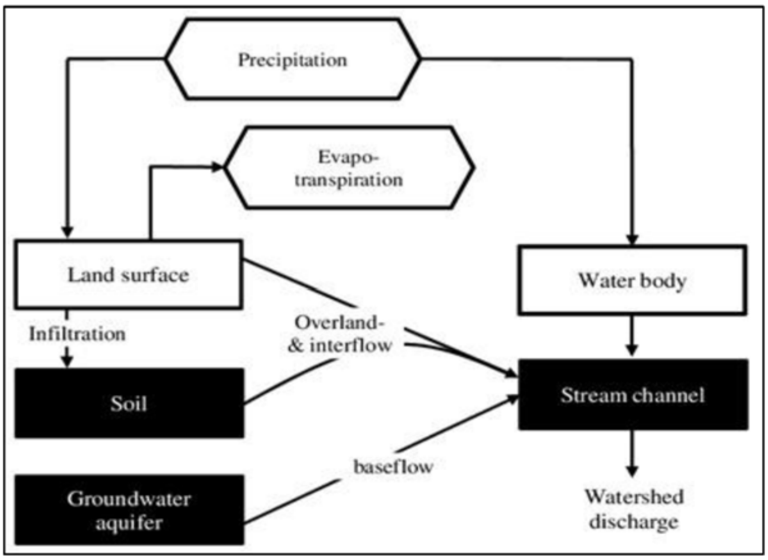

Figure 2-2 : Typical representation of watershed runoff (Engineers, 2000)

This simplified representation of the runoff process does not account for the storage and movement of water vertically within the soil layer (Engineers, 2000, Heimhuber, 2013).The models included in the software can thus be categorized as follows.

Loss Method: A model to calculate the volume of runoff is often referred to as loss, as the method accounts for losses that occur during a rainfall event as a result of infiltration and evapotranspiration. For each time interval in the modeling process, the method calculates the amount of water lost that contributes to the flow in the river (effective rainfall).

Transform Method: Direct runoff models are also called transform, since they convert the effective rainfall over a watershed into a hydrograph at the outlet of the watershed. These models take into account the roughness and surface geometry of the watershed**.**

Baseflow Method: Baseflow models are used to simulate the fraction of the runoff contributed by groundwater.

Routing Method: If the analyzed watershed is divided into sub-watersheds, the flow at the outlet of a certain upstream watershed must be routed through the river channel in the downstream watershed. The models used to simulate this routing process are therefore called routing methods. They account for the geometry and roughness of the relevant river channel.

2.4.2 **Loss Method: Gridded SCS -CN Loss Method**

The gridded soil conversation service (SCS) curve number (CN) loss method was used in this study to estimates the effective rainfall as a function of accumulated. The model was described in detail in the National Engineering Handbook (NEH) (NRCS, 2004). It was created based on the analysis of a large number of small and gauged agricultural watersheds throughout the US. In addition to input precipitation, the method uses a single parameter, CN, to characterize the watershed. CN quantifies the infiltration capacity and theoretically ranges between 0 to 100 (100% of the total rainfall infiltrate) (0% of the total rainfall infiltrate). The basic runoff equation of the CN method is shown in Eq. (2.1).

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{2.1}$$

Where, Q = runoff (mm), P = rainfall (mm), S = potential maximum retention after runoff begins (mm), Ia= initial abstraction.

The initial abstraction includes all the losses that occur before surface runoff begins. According to the NRCS (2004), it contains water retained in surface depressions as well as water intercepted by vegetation, evaporation and infiltration. In the CN model, Ia is assumed to be correlated to S through Eq (2.1).

$$I_a = 0.2\,S \qquad (2.2)$$

The maximum retention S is further related to the soil and cover conditions of the analyzed watershed through the CN by Eq (2.3).

$$S = \frac{25400}{CN} - 254 \qquad (2.3)$$

In the HEC-HMS modeling process, the incremental excess rainfall for each computation time interval is calculated as the difference between the accumulated excess at the end of and the beginning of the period. The cumulative excess Pe is computed with Eq (2.4).

$$P_e = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} \qquad (2.4)$$

2.4.3 Model Representation of Rainfall

In order to meet different hydrological modeling requirements, HEC-HMS includes a variety of different ways to model precipitation. The suitable of the system depends on information needs of a hydrologic-engineering study. For some analyses, a detailed account of the movement and storage of water through all components of the system is necessary. For example, to estimate changes due to land use changes in watersheds, it may be appropriate to use a long precipitation record to construct a corresponding long runoff record, which can be analyzed statistically. In that case, evapotranspiration, infiltration, percolation, and other movement and storage should be monitored over a long period. To do so, a detailed accounting model is required.

On the other hand, such detailed accounting is not necessary for many reasons to conduct a water resources study. For example, if the objective of the study is to determine the area flooded by a storm of selected risk, a detailed accounting and reporting of the amount of water stored in the upper layers of the soil is not required. Instead, the model needs only compute and report the peak, or the volume, or the hydrograph of watershed runoff.

2.4.4 General Applicability and Limitations.

HEC-HMS has been successfully applied for more than 30 years and is accepted for many official purposes such as the determination of floodways for the U.S. Federal Emergency Management Agency (Engineers, 2000). One of the main advantages of this software is the wide choice of different hydrological models adapted to different environments and under different conditions. HEC-HMS includes options for calibrating selected models against measured precipitation and runoff data. With HEC-HMS being a widely used, comprehensive and flexible software solution for the modeling of the rainfall-runoff process, applicability is more dependent on the suitability of hydrological models for a given situation than on the software itself.

In this study, HEC-HMS is used to perform runoff volume model based on gridded SCS CN method. The major limitations of gridded SCS-CN method are default initial abstraction (0,2S) does not depend upon storm characteristics or timing (Engineers, 2000). Rainfall intensity is not considered (same loss for 25mm rainfall in one hour or one day). Infiltration rate will approach zero during a storm of long duration, rather than constant rate as expected(Engineers, 2000).

2.5 Water Evaluation and Planning System (WEAP)

The Water Evaluation and Planning (WEAP) is Integrating Water Resources Management (IWRM) model seamlessly integrates water supplies generated by hydrological processes at the watershed scale with a water management model driven by water demand and environmental requirements and is governed by the natural watershed and the physical network of reservoirs, canals and diversions.

The model provides a comprehensive, flexible and user-friendly framework for planning and policy analysis. WEAP has an integrated approach of simulating both the natural inflows and engineered components of water system. This allows the planner access to an overview of the factors that need to be considered in the management of water resources for present and future use. This enables us to predict the outcomes of the whole system under different scenarios, and to make comparisons between the different alternatives in order to evaluate a full range of water development and management options.

Based upon the following criteria, WEAP was selected to perform water resources management modeling, since it meets the requirements of criteria such as:

- WEAP can be used at different spatial and temporary levels.
- Easy to use with a friendly interface.
- Recently, WEAP received a great deal of attention where it is being applied at national and international levels.
- Capable of simulating hydrology, groundwater use, surface groundwater interactions and wastewater treatment.
- Able to build and compare scenarios.
- Priority –based water allocation system.
- WEAP can handle variable time steps.
- Allow users to have interactive control over data entry, editing model operation and output display.

CHAPTER 3 MATERIALS AND METHODS

In order to achieve the study objectives, the researcher identifies relevant used concepts and models including definition of land use change, IWRM, data processing and modeling procedures, ArcMap for GIS related tasks, HEC-HMS for hydrologic modeling, and HEC-GeoHMS was the interface between GIS and, HEC-HMS modeling. The researcher applied Water Evaluation and Planning (WEAP) system to assess the change in the land use under different management scenarios.

3.1 Data Acquisition

Ecological infrastructure such as land use and land cover type and soil characteristics affects the runoff characteristics. Surface runoff depends on the spatial distribution of rainfall. Digital elevation model (DEM) with spatial resolution 20 m was used to delineate Wadi Al Mulaikhy sub-watershed in Sana'a basin. The stream network, model input file, and a meteorological model were created by Hydrologic Engineering Center-Geospatial Hydrologic Modeling (HEC-GeoHMS) GIS Extension for the next use in HEC-HMS model (Ibrahim-Bathis and Ahmed, 2016).

3.1.1 Rainfall Data

According to Technical Reference of Hydrologic Modeling System (HEC-HMS), and to estimate the change in runoff due to the change of land use in the watershed, it may be appropriate to use of long record of precipitation to construct a corresponding record of runoff, which can be statistically analyzed (Engineers, 2000). According to the summary report of Sana'a Basin Water Management Project (SBWMP), Sana'a Basin has about 24 rainfall stations which have been installed since 1970. Out of these stations, 15 were installed within the basin area itself, while 9 others stations were installed just outside Sana'a Basin boundary. These stations were installed through the support of different projects. A review of the reliability of the records available from these stations showed that some of these stations recorded rainfall over a two-year period, while others recorded from a five to seven-year period, and the longest available period of records is 22 years (Al-Salf station) (SBWMP, 2010). The analysis for 15 stations records in Sana'a basin showed the average annual rainfall for the period from 1970 to 2006 as it is shown in Table 3-1)

Rainfall meteorological model for all Sana'a Basin was built by using Inverse-Distance-Squared Method and extract the study area to run the HEC-HMS model and compute the average sub-basins rainfall to calculate the volume runoff for the two periods of time 1994 and 2018.

Table 3-1 : Average annual rainfall at the reliable rainfall stations for the period of 1970 to 2006

Ser. No.	Station Name	UTM E (M)	UTM N (M)	Yearly rainfall (mm/year)
1	Adabat	432250	1698700	209.5
2	Asalf_a	385300	1683400	424.8
3	Astan-a	427550	1743027	221.3
4	Birbasla	444000	1729284	220.8
5	Darawan	402126	1718733	193.1
6	Maadia	442250	1737750	187.7
7	Mind	399550	1690005	279.4
8	Qarwah-a	447785	1689375	132.1
9	Samanaha	426650	1730085	180.2
10	Sana-Cama	416700	1711150	236.5
11	Shibam-t	383807	1715787	416.4
12	Shuub	417500	1701000	223.3
13	wallan	421199	1671381	249.3
14	Sana,a Airport	410000	1710000	234.1
15	NWRA -OLD	414581	1701935	226.6

3.1.2 Land-Use

Information about land use and its spatial distribution pattern is one of the criteria to select CN values. In the present study, aerial photo with spatial resolution one meter for the year 1994 were provided by the General Authority of Land, Survey & Urban Planning (GALSUP) was used for the generation of land use classes after geo-referencing it on the digital map of Yemen in Yemen Remote Sensing and GIS Center (YRSGISC) as shown in Figure 3-1). Satellite image with spatial resolution 60 cm from Google Earth was used to digitizing land use classes of the year 2018 Figure 3-2). Land use classes for the years 1994, and 2018 were defined according to the United States Geological Survey (USGS) and land cover institute (LCI) classification (Merwade, 2012).

Barren land: Barren Land is land of limited ability to support life, less than one-third of its area has vegetation or other cover. In general, it is an area of thin soil, sand, or rocks (Anderson, 1976).

Agricultural land: Agricultural Land may be defined broadly as land used primarily for production of food and fiber (Anderson, 1976).

Shrub/ scrub: The typical shrub which is found in arid and semiarid regions, characterized by such xerophytic vegetative types with woody stems as big sagebrush(Anderson, 1976).

Urban: Urban or Built-up Land comprised of areas of intensive use with much of the land covered by structure. This category includes cities, towns, villages, strip developments along highways, transportation, power, and communications facilities, and areas such as those occupied by mills, shopping centers, industrial and commercial complexes, and institutions that may, in some instances, be isolated from urban areas(Anderson, 1976).

