THE USE OF GEOGRAPHICAL INFORMATION SYSTEMS IN CATCHMENT HYDROLOGY MODELING:
A CASE STUDY FROM THE GÖKSU RIVER

by

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ABSTRACT

During the past few decades many enhancements have been made to traditional catchment-scale hydrological modeling by the help of Geographical Information Systems (GIS); with gradual availability of such data and increased computer power, most of the recent hydrological analyses make use of GIS as the main methodological approach to catchment discretization. GIS have also frequently been used in input-output data handling for hydrological modeling purposes, derivation of flow direction-length and slope maps from Digital Elevation Models (DEMs). As a methodological protocol, this study is uniquely applicable to rainfall-runoff analysis using SWMM and ArcGIS software. Integration of data file exchange was a critical link for this study. In this case, attribute tables for soil, land-use and virtual rainfall were generated by ArcMap and analyzed to develop the parameters for the input files for SWMM. SWMM and ArcGIS were chosen because of their relative popularity with many professionals.

The main aim in this study is to determine a solid information collection and implementation strategy that could make maximum use of geographical information systems, with which; data, results, images and graphs also become more understandable during and after the study overall. As noted by Intergovernmental Panel on Climate Change (IPCC, 2007), we still do not have an adequate understanding and ability to model and predict water cycle processes and the associated feedbacks. This study is just a brick in this tower of learning.

ÖZET

Coğrafi bilgi sistemlerinin yoğun olarak kullanılmaya başlaması ile birlikte son birkaç on yılda havza modelleme çalışmalarında birçok değişim meydana gelmiştir. Coğrafi bilgi sistemleri teknolojisinin araştırmacılara sunduğu yüksek veri miktarı ve hızlı çözümleme yapan bilgisayarlar sayesinde bu sistemler hidrolojik olarak havzayı modelleyen araştırmacıların kullandığı en önemli araçlardan bir tanesi olmuştur. Coğrafi bilgi sistemleri ayrıca verilerin saklanması, kullanıma sunulması, topografik ve eğim haritalarının elde edilmesi sırasında da başvurulan en önemli araçtır. Çalışma çağdaş methodolojiye de uyarak yağış akış modellemesinin ArcGIS ve SWMM programlarını kullanarak nasıl yapılacağına bir örnek teşkil etmektedir. Bu iki program arasındaki very akışının sağlanması da ayrıca bu çalışmanın önemli bir ürünüdür. Bu akış sağlanarak cağrafi bilgi sistemlerinden elde edilen bilgiler modelleme programına aktarılmış ve modellemenin hızlı ve güvenilir bir şekilde yapılması sağlanmıştır. Bu iki programın bu çalışma için seçilmiş olma nedeni ikisinin de araştırmacılar tarafından çok tercih edilen programlar olması ve iki programın da birçok yardımcı yazılı dökümanının bulunmasıdır.

Bu çalışmanın ana amacı coğrafi bilgi sistemlerini kullanarak yapılacak olan hidrolojik modelleme çalışmalarında gerekecek bilgilerin en verimli ve kullanışlı şekilde depolama stratejilerinin sunulması ve bu çalışmalar sırasında coğrafi veriyi imaja dökerek verinin kolayca anlaşılabilir bir hal almasının sağlanmasıdır. 2007 senesinde yapılan uluslararası iklim panelinde odaklanıldığı gibi insanoğlunun suyun devirdaimine ilişkin bilgisi hala yeterli değildir ve bu çalışma bu konuda oluşturulacak bilgi kütüphanesinin bir tuğlası olma amacındadır.