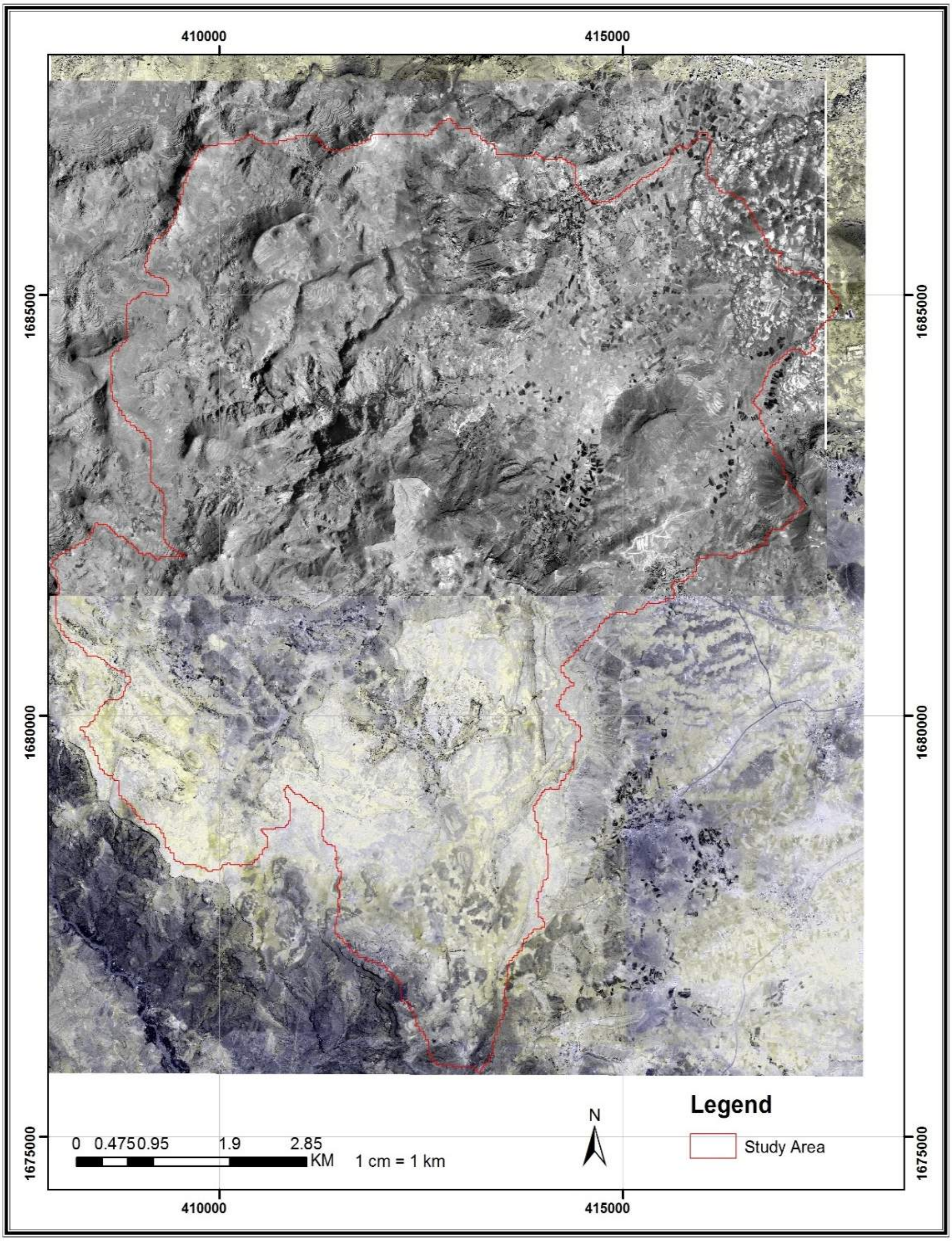

Figure 3-1: Aerial photo with resolution one meter for the year 1994

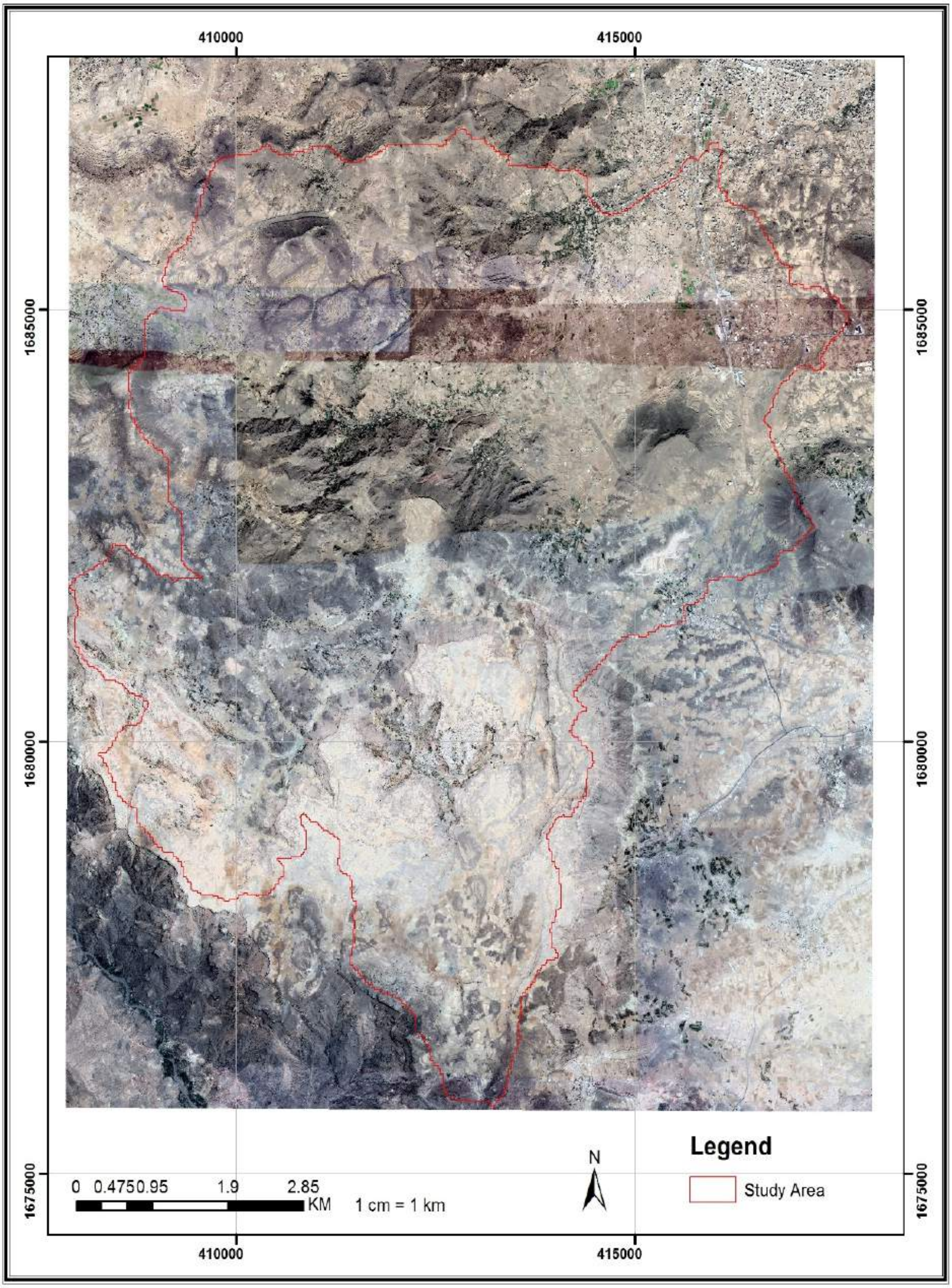

Figure 3-2 Satellite Images with Resolution 60 cm

3.1.3 Soil Data

The soil data which used in this study was the Harmonized World Soil Database (HWSD). This database was generated in 2012 with spatial resolution of 30 seconds (~1 km). There are 12 classes of soil properties in the United States Department of Agriculture (USDA), textural soil classification through the percentage mass of components, such as sand, silt, clay and loam, can be defined. After clipping the data of the study area from the global database, two classes were identified; (7% of the area) loam, and (93% of the area) sandy loam as shown in Table 3-2).

Table 3-2 : Textural Soil Classification in the study area

Textural Soil Classification	Area km2	Area %
Loam	4.133049	6.5598
Sandy loam	58.87205	93.4401
Sum	63.0051	100

3.1.4 Topographic Data

Digital Elevation Model (DEM) was used to extract stream networks, watershed delineation and their relevant characteristics like slope, drainage network and watershed boundary by using HEC-GeoHMS GIS extension. The DEM was obtained from (YRSGISC) with spatial resolution 20 m Figure **3-4**). This data was projected to Universal Transverse Mercator (UTM) on spheroid of WGS84 and it was in raster format to fit in to the model requirement.

3.2 Source of data and software

The present study used the following data and software as showed in table (3-3).

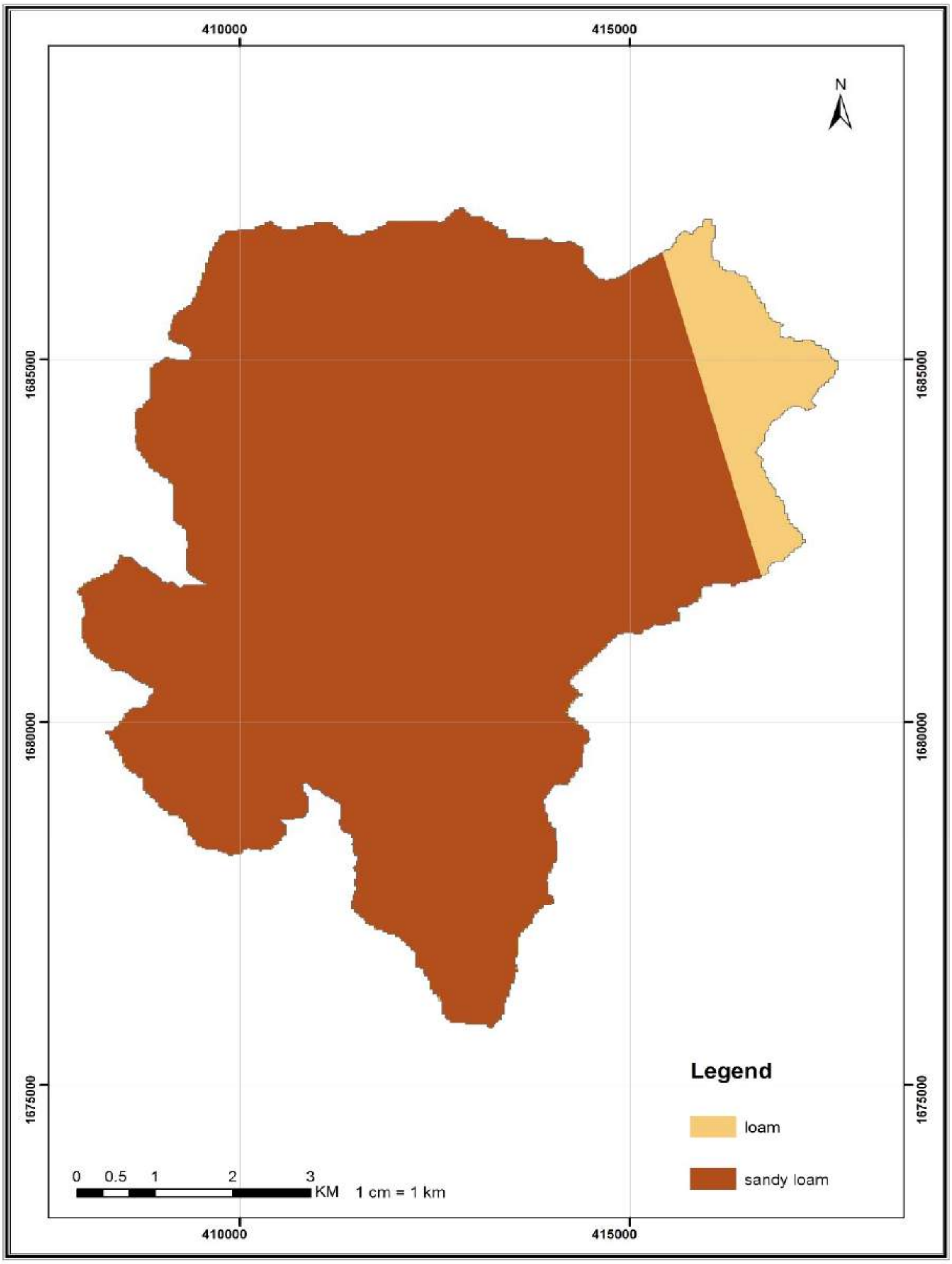

Figure 3-3 Soil Map of the study area (HWSD, 2012)

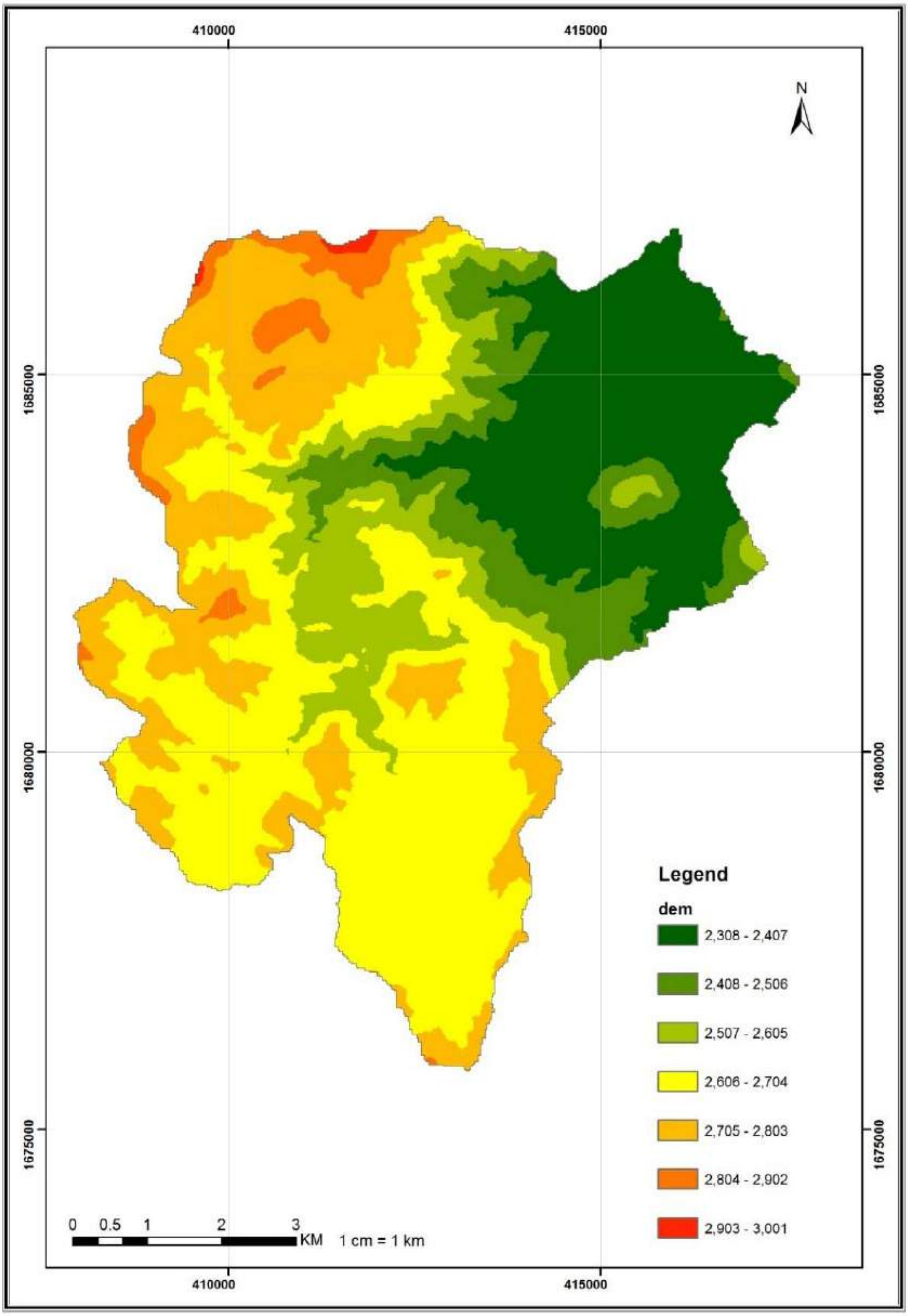

Figure 3-4 Digital Elevation Model (DEM) with spatial resolution 20m of the study area

Table 3-3 : Source of Study Data and Software

Type of data	Description	Source of data
Rainfall	Long period rainfall (15 years)	National Water Resource Authority (NWRA)
Aerial photo 1994 for production land-use	High resolution (1 meter)	General Authority of Land, Survey & Urban Planning (GALSUP)
Satellite Images for production land-use	High resolution from Google Earth (60 cm) 2018.	Yemen Remote Sensing and GIS Centre (YRSGIS)
Soil map	30 seconds (~1 km).	Harmonized World Soil Database (HWSD)
Digital Elevation Model (DEM)	DEM with resolution 20m	Yemen Remote Sensing and GIS Centre (YRSGIS)
Land-use/ 1994 and 2018	Land-use with details	digitized manually
Software used	ARCGIS ARCINFORM 10.4.1 HEC-GeoHMS GIS extension 10.4.1 WEAP Program Microsoft office 2016 HEC-HMS 4.2.1 program EndNote x6	Yemen Remote Sensing and GIS Centre (YRSGIS)

3.3 Creation of the Basin Model

The basin model was created by using the HEC-GeoHMS GIS extension functionality in ArcMap GIS environment. The first major step is creating the basin model which was delineating the stream network and the watershed boundaries of the study area. This process is commonly referred to as terrain preprocessing and is entirely based on the input DEM. The following grid files were derived from the DEM by following the steps function of HEC-GeoHMS.

- **Fill Sinks grid**: This function creates a depression less or hydrologically corrected DEM based on the input DEM. Therefore, the software automatically increases the elevation value of any pit cell to the level of the surrounding terrain.
- **Flow Direction grid**: This GRID is delineated from the Fill Sinks GRID. In the grid processing, the direction of the steepest descent to a neighbor cell which is defined for each grid cell.
- **Flow Accumulation grid**: This GRID is delineated from the flow direction GRID and defines the number of upstream cells draining into any given cell in the grid.
- **Stream Definition grid**: In this step, the cells that form the stream network are defined based on a threshold number of cells that drain into a given cell. In this analysis the threshold for the definition of streams was set to 5 km^2. The result is a GRID, in which the stream network is represented by lines of connected grid cells which fulfill all the threshold criteria.
- **Stream Segmentation grid**: This GRID is created by splitting the streams as defined in the stream definition GRID at any junction.
- **Catchment grid**: For every stream segment defined by the stream segmentation GRID, the corresponding watershed is delineated and stored in a GRID file.

Based on the products of the previous computational steps, three vector layers were created complete the terrain preprocessing:

- **Catchment Polygons**: This function uses the catchment GRID to delineate the boundaries of each sub-basin in the form of a vector layer.
- **Drainage Line**: The stream segments defined by the stream segmentation GRID are transformed into a vector stream layer by this function.

- **Adjoint Catchment**: In this step, the upstream sub-basins are aggregated at any stream confluence. This step is not hydrologically relevant but enhances the computational performance in subsequent steps.

HEC-GeoHMS delineates the study area and creates all required layer files for this area. All the created data is stored in a new geodatabase such as Sub-basin, slope, length, longest flow path and River layers.

The location of the projected points which were defined for the different sub-basins (W300 -W310-W320-W330-W340-W350-W360) is shown in Figure (3-5).

For each of the resulting stream segments and the related sub-basins, a serious of physically based characteristics were calculated based on the depression of DEM by using HEC-GeoHMS functions. These characteristics include the lengths and slopes of each river segment as well as the average basin slope and the longest flow path of each sub-basin. The resulting data is automatically stored in the attribute table of the river and sub-basin layer as shown in Table 3-4). As mentioned in chapter two the hydrologic modeling was based on the Gridded SCS-CN loss method. The determination of the input parameters for these models was described with detail in the following sections.

Table 3-4 Streams and sub-basins of the study area

Ser .No	Sub-Basin	Area km^2	Slope	Length of sub-basins	Longest Flow Path (m)
1	W300	7.9154	22.322605	19520	7925.239533
2	W310	12.6014	25.379253	24840	9818.326112
3	W320	6.9156	15.591544	20160	6339.848481
4	W330	6.9256	28.659689	17360	5792.985566
5	W340	8.4888	28.590012	17960	6841.980515
6	W350	8.5128	23.14184	18600	5939.137803
7	W360	11.6458	12.700245	20240	6939.848481
Sum		63.0051			

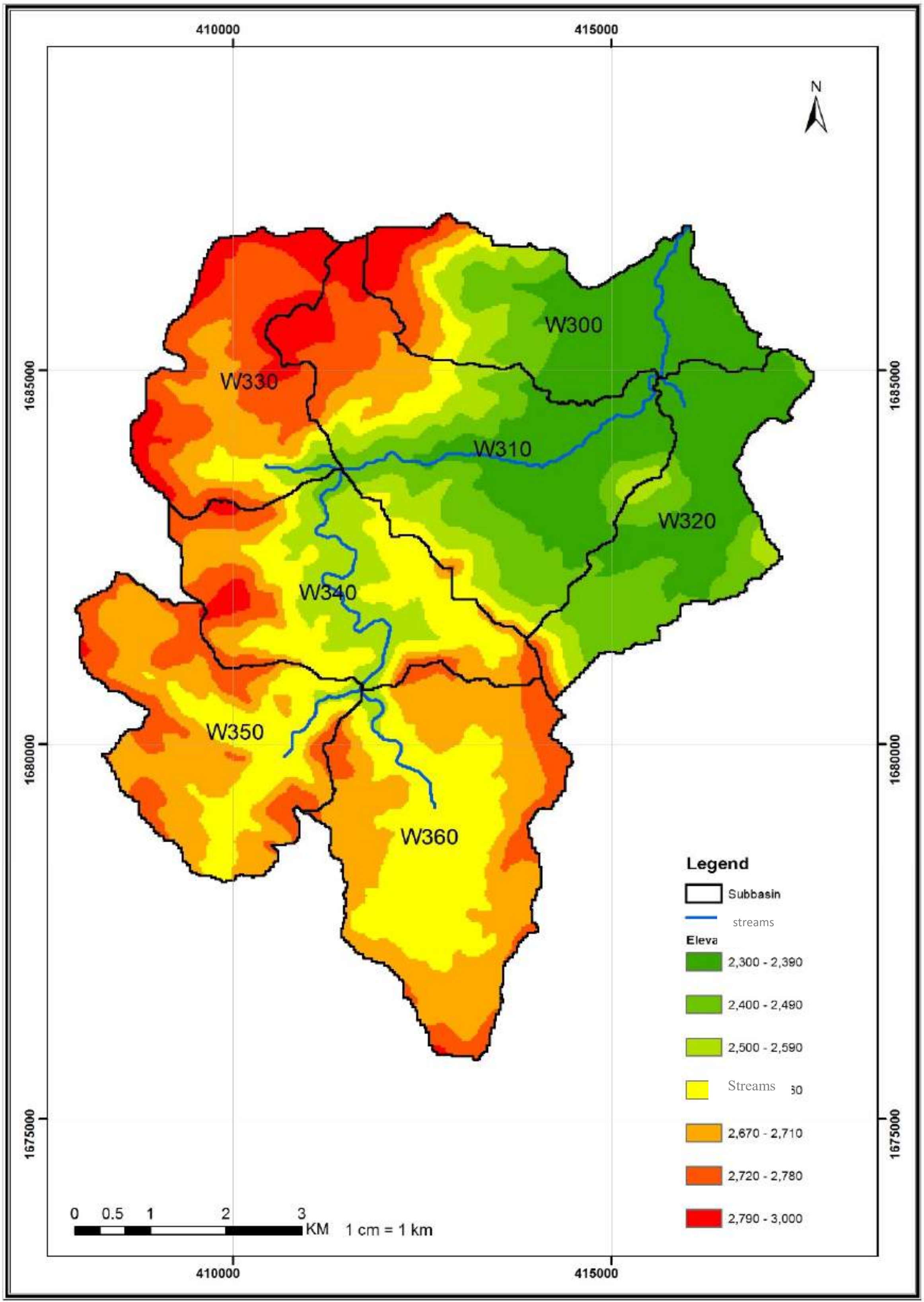

Figure 3-5 : Delination Sub-basins of the study area

3.4 Gridded Soil Conservation Service (SCS) Curve Number (CN) Loss Method

As described in Chapter two, this loss method only requires the definition of a single input parameter, the CN. CN depends on the land use and, the hydrologic soil group and the hydrologic condition of the top soil. The land use classification, hydrologic soil group map, CN table for arid and semi-arid rangelands Table 3-5), CN parameter adapted to physical Spanish conditions and available data Table 3-6), and Runoff CN numbers for urban areas Table 3-7) were used to define the values of CN numbers. The steps for creating CN grid were presented in the following sections.

Table 3-5 Curve number table for semi-arid and arid rangelands(NRCS, 2004)

Cover description		**Curve numbers for hydrologic soil group**			
Cover type	**Hydrologic condition[2]**	**A**	**B**	**C**	**D**
Herbaceous—mixture of grass, weeds and low-brush, with brush the minor element growing	Poor Fair Good		80 71 62	87 81 74	93 89 85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush	Poor Fair Good		66 48 30	74 57 41	79 63 48
Pinyon-juniper—pinyon, juniper, or both; grass understory	Poor Fair Good		75 58 41	85 73 61	89 80 71
Sage-grass—sage with an understory of grass	Poor Fair Good		67 51 35	80 63 47	85 70 55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, paloverde, mesquite, and cactus		63 55 49	77 72 68	85 81 79	88 86 84
1/ Average runoff condition, and Ia = 0.2s. For range in humid regions, use table 9–1. 2/ Poor: 70% ground cover. 3/ Curve numbers for group A have been developed only for desert shrub.					

Table 3-6 Curve number parameter adapted to physical Spanish conditions and available data(Ferrer-Julia et al., 2003)

Land use and treatment	**Slope (%)**	**A**	**B**	**C**	**D**
Fallow R	>= 3	77	86	89	93
Fallow N	>= 3	75	82	86	89
Fallow R/N	< 3	72	78	82	86
Row crops R	>= 3	69	80	86	89
Row crops N	>= 3	67	76	82	86
Row crops R/N	< 3	64	73	78	82
Small grain R	>= 3	64	75	84	86
Small grain N	>= 3	61	73	81	84
Small grain R/N	< 3	60	71	78	81
Poor rotation crops R	>= 3	66	77	85	89
Poor rotation crops N	>= 3	64	75	82	86
Poor rotation crops R/N	< 3	63	73	80	84
Dense rotation crops R	>= 3	58	72	81	85
Dense rotation crops N	>= 3	55	69	78	82
Dense rotation crops R/N	< 3	52	67	76	80
Pasture	>= 3	68	78	86	89
Medium meadow	>= 3	49	69	78	85
Dense meadow	>= 3	42	61	74	80
Very dense meadow	>= 3	39	55	70	77
Pasture	< 3	47	67	81	88
Medium meadow	< 3	39	59	75	84
Dense meadow	< 3	30	48	70	78
Very dense meadow	< 3	17	34	67	76
Sparse orchard or tree farm	>= 3	45	66	77	84
Medium orchard or tree farm	>= 3	39	60	73	78
Dense orchard or tree farm	>= 3	34	55	70	77
Sparse orchard or tree farm	< 3	40	60	73	78
Medium orchard or tree farm	< 3	35	55	70	77
Dense orchard or tree farm	< 3	25	50	67	76
Very sparse wood or forest land (trees, brushes, …)		56	75	86	91
Sparse wood or forest land (trees, brushes, …)		46	68	78	84
Medium wood or forest land (trees, brushes, …)		40	60	70	76
Dense wood or forest land (trees, brushes, …)		36	52	62	69
Very dense wood or forest land (trees, brushes, …)		30	44	54	61
Permeable rocks	>= 3	94	94	94	94
Permeable rocks	< 3	91	91	91	91
Impermeable rocks	>= 3	96	96	96	96
Impermeable rocks	< 3	93	93	93	93

Table 3-7 Runoff curve numbers for urban areas 1/(NRCS, 2004)

Cover description cover type and hydrologic condition	Average percent impervious area 2/	CN for hydrologic soil group			
Fully developed urban areas (vegetation established)		**A**	**B**	**C**	**D**
Open space (lawns, parks, golf courses, cemeteries, etc.) 3/					
• Poor condition (grass cover < 50%).		68	79	86	89
• Fair condition (grass cover 50% to 75%).		49	69	79	84
• Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
• Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
• Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
• Paved; open ditches (including right-of-way).		83	89	92	93
• Gravel (including right-of-way)		76	85	89	91
• Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
• Natural desert landscaping (pervious areas only) 4/		63	77	85	88
• Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
• Commercial and business	85	89	92	94	95
• Industrial	72	81	88	91	93
Residential districts by average lot size:					
• 1/8 acre or less (town houses)	65	77	85	90	92
• 1/4 acre	38	61	75	83	87
• 1/3 acre	30	57	72	81	86
• 1/2 acre	25	54	70	80	85
• 1 acre	20	51	68	79	84
• 2 acres	12	46	65	77	82
Developing urban areas					
• Newly graded areas (pervious areas only, no vegetation)		77	86	91	94

1. Average runoff condition, and Ia = 0.2S.
2. The average percent impervious area shown was used to develop the composite CNs. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition.
3. CNs shown are equivalent to those of pasture. Composite CNs may be computed for other combinations of open space type.
4. Composite CNs for natural desert landscaping should be computed using figures 9–3 or 9–4 based on the impervious area percentage (CN=98) and the pervious area CN. The pervious area CNs are assumed equivalent to desert shrub in poor hydrologic condition.

3.4.1 Determination of the land-use Type

Determination of land use types in watershed areas is the first step for the estimation of the CN method. The land use classes for the periods 1994 and 2018 were digitizing manually.

3.4.2 Determination of the Hydrologic Soil Group

In CN method, there are four possible hydrologic soil groups (HSGs) for the categorization of the soils in the watershed as shown in Table 3-8).

Table 3-8 Definition of the hydrologic soil group according to the NRCS (NRCS, 1986)

HSG	Soil textures
A	Sand, Loamy sand, or Sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

The Soil Conservation Service (SCS) has identified four hydrologic soil groups A, B, C, and D, based on their infiltration and transmission rates. Infiltration is defined as the rate at which the water enters the soil at its surface and is therefore controlled by surface conditions (Mishra and Singh, 2013).

Group A. The soils falling in group A have high infiltration rates, even when completely wet, high water transmission rates, and low runoff potential. Such soils include primarily deep, well to excessively drained sands or gravels.

Group B. These soils have moderate infiltration rates when completely wet, and consist mainly of moderately deep to deep, moderately well to well drained soils with fine, moderately fine to moderately coarse textures, for example, shallow loess and sandy loam. These soils exhibit moderate rates of water transmission (Mishra and Singh, 2013).

Group C. Soils in this group have low infiltration rates when completely wet. These soils mainly contain a layer that prevents the movement of water. Such soils are of moderately fine to fine texture as, for example, clay loams, shallow sandy loam, and soils low in organic content. These soils have a low rate of water transmission (Mishra and Singh, 2013).

Group D. The soils of this group have very low infiltration rates when completely wet. Such soils are primarily clay soils of high swelling potential, soils with a permanent high-water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission. The hydrologic soil group was digitized depending on the soil map (Mishra and Singh, 2013).

According to HWSD soil classification, hydrologic soil group classification by Natural Resources Conservation Service (NRCS), and soil conservation service classification, the soils in the study area were classified into two types of hydrologic soil group B and C as it is shown in Figure 3-6) and Table 3-9).

Table 3-9 : Hydrologic Soil Group

Hydrologic Soil Group	Area km2	Area %
B	4.133049	6.5598
C	58.87205	93.4401
Sum	63.0051	100

3.4.3 Determination of the Hydrologic Condition of the Soil

The hydrologic condition of the top soil was defined depending on the classification in CN table for arid and semi-arid rangelands for classes (Agricultural general and Shrub/Scrub). CN for Barren/Minimal Vegetation class was defined from the table CN parameter adapted to physical Spanish conditions and available data because it is permeable rocks and its slope >= 3%. CN for built up area and roads was defined from the CN table for urban areas. In order to accurately define the hydrologic condition of the Soil. The satellite images which are used for land use classification were analyzed in

ArcMap. The relevant areas were found to have mostly fair hydrologic conditions due to the vegetation cover from 30-70% at ground level.

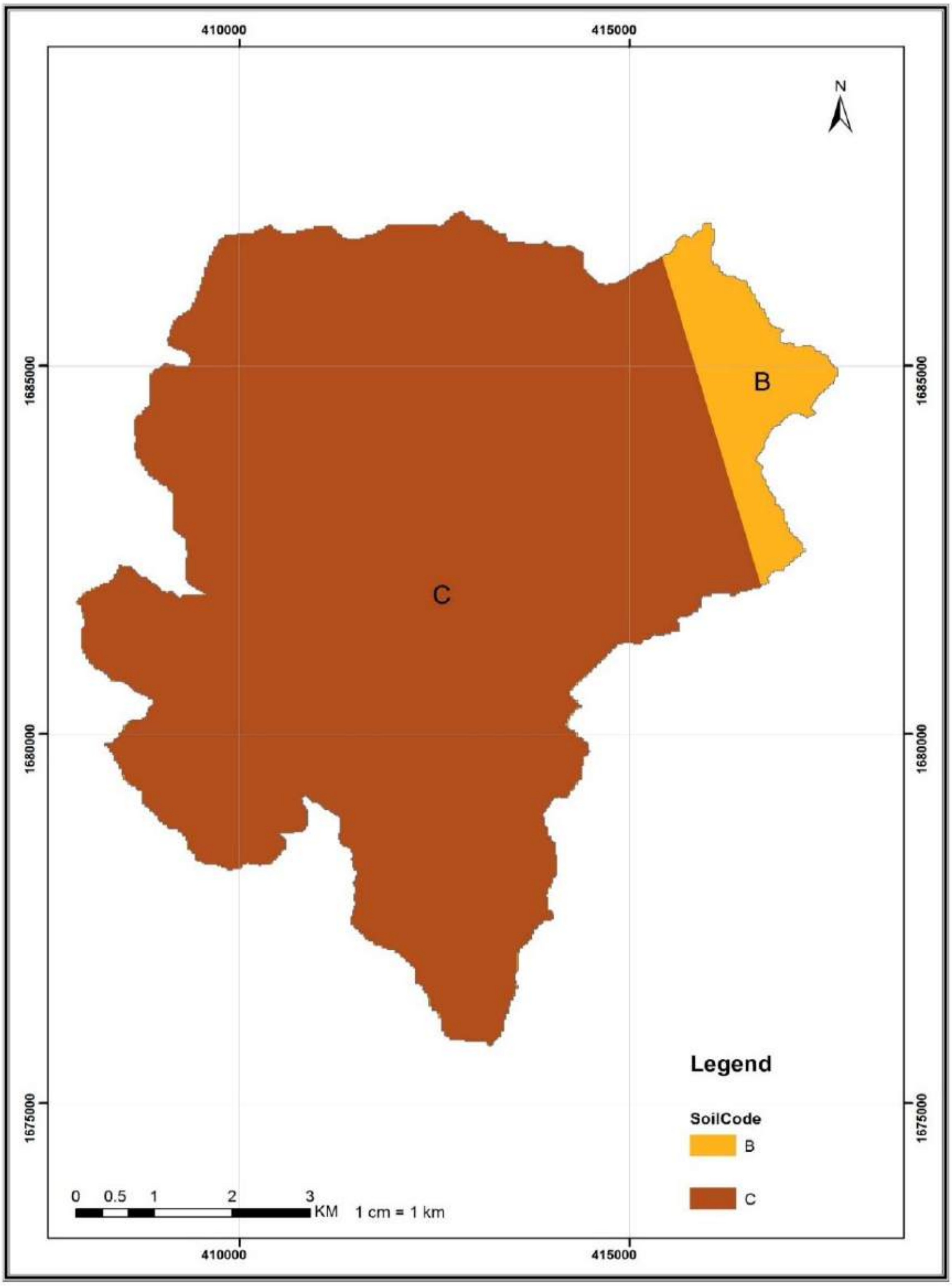

Figure 3-6 Map of the Hydrologic Soil Group in the study area

3.4.4 Merging of hydrologic Soil group and Land-use Data

To merge/union of the hydrologic soil group and land use data, Union Tool was used in Arc Toolbox which was available under Analysis Tools – Overlay. The result of union/merge features inherit attributes from both land use and hydrologic soil group for the years 1994 and 2018 was used for creating CN Lookup table (Merwade, 2012).

3.4.5 Creating CN Look-up table

CN LookUp table was created and named for populating and storing A/B/C/D CN values for corresponding soil groups as shown in Table 3-10) for each land use category according to SCS TR55 for the years 1994 and 2018 (Merwade, 2012).

Table 3-10 : CNLookUp for the study area

No	Description	A	B	C	D
1	Urban High Density	-	98	98	98
2	Urban Medium to Low Density	-	70	80	85
3	Agriculture General	-	48	57	80
4	Barren/Minimal Vegetation	-	94	94	94
5	Shrub/Scrub	-	71	81	80
6	Roads	-	82	87	89

3.4.6 Creating CN Grid

HEC-GeoHMS was used to create the CN grid. HEC-GeoHMS uses the merged of land use and hydrologic soil group feature class and the lookup table (CN LookUp) to create the CN grid for the years 1994 and 2018 Figures (3-7) and (3-8).

Based on the results of CN grid layers, and sub-basins parameters from features, HEC-GeoHMS function was used to assign CNs for each sub-basin. This function computes the average CN for each sub-basin based on the percentage of the areas with fair hydrologic conditions.

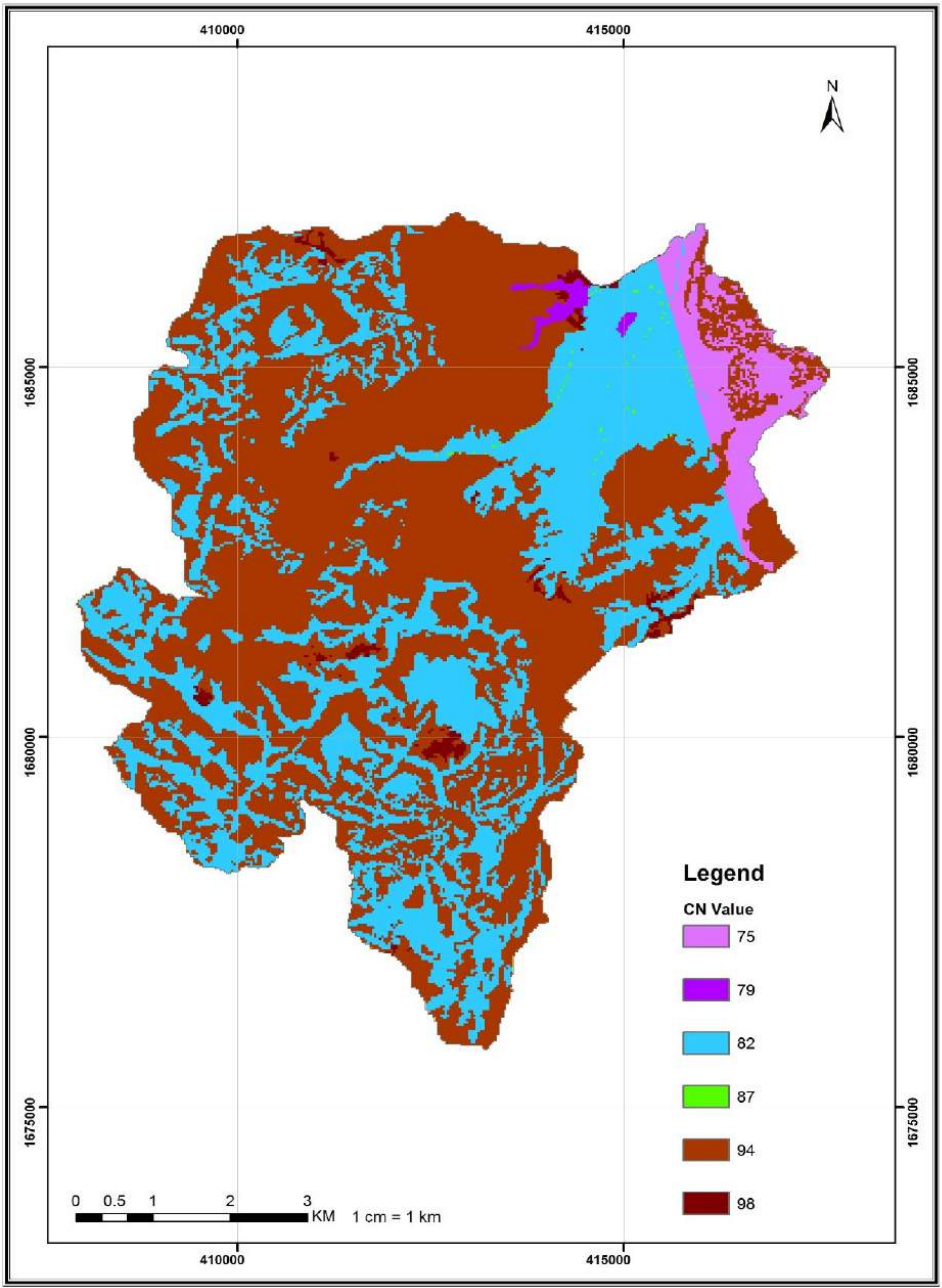

Figure 3-7 CN Grid for the year 1994 in the study area

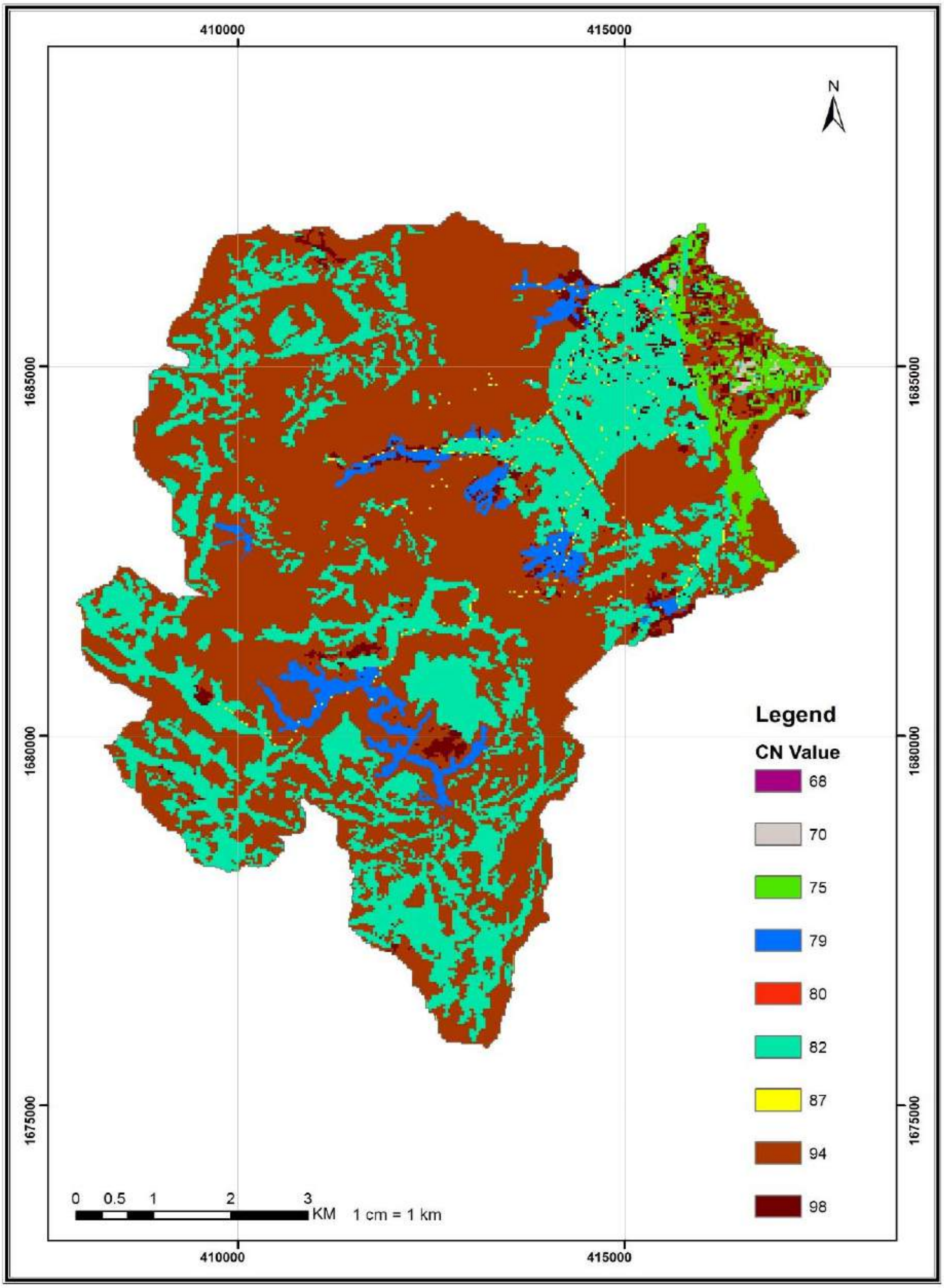

Figure 3-8 CN Grid for the year 2018 in the study area

3.4.7 Create initial abstraction layer (Ia)

The initial abstraction comprises all the losses that occur before surface runoff begins. In the CN model, Ia is assumed to be correlated to S through Eq (2.2), and the maximum retention S is further related to the soil and cover condition of the analyzed watershed through the CN Eq(2.3). The maximum retention S layers were produced by using the raster calculator function in spatial analyst tools. The Ia grid layer was generated from the Eq number (2.2) by using the raster calculator function in spatial analyst tools. Based on the Ia grid layer, the sub-basin parameters from raster were used to assign an average Ia numbers for each sub-basin.

3.5 Developed modeling system

HEC-GeoHMS developed a number of hydrologic inputs for HEC-HMS. Background map file, basin model file, grid cell parameter file, and meteorological model files by the following steps.

- Map to HMS unit.

  Convert the physical characteristics of reaches and sub-basins to International System (SI) units.

- HEC-HMS schematic.

  In this step, we built a simple hydrologic network that contained in HEC-HMS model elements and showed their connectivity by creating HMS link layer as shown in Figure 3-9).

- HMS legend.

  We used the HEC-HMS element icons to represent point and line features in the HMS node and HMS link layer as shown in Figure 3-9).

3.5.1 **Prepared data for model export.**

HMS basin model file contains the hydrologic data structure, which includes the hydrologic elements, their connectivity, and related parameters. HEC-GeoHMS can export some of the hydrologic parameters to the HMS basin model file.

- Background map.

  Background map layer capture the geographic information of the sub-basins boundaries and stream reaches.

- Basin file.

  The basin model captures the hydrological elements, their connections and geographic information's that can be loaded into HEC-GeoHMS model.

- Meteorological model.

  The tool is available in HEC-GeoHMS to create the meteorological model file. HEC-GeoHMS contains four options for creating a meteorological model which includes sub-basin time series, design gage, gage weight, and inverse distance weight. The last one was used to create the meteorological model by creating the rainfall gage grid layer and import it to HEC-GeoHMS geodatabase as shown in Figure (3-10). Based on the gage grid layer, the sub-basin parameters from raster HEC-GeoHMS function were used to assign an average rainfall numbers for each sub-basin.

3.5.2 **Setup HMS model**

The HMS model project was created by using HEC-GeoHMS, and creating a copy of all HEC-HMS project files which were used in HEC-HMS model.

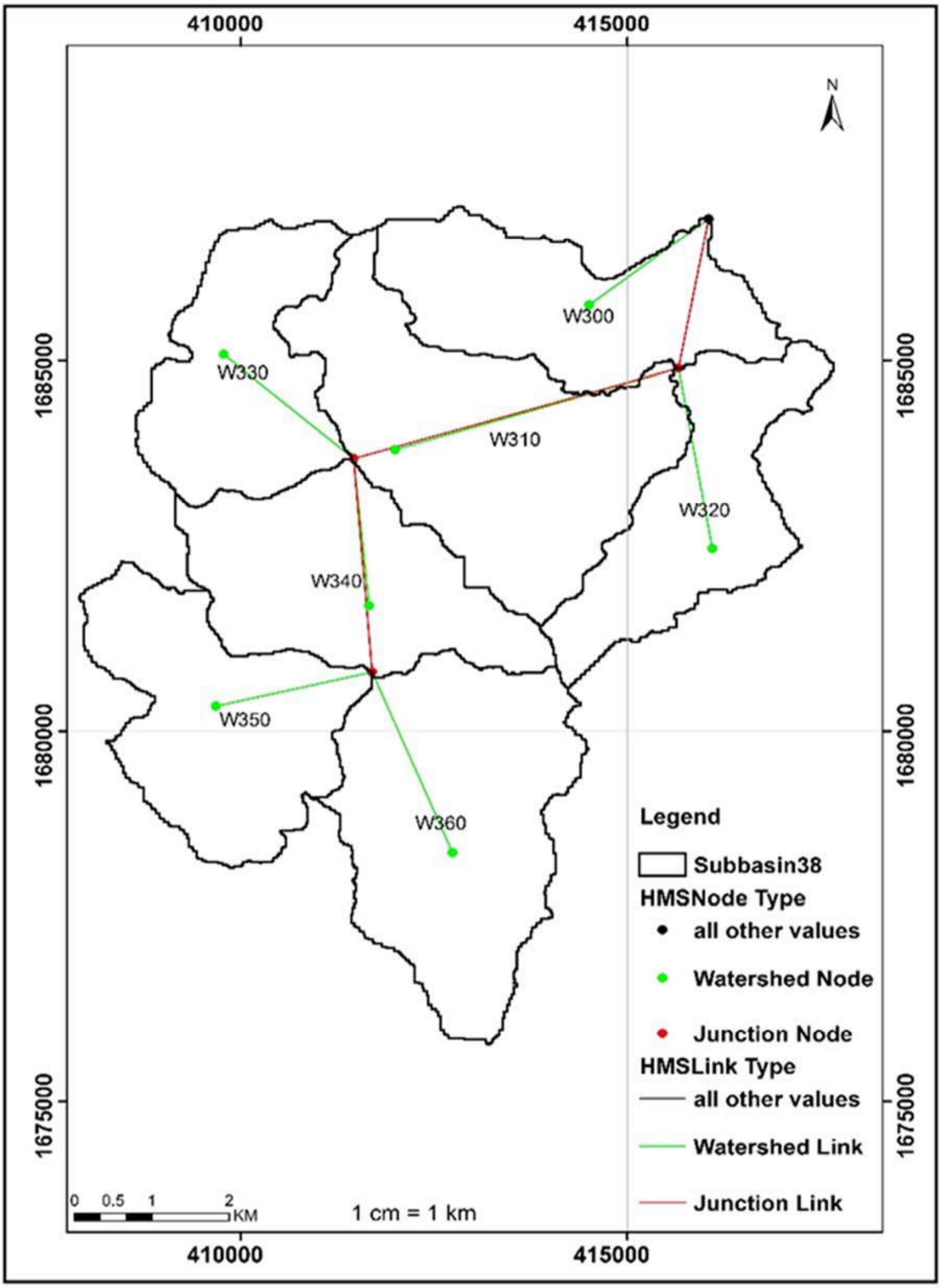

Figure 3-9 Model representation of Wadi Al-Mulaikhy watershed in HEC-GeoHMS

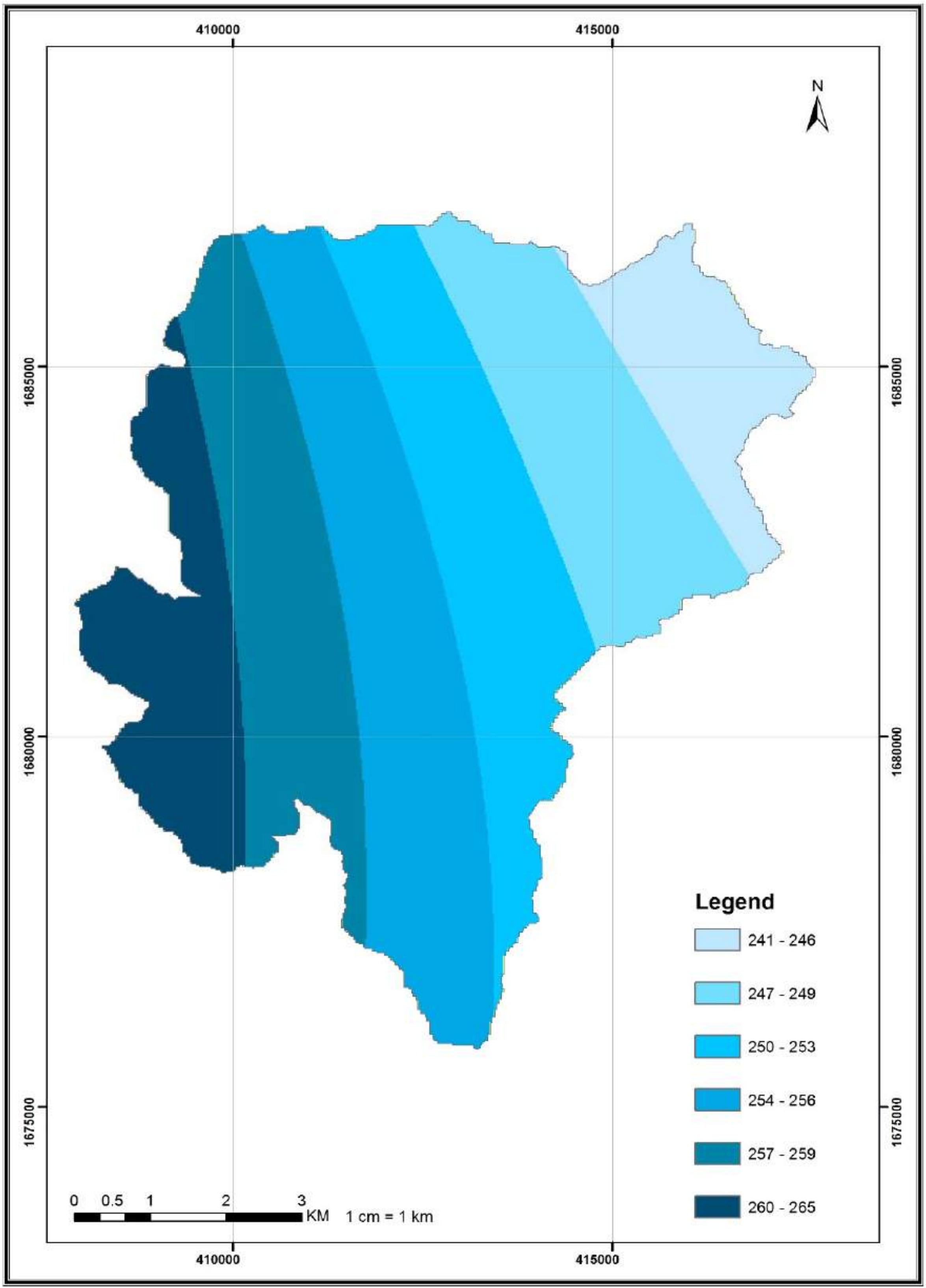

Figure 3-10 Average Rainfall Map of the study area

3.6 Model Completion in HEC-HMS

After the completion of the basin model with HEC-GeoHMS, the model was imported into a HEC-HMS project file, by using the HEC-GeoHMS data export to HMS functions. The model consists of seven sub basins, eight junctions, four reaches and the main outlet and it includes all the previously defined basin, reach and model parameters.

In addition to the basin model, and the meteorological model. Gridded SCS-CN Loss method was used to simulate runoff volume in HEC-HMS. The control specification defines the beginning and end date of the simulation run as well as the computational time step. It was chosen 1 min for the computational time step. According to technical reference manual for hydrologic modeling system HEC-HMS, it may be an event that represents the upper limit of precipitation possible at a given location (Engineers, 2000). The model was calibrated to deal with the average yearly precipitation instead of an event to calculate only yearly runoff volume. The meteorological data already existed during creating the model in HEC-GeoHMS. Depending on the input's parameters CN grid, Ia grid and meteorological model, runoff volume was calculated by using HEC-HMS model with different parameters inputs for the two periods of time 1994 and 2018.

3.7 Building scenarios for water uses

WEAP program was used for applying the integrated water resources management for water uses in domestic and agricultural was conducted by building the scenarios for the changes in water demand between 2018 and 2050. The previous results about the land use changes in agriculture between the years 1994 and 2018 and the runoff volume for the year 2018 were used to build the reference scenarios. Other data about the population, annual population growth rate, annual domestic water use per capta, and annual agricultural use per hectare…. etc. As shown in Table 3-11).

Table 3-11 : Refernce Data for Scenarios water demands inputs

No	Data	Account	Units	Source
1	Population	10283	people	Jica
2	Annual population growth rate (annual activity level)	5.5	%	Assumption by researcher
3	Runoff volume	1291900	m^3	Previous results
4	Agricultural land area (annual activity level)	2057	hectare	Previous results
5	Annual percentage change in agricultural land	-0.23	%	Previous results
6	Annual domestic water use (annual water use rate)	25.55	m^3	Assumption by researcher
7	Annual agricultural water uses per hectare (annual water uses rate)	4252	m^3	(alzoatree, 2009)

The scenarios were built according to the procedures in WEAP tutorial modules guide as follows.

- **Schematic the study area**

  Adding sub-basins shapefile to define the boundary of study area which was generated by HEC-GeoHMS.

- **Setting general parameters**

  Setting the current account periods is to year 2018 and the last year to 2050. The year 2018 served as the current account year for this study. The current account year was chosen to serve as the base year of the model. The system data was input into the current account. The current account is the dataset from which the scenarios were built. A default scenario, the reference scenario carried forward the current accounts data into entire project period that was specified (2018-2050) and served as a point of comparison for other scenarios in which change may be made to the system data.

- **Entering elements into the schematic**

  Drawing river (main flow) depended on the longest flow path shapefile layer which was generated during the built of hydrological model.

- **Enter data to the river (main flow)**

  The data which entered to the main river about the main flow for the year 2018, was calculated by HEC-HMS program.

- **Create domestic and agricultural demands sites**

  Creating demands nodes for domestic and agricultural sites, and setting the demands priority to one. Setting the units before entering the data for the annual activity level tab, and the annual water uses rate under the year 2018.

- **Connected the demands with supply**

  Connected supply resources to each demand sites by creating a transmission links from the main river to the demand sites, and setting the supply preference to one for each transmission link.

- **Creating key assumption**

  Key assumptions are pieces of data that may be useful to apply across multiple elements. Creating one key assumption for domestic water uses to 25.55 m^3/person was specified to domestic use/water use/annual water use rate. And creating another key assumption to agricultural/water use/annual water uses rate 4252m^3/hectares.

- **Creating references to key assumptions**

Creating keys assumptions references to annual water uses for domestic use key\unit domestic use (m^3), and creating another key assumption reference for annual water use for agricultural key\ unit agricultural use (m^3).

- **Creating the reference scenario**

The reference scenario already exists for the year 2018, and creating three scenarios for water demands between 2018 and 2050.

- A new scenario for water demand to evaluate the impact of the population growth rate to 5.5% per year for the periods 2018-2050, and the changes in agricultural area rate to -0.23 per year according to the previous results of land use changes between the years 1994 and 2018.
- Creating second scenario for water demand in the case of the development activity in agricultural, which increase the water demand to 6000 cubic meter per hectares.
- Creating third scenario for water demand in the case that the annual urbanization was 4%, and the population growth was 5.5%.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Land-use change

Land use maps of the study area for the years 1994, and 2018 which were generated manually, included land use classes (agriculture general, barren/minimal vegetation, shrub/scrub, roads, urban high density and urban medium to low density). The area of each land use class for different years and the changes procedures over 24 years are shown in Table 3-2). Most of the area of Wadi Al-Mulaikhy is covered by barren/minimal vegetation distributed throughout the study area for the two periods of time 1994 and 2018, also agriculture general distributed throughout the study area. Shrub/Scrub areas were covering a small area and spread in the north and middle of the study area. The low, medium and high density of urban areas were located in the northeast of the study area. The land use map classification of 1994 Figure 4-1) was compared to the land use map classification of 2018 Figure 4-2) to identify the area where the main changes between 1994 and 2018 occurred. The results of land use changes showed a decrease in the agriculture general land use class as shown in Figure (4-3).

Table *4-1*) shows that the area of Wadi Al Mulaikhy sub-watershed with the land use classes Urban High Density, Urban Medium to Low Density, Barren/Minimal Vegetation, Shrub/Scrub and roads increased about 1.5%, 0.22%, 0.53%, 2.84%, 0.55% respectively, increasing total area of 5.65km^2. Whereas the agriculture general has decreased by about 5.65% over 24 years' period. The major change in agriculture general class was the conversion to Shrub/Scrub and urban with high and medium to low-density classes (2.8% and 1.7%) respectively. The major increase in the urban area occurred on the north at the boundary of the study area due to urban expansion of Sana' a city in addition to the simple conversion of agricultural general class to roads, shrub/scrub and Barren/Minimal Vegetation

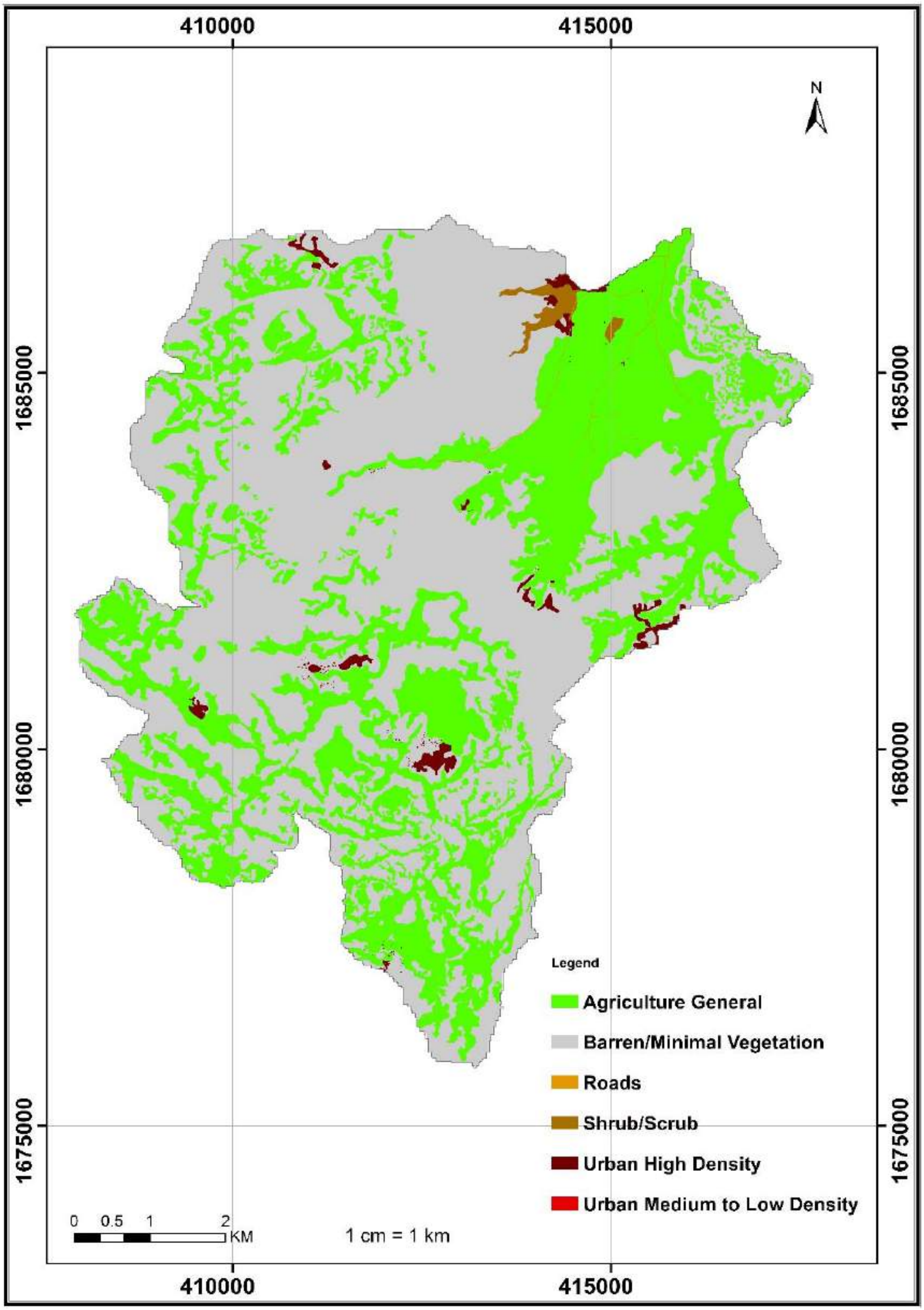

Figure 4-1 Land use Map of Wadi Al-Mulaikhy in 1994

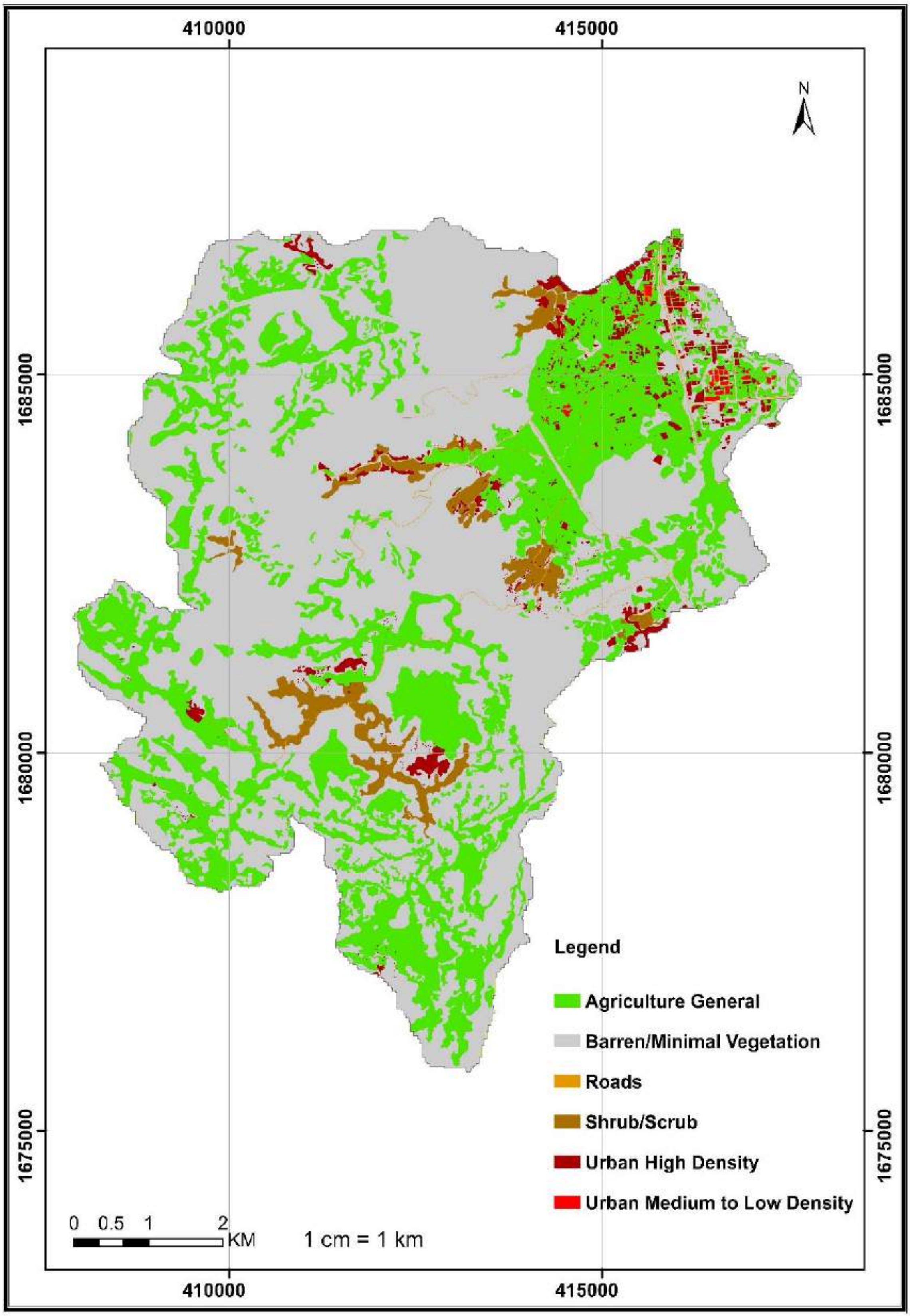

Figure 4-2 Land use Map of Wadi Al-Mulaikhy in 2018

Table 4-1 Total estimated area of Land use classes in Wadi Al-Mulaikhy Sub-watershed in 1994 and 2018

N	Land-use classes	Area 1994 in (km^2)	Area 1994 (%)	Area 2018 in (km^2)	Area 2018 (%)	Change percent (%)
1	Urban High Density	0.62	0.98	1.57	2.49	1.51
2	Urban Medium to Low Density	0	0	0.13	0.22	0.22
3	Agriculture General	24.14	38.32	20.57	32.65	-5.67
4	Barren/Minimal Vegetation	37.86	60.09	38.19	60.62	0.53
5	Shrub/Scrub	0.32	0.50	2.11	3.35	2.84
6	Roads	0.05	0.089	0.40	0.63	0.55
Sum		**63.00**	100	**63.00**	100	

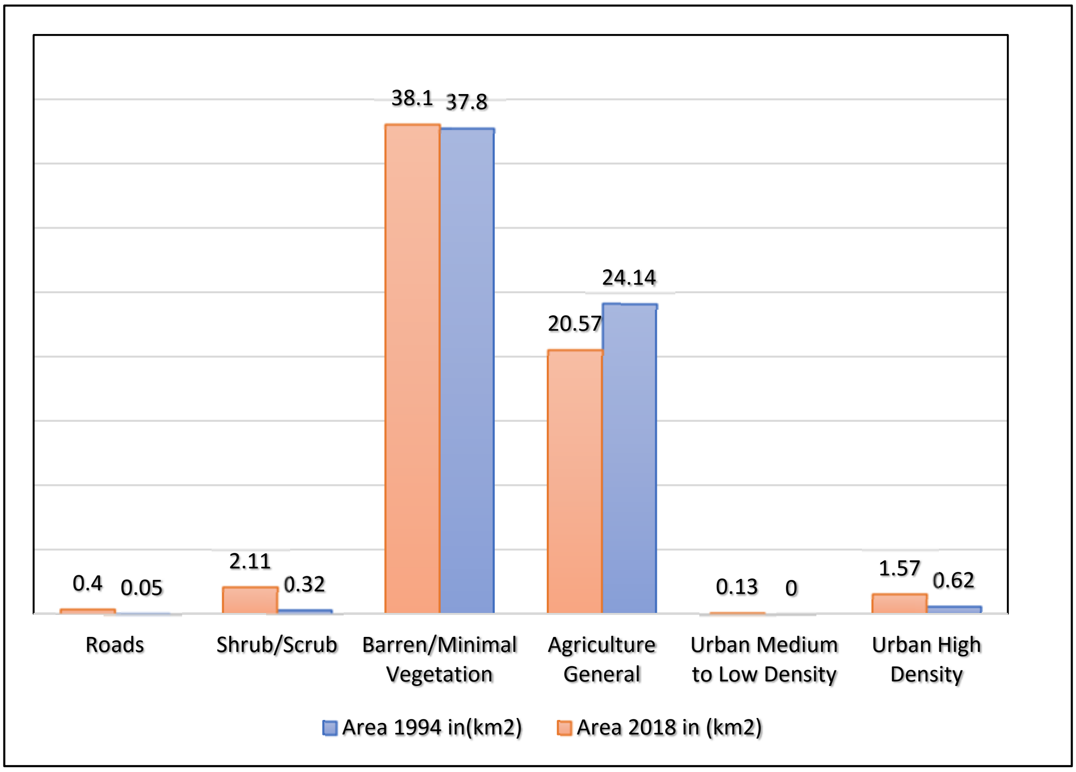

Figure 4-3 Comparison of land use classes area in Wadi Al-Mulaikhy Sub-watershed between 1994 and 2018

4.2 Runoff changes

The HEC-HMS model was used to calculate runoff volume for the two periods of land use (1994, 2018). The results of runoff changes that are related to land use changes for the periods 1994, 2018 are presented in Table 4-2). Modeling results indicated that the largest volume of runoff in 2018 was1.291 MCUM/year, and the volume of runoff in 1994 was1.270MCUM/year. Thus, it increased by 2100 m^3 about 1.652% over 24 years Figure 4-4). The results of land use changes between the two periods is indicating that the total change in land use categories increased by 5.66% in the classes (urban high density, urban medium to low density, barren/minimal vegetation, shrub/scrub, and roads) by (1.5%, 0.22%, 0.53%, 2.84%, and 0.55%) respectively, and 5.66% decreased from agriculture general. Due to the increase in urban high density and urban medium to low density which was 1.7%, the increase in roads was 0.5% and the increase in barren/minimal vegetation and shrub/scrub was 3.6%. The decrease in agriculture general 5.66% means an increase in the volume of runoff 1.652% due to the increase in urban high density and urban medium to low density about 1.73%.

Table 4-2 Total Runoff Volume Wadi Al-Mulaikhy Sub-watershed in 1994 and 2018

Ser No	**Sub-Basin**	**Drainage area km^2**	**Runoff volume (1000 m^3) 1994**	**Volume (mm)**	**Runoff volume (1000 m^3) 2018**	**Volume (mm)**
1	W300	7.9154	138.5	17.42	153.1	19.24
2	W310	12.6014	240.6	19.10	241.7	19.18
3	W320	6.9156	118.3	17.11	126.5	18.29
4	W330	6.9256	152.2	21.85	151.9	21.81
5	W340	8.4888	189.5	22.32	188.8	22.24
6	W350	8.5128	191.0	22.44	190.3	22.35
7	W360	11.6458	240.7	20.67	239.6	20.58
Outlet		63.00	1270.9	20.15	1291.9	20.48

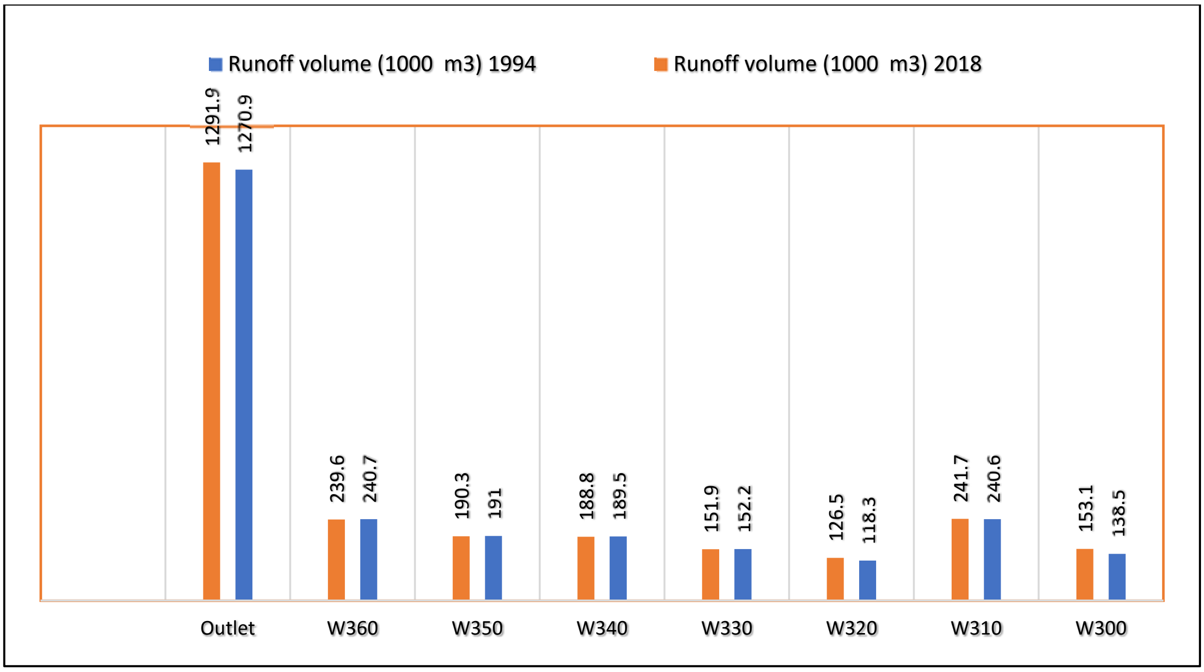

Figure 4-4 Comparing of Runoff Volume in Wadi Al-Mulaikhy in 1994 and 2018

4.2.1 CN Values.

The average of CN values for land use in the years 1994, and 2018 were (88.69, and 89.46) respectively as shown in Table 4-3). The increase in CN values from 88.69 in 1994 to 89.46 in 2018 led to the increase in surface runoff values. The comparison of CN values for each sub-basin showed that there was an increase in CN values in sub-basins (W300, W310, and W320) which were agricultural general area converted to the urban area due to the urbanization of Sana'a city and its location at the boundary of the study area.

Table 4-3 Comparing of CN values for Land use classes in Wadi Al-Mulaikhy in 1994 and 2018

No	Sub-Basin	Area (km^2)	CN 1994 (mm)	CN 2018 (mm)
1	W300	7.9154	86.17	89.56
2	W310	12.6014	89.02	89.19
3	W320	6.9156	86.11	88.37
4	W330	6.9256	90.97	90.92
5	W340	8.4888	91.13	91.01
6	W350	8.5128	89.02	88.90
7	W360	11.6458	88.43	88.30
Average		63.00	88.69	89.46

4.2.2 S Values.

This parameter describes the state of water-saturated soil after runoff begins. Therefore, the factor S is related to soil type and LU, which was reflected in the CN values. S values near-zero indicate that the low potential for soil water retention after the surface runoff, and increasing the surface runoff. Table 4-4) shows that S values were decreased from 32.5 in 1994 to 29.94 in 2018. The decrease in S values led to a decrease in the water retention potential of soil after surface runoff. When comparing the S values in the sub-basins, a decrease in the S values was observed in the sub-basin W300, W310 and W320, which were converted from agriculture general to urbanization.

Table 4-4 Comparing of the Maximum Retension(S) for Land use classes in Wadi Al-Mulaikhy in 1994 and 2018

No	Sub-Basin	Area (km^2)	S 1994 (mm	S 2018 (mm)
1	W300	7.91	40.76)	29.60
2	W310	12.60	31.32	30.78
3	W320	6.91	40.97	33.42
4	W330	6.92	25.21	25.36
5	W340	8.48	24.72	25.09
6	W350	8.51	31.32	31.71
7	W360	11.64	33.23	33.65
Average		63.00	32.50	29.94

4.2.3 Ia Values

The initial abstraction (Ia) reflects the water loss by evaporation, plants, and infiltration. The low value of initial abstraction (Ia) which is close to zero indicates low water losses before surface runoff, and leading to generate the surface runoff quickly. Table 4-5) shows that the average value of Ia decreased from 6.49 in 1994 to 5.98 in 2018, which led to a decrease in water loss and an increase in surface runoff.

Table 4-5 Comparing of the Initial Abstraction (Ia) for Land use classes in Wadi Al-Mulaikhy in 1994 and 2018

No	Sub-Basin	Area (km^2)	Ia 1994 (mm)	Ia 2018 (mm)
1	W300	7.9154	8.15	5.92
2	W310	12.6014	6.26	6.15
3	W320	6.9156	8.19	6.68
4	W330	6.9256	5.04	5.07
5	W340	8.4888	4.94	5.01
6	W350	8.5128	6.26	6.34
7	W360	11.6458	6.64	6.73
Average		63.00	6.49	5.98

4.3 Building scenarios for water uses (2018-2050)

Building scenarios for water uses depended on the previous results of land use changes and its effect on the volume of runoff in Wadi Al Mulaikhy sub-watershed between 1994 and 2018. The results of the annual change in land use classes, and the volume of runoff of the year 2018 were used as input data. Population information and annual population growth rates were used to construct scenarios for water demands in domestic and agricultural sector between 2018 and 2050 by using WEAP program. As the area of agricultural land 2057 hectares and its annual changed -0.23%. Water consumption per hectare was 4252 m^3 per year. The runoff volume for the base year of the year 2018 was (1291900 m^3).

4.3.1 First scenario

Before the calculation of the first scenario we need to calculate the current account 2018 (reference scenario). The current account (reference scenario) was populated when the total population is 10283, the annual population growth rate was 5.5%, and the annual domestic water consumption per capita was 25.55 m^3. The amounts of water demand for agricultural use was 8.75 MCUM, and the amounts of water demand for domestic use was (0.26) MCUM Table 4-6). After that, we calculated the first scenario from the reference scenario in case there was variation in the scenario inputs. The annual population growth was 5.5%, and the change in agricultural area was -0.23% between 2018 and 2050. The results was presented in Figure 4-5) , the amount of water demand for domestic use will be increased from 0.26 MCUM from the year 2018 to 1.46 MCUM by the year 2050, and the amount of water demand for agricultural use will be decreased from 8.75 MCUM from the year 2018 to 8.13 MCUM by the year 2050 as shown in Figure 4-5) and Table 4-6).

4.3.2 Second scenario

From the reference scenario we constructed a new scenario in case the annual population growth was 5.5 % and there was development in agricultural activity led to an increase in water demand consumption to 6000 m^3 per hectares. The results are shown in **Error! Reference source not found.**) and Table 4-7). The amount of water demand for domestic use will be increased from 0.26 MCUM from the year 2018 to 1.46 MCUM by the year 2050, and the amount of water demand for agricultural use will be increased from 8.75 MCUM from the year 2018 to 11.47 MCUM by the year 2050.

4.3.3 Third scenario

This scenario assumed there will be annual urban expansion in Sana, a city will be about 4%, the annual population growth will be 5.5%, and the agricultural water demand will be about 6000 m^3 per hectares. The results are shown in Table 4-8) and Figure 4-7), the amount of water demand for domestic use will be increased from 0.26 MCUM from the year 2018 to 1.46 MCUM by the year 2050, and the amount of water demand for agricultural use will be decreased from 8.75 MCUM from the year 2018 to 3.34 MCUM by the year 2050.

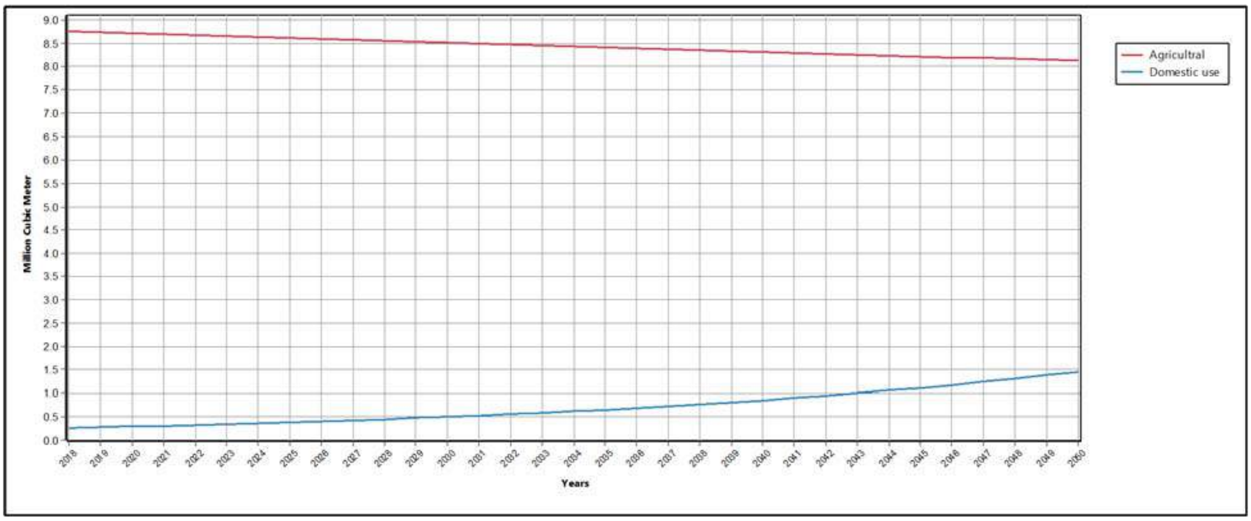

Figure 4-5 : Water Demands for the First Scenario in agriculture and domestic use

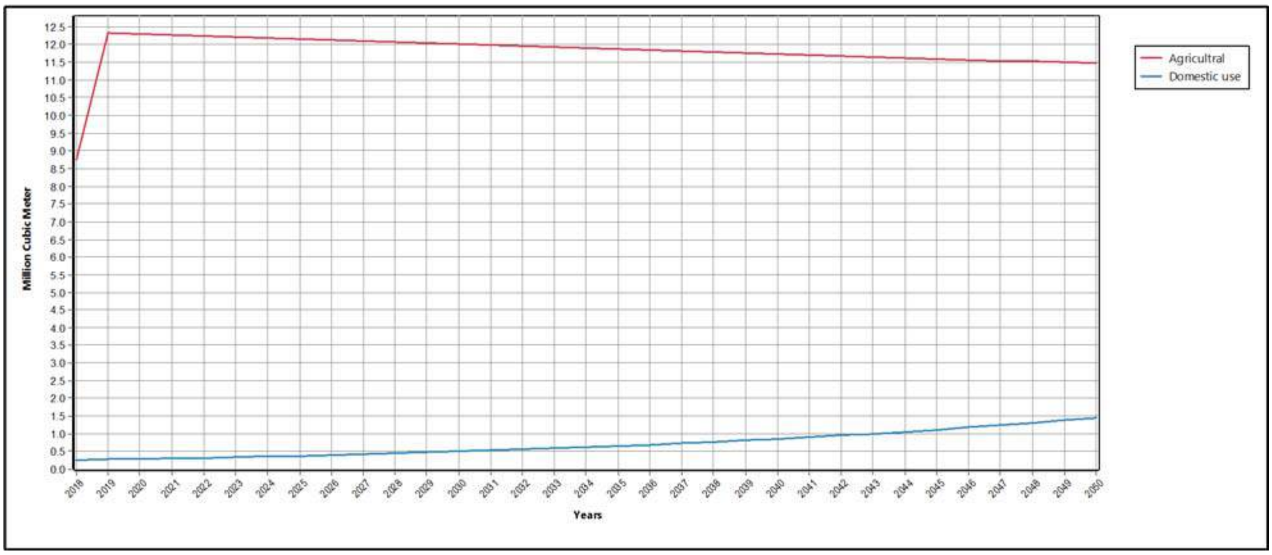

Figure 4-6 : Water Demands for the second Scenario in agriculture and domestic use

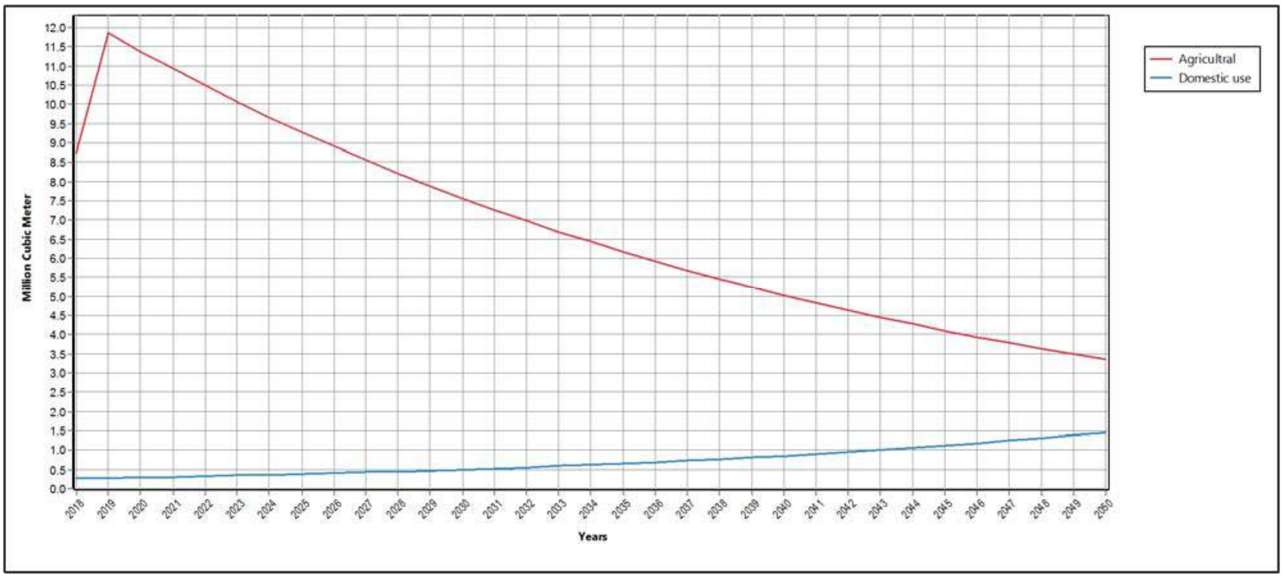

Figure 4-7 : Water Demands for the Third Scenario in agriculture and domestic use

Table 4-6 Water Demands for the First Scenario in agriculture and domestic use

years	Agricultural use/ MCUM	Domestic use/ MCUM	Sum
2018	8.75	0.26	9.01
2019	8.73	0.28	9
2020	8.71	0.29	9
2021	8.69	0.31	8.99
2022	8.67	0.33	8.99
2023	8.65	0.34	8.99
2024	8.63	0.36	8.99
2025	8.61	0.38	8.99
2026	8.59	0.4	8.99
2027	8.57	0.43	8.99
2028	8.55	0.45	9
2029	8.53	0.47	9
2030	8.51	0.5	9.01
2031	8.49	0.53	9.02
2032	8.47	0.56	9.02
2033	8.45	0.59	9.04
2034	8.43	0.62	9.05
2035	8.41	0.65	9.06
2036	8.39	0.69	9.08
2037	8.37	0.73	9.1
2038	8.35	0.77	9.12
2039	8.33	0.81	9.14
2040	8.31	0.85	9.17
2041	8.3	0.9	9.2
2042	8.28	0.95	9.23
2043	8.26	1	9.26
2044	8.24	1.06	9.3
2045	8.22	1.12	9.33
2046	8.2	1.18	9.38
2047	8.18	1.24	9.42
2048	8.16	1.31	9.47
2049	8.14	1.38	9.53
2050	8.13	1.46	9.58
Sum	278.26	23.18	301.44

Table 4-7 Water Demands for the Second Scenario in agriculture and domestic use

years	Agricultural use/ MCUM	Domestic use/ MCUM	Sum
2018	8.75	0.26	9.01
2019	12.31	0.28	12.59
2020	12.29	0.29	12.58
2021	12.26	0.31	12.57
2022	12.23	0.33	12.55
2023	12.2	0.34	12.54
2024	12.17	0.36	12.53
2025	12.14	0.38	12.53
2026	12.12	0.4	12.52
2027	12.09	0.43	12.51
2028	12.06	0.45	12.51
2029	12.03	0.47	12.51
2030	12.01	0.5	12.51
2031	11.98	0.53	12.51
2032	11.95	0.56	12.51
2033	11.92	0.59	12.51
2034	11.9	0.62	12.51
2035	11.87	0.65	12.52
2036	11.84	0.69	12.53
2037	11.81	0.73	12.54
2038	11.79	0.77	12.55
2039	11.76	0.81	12.57
2040	11.73	0.85	12.59
2041	11.71	0.9	12.61
2042	11.68	0.95	12.63
2043	11.65	1	12.65
2044	11.62	1.06	12.68
2045	11.6	1.12	12.71
2046	11.57	1.18	12.75
2047	11.54	1.24	12.79
2048	11.52	1.31	12.83
2049	11.49	1.38	12.87
2050	11.47	1.46	12.92
Sum	389.05	23.18	412.23

Table 4-8 Water Demands for the Third Scenario in agriculture and domestic use

years	Agricultural use/ MCUM	Domestic use/ MCUM	Sum
2018	8.75	0.26	9.01
2019	11.85	0.28	12.13
2020	11.37	0.29	11.67
2021	10.92	0.31	11.23
2022	10.48	0.33	10.81
2023	10.06	0.34	10.41
2024	9.66	0.36	10.02
2025	9.27	0.38	9.66
2026	8.9	0.4	9.31
2027	8.55	0.43	8.97
2028	8.21	0.45	8.65
2029	7.88	0.47	8.35
2030	7.56	0.5	8.06
2031	7.26	0.53	7.79
2032	6.97	0.56	7.53
2033	6.69	0.59	7.28
2034	6.42	0.62	7.04
2035	6.17	0.65	6.82
2036	5.92	0.69	6.61
2037	5.68	0.73	6.41
2038	5.46	0.77	6.22
2039	5.24	0.81	6.05
2040	5.03	0.85	5.88
2041	4.83	0.9	5.73
2042	4.63	0.95	5.58
2043	4.45	1	5.45
2044	4.27	1.06	5.33
2045	4.1	1.12	5.21
2046	3.94	1.18	5.11
2047	3.78	1.24	5.02
2048	3.63	1.31	4.94
2049	3.48	1.38	4.86
2050	3.34	1.46	4.8
Sum	224.74	23.18	247.9

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

local land use maps for Wadi Al Mulaikhy sub-watershed in Sana’a basin were used to simulate surface runoff by using HEC-HMS model to assess the impact of land use changes on runoff characteristics, the runoff was simulated with the land use maps of the years 1994, and 2018.

1. The major change in land use classes was identified in agricultural general class converted to other classes (urban high density, urban medium to low density, barren/minimal vegetation, shrub/scrub and roads).
2. The impact of land use change on runoff characteristics only existed through the conversion of 5.65% from agricultural general class to the classes (urban high density, urban medium to low density, barren/minimal vegetation, shrub/scrub and roads) by (1.5%, 0.22%, 0.53%, 2.84% and 0.55%) respectively.
3. The runoff volume increased from 1270900 m^3 of the year 1994 to 1291900 m^3 in the year 2018 about 1.625% over 24 years' period.
4. It was found that there is no big change in runoff volume comparing with the change in land use due to some of the agricultural general class changes to other classes (Shrub/Scrub), which has the similar runoff characteristics. The second changes from agricultural general class changes to urban classes (urban high density, urban medium to low density and roads) occurred in the north of the study area at the boundary of Sana'a city which has urban expansion.
5. The average of CN values increased from 88.69 in the year 1994 to 89.46 in the year 2018. The average of S values decreased from 32.5 in the year 1994

to 29.94 in the year 2018, while, the average of Ia values decreased from 6.49 in the year 1994 to 5.98 in the year 2018.

6. The results use of water demand in the first scenario between the years 2018 and 2050 for domestic and agricultural in the case of population growth was 5.5%, the change in agricultural area was -0.23% per year, the annual domestic consumption per capita was 25.55 m^3 per year, and the consumption of water use for agricultural was 4252 m^3 per hectares. The amount of water demand for domestic use will be increased from 0.26 MCUMs in the year 2018 to 1.46 MCUM by the year 2050. The amount of water demand for agricultural use will be decreased from 8.75 MCUM in the year 2018 to 8.13 MCUM by the year 2050.
7. The results of the second scenario in the case population growth was 5.5% and the development of the agricultural activity led to an increase in water consumption to 6000 m^3 per hectares. The amount of water demand for domestic use will be increased from 0.26 MCUM in the year 2018 to 1.46 MCUM by the year 2050. The amount of water demand for agricultural use will be increased from 8.75 MCUM in the year 2018 to 11.74 MCUM by the year 2050.
8. The results of the third scenario are based on the fact that there were 4% of annual urbanization expansion, 5.5% of population growth, and agricultural water demand of 6000 m^3 per hectares. The amount of water demand for domestic use will be increased from 0.26 MCUM from the year 2018 to 1.46 MCUM by the year 2050. The amount of water demand for agricultural use will be decreased from 8.75 MCUM in the year 2018 to 3.34 MCUM by the year 2050.

5.2 Recommendations

The recommendations of the study are as follows:

1- Preserving the vegetation cover area in Wadi Al Mulaikhy sub-watershed area is affected by human-induced factors and lead to climate changes and may create new changes in the temporal distribution pattern of climate factors such as precipitation, temperature. The increase in vegetation cover leads to decreasing runoff volume and groundwater recharge.

2- Applying the integrated water resource management during the planning in order to preserve the component of the natural environment. Increasing urban expansion leads to increasing impermeable surface and runoff volume which sometimes lead to flash flooding.

3- Carrying out a study for selecting the best locations for rainwater harvesting which leads to increasing the recharge of groundwater and decreasing runoff volume, flash flooding and its effect on Sana'a city.

4- Establishing rainfall stations in order to create spatial hydrological database for the next climate and hydrological studies.

5- Conducting more studies related to runoff by using remote sensing and geographic information system technology which play an important role for achieving more accurate results with various models.

6- The study conducted three scenarios for applying the integrated water resource management in water uses for domestic and agricultural demand and recommended to apply scenario two for the following reasons:

- Increasing the agricultural development in the study area.
- More consumption of water for agricultural leads to increasing groundwater recharge.

- Decreasing runoff volume leads to decreasing flash flooding hazard and its effect on Sana'a city.

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تأثير التغير في استخدام الاراضي على الجريان السطحي من منظور الادارة المتكاملة للموارد المائية

دراسة حالة وادي المليكي حوض صنعاء، اليمن

اطروحة مقدمة كاستيفاء جزئي لمتطلبات الحصول على درجة الماجستير في الإدارة المتكاملة للموارد المائية

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جامعة صنعاء

٢٠٢٠

الملخص

يتأثر الجريان السطحي بالعديد من المعاملات مثل نوع التربة والتغير في استخدام وغطاء الارض ، والتي تشمل الغطاء النباتي ومستوى التحضر. وتقيم هذة الدراسة تأثير التغير في استخدام وغطاء الارض بين عامي 1994 و 2018 على خصائص الجريان السطحي في وادي المليكي والذي يعتبر حوض جزئي من حوض صنعاء اليمن ، من خلال تكامل برامج نظم المعلومات الجغرافية GIS وملحقاته HEC-GeoHMS ، وكذلك برنامج حساب الجريان السطحي HEC-HM.تعتبر بيانات الاستشعار عن بعد واستخدام الأراضي ونوع التربة وهطول الأمطار المدخلات الرئيسية للبرنامج. أظهرت نتائج الدراسة انخفاض مساحة الاراضي الزراعية بنسبة 5.67٪. على العكس من ذلك ، كانت الزيادة في الجريان السطحي بنسبة 1.65٪. حيث وجد انه لا يوجد تغيير كبير في حجم الجريان السطحي نسبة إلى التغير في استخدام الأرض بسبب بعض التغييرات في مساحة الاراضي الزراعية إلى فئات أخرى (المراعي) والتي لها خصائص جريان مماثلة لخصائص الجريان السطحي للاراضي الزراعية. التغيير الثاني ، كان التغير في مساحة الاراضي الزراعية إلى مساحات حضرية (مناطق حضرية عالية الكثافة ، ماطق حضرية متوسطة الى ضعيفة الكثافة والطرقات) التي حدثت في شمال منطقة الدراسة بالقرب من حدود مدينة صنعاء التي تشهد توسع عمراني. كما اظهرت نتائج الدراسة ان التغير في معاملات الجريان السطحي كانت في الاحواض الفرعية (W300، W310 و W320) التي تقع في شمال منطقة الدراسة بسبب التغيرات في مساحة الاراضي الزراعية إلى مساحات الحضرية (مناطق حضرية عالية الكثافة ، ماطق حضرية متوسطة الى ضعيفة الكثافة والطرق).

ولتطبيق الإدارة المتكاملة للموارد المائية على الطلب على المياه ، تم تطبيق ثلاثة سيناريوهات مختلفة بين 2018 و 2050 للاستخدام المنزلي والزراعي. تم تطبيق السيناريو الأول على الوضع الحالي للعام 2018 و 2050. حيث كان معدل النمو السكاني السنوي 5.5٪ ، والتغير في مساحة الاراضي الزراعية -0.23٪ ، ومعدل الاستهلاك السنوي للفرد من المياه 25.55 متر مكعب ، ومعدل الاستهلاك السنوي للزراعة 4000 متر مكعب للهكتار الواحد. حيث لوحظ زيادة في كمية استهلاك المياه للاستخدام المنزلي من 0.26 مليون متر مكعب في 2018 إلى 1.46 مليون متر مكعب بحلول 2050 ، وانخفاض كمية الطلب في استهلاك المياه للاستخدام الزراعي من 8.75 مليون متر مكعب في 2018 إلى 8.13 متر مكعب في 2050.

تم حساب السيناريو الثاني في حالة ثبات النمو السكاني بنسبة 5.5٪ وزيادة معدل الاستهلاك السنوي للمياه في الزراعة إلى 6000 متر مكعب للهكتار . لوحظ زيادة في حجم الطلب على المياه للاستخدام المنزلي من 0.26 مليون متر مكعب في 2018 إلى 1.46 مليون متر مكعب بحلول عام 2050. وزيادة حجم الطلب على المياه للاستهلاك الزراعي من 8.75 مليون متر مكعب في 2018 إلى 11.74 مليون متر مكعب بحلول عام 2050.

أما السيناريو الثالث فقد تم تطبيقه في حالة الزيادة السنوية في التوسع العمراني الحضري الى 4٪ ، وثبات الاستهلاك السنوي للطلب على المياه للاراضي الزراعية على 6000 متر مكعب للهكتار. لوحظ زيادة في كمية الطلب على المياه للاستخدام المنزلي من 0.26 مليون متر مكعب في 2018 إلى 1.46 مليون متر مكعب بحلول 2050. وانخفاض كمية الطلب على المياه للاستخدام الزراعي من 8.75 مليون متر مكعب في 2018 إلى 3.34 مليون متر مكعب بحلول 2050.

الكلمات المفتاحية :الجريان السطحي , استخدام الاراضي, نظم المعلومات الجغرافية, HEC-HMS. الاراضي الزراعية , الطلب على المياه, وادي المليكي.