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LIST OF ABBREVIATIONS

Symbol	**Explanation**
CFD	Computational Fluid Dynamics
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DSI	State Hydraulic Works
EIEI	State Electrical Works
EPA	Environmental Protection Agency
GIS	Geographical Information Systems
SWMM	Storm Water Management Model
TÜBİTAK	The scientific and Technological Research Council of Turkey
WEHY	Watershed Environmental Hydrology

1. INTRODUCTION

Although use of hydrological models to better understand and predict the behavior of water within catchments has a long history, characterization and modeling of catchments -as important components of the hydrological cycle- are extremely challenging due to their i) complex structures, consisting of interconnected and interwoven parts ii) occurrence in disparate media (ground, land surface, atmosphere and plants) iii) vast spatial scales (that can range from a few centimeters for infiltration to few kilometers for groundwater flow), and iv) variations in time scales (that can extend from a few seconds, typical for evaporative fluxes, to the several years or decades). In order to overrun the challenges faced, accurate implementation of spatial and temporal data is crucial in distributed or semi-distributed hydrological models. These data include; topological, geomorphologic, meteorological, and data regarding land use, land cover and subsurface characteristics of catchments.

During the past few decades many enhancements have been made to traditional catchment-scale hydrological modeling by the help of Geographical Information Systems (GIS); with gradual availability of such data and increased computer power, most of the recent hydrological analyses make use of GIS as the main methodological approach to catchment discretization. GIS have also frequently been used in input-output data handling for hydrological modeling purposes, derivation of flow direction-length and slope maps from Digital Elevation Models (DEMs).

Physically-based, semi-distributed hydrologic models simulate hydrologic state variables in space and time while using information regarding heterogeneity in climate, land use, topography and hydrogeology. Because of the heterogeneity and fine resolution of the observed data, a strategy to accurately represent geo-data in models must take into account the associated increase in computational and manual load. Representational accuracy of geo-data (topography, land cover, soil, geology, vegetation and climate) on a distributed model grid depends on the resolution of observed data and model grid and the type of discretization strategy (unstructured or structured) which determines its flexibility to conform to data boundaries.

As a methodological protocol, this study is uniquely applicable to rainfall-runoff analysis using SWMM and ArcGIS software. Integration of data file exchange was a critical link for this study. In this case, attribute tables for soil, land-use and virtual rainfall were generated by ArcMap and analyzed to develop the parameters for the input files for SWMM. SWMM and ArcGIS were chosen because of their relative popularity with many professionals.

The main aim in this study is to determine a solid information collection and implementation strategy that could make maximum use of geographical information systems, with which; data, results, images and graphs also become more understandable during and after the study overall. As noted by Intergovernmental Panel on Climate Change (IPCC, 2007), we still do not have an adequate understanding and ability to model and predict water cycle processes and the associated feedbacks. This study is just a brick in this tower of learning.

2. THEORETICAL BACKGROUND

Distributed models simulate hydrologic states in space and time while using discretized information regarding the distribution and parameters of climate, land use, topography and hydrogeology (Freeze and Harlan 1969). These models have inherent advantages over conventional lumped models particularly because natural heterogeneities control watershed behavior(s) and also help in resolving the feedback processes between state variables (Entekhabi and Eagleson 1989; Pitman et al. 1990). The numerical solution strategies require spatial discretization of the model domain into spatially connected units. For example grid decomposition for land surface models may take advantage of relevant physical sub domains such as hill slopes (Band 1986), a contour (Moore et al. 1988), structured (Panday and Huyakorn 2004) or unstructured grids. In the case of multi-process/multi-scale models, the representation of topography, land cover, soil, geology, vegetation and climate on a distributed model grid must, by necessity, deal with questions of computational efficiency and limits of parameterization. Since our goal is to perform physics based simulations on large watersheds, our strategy is to minimize the resolution of spatial discretization (fewest number of elements to preserve the essential physics) while still capturing the local heterogeneities in parameters and process dynamics. In this study this has been achieved by dividing the area into grids.

2.1. Catchment Hydrological Modeling

In recent years it has become apparent that the accurate simulation of water movement within a catchment requires the integration of the various individual components of the hydrologic cycle, including overland flow, channel flow, infiltration, depression storage, evaporation, interception, subsurface flow, and base flow (Singh and Woolhiser, 2002); Geographical Information Systems (GIS) have been traditionally used to accomplish the management functionalities in hydrologic applications.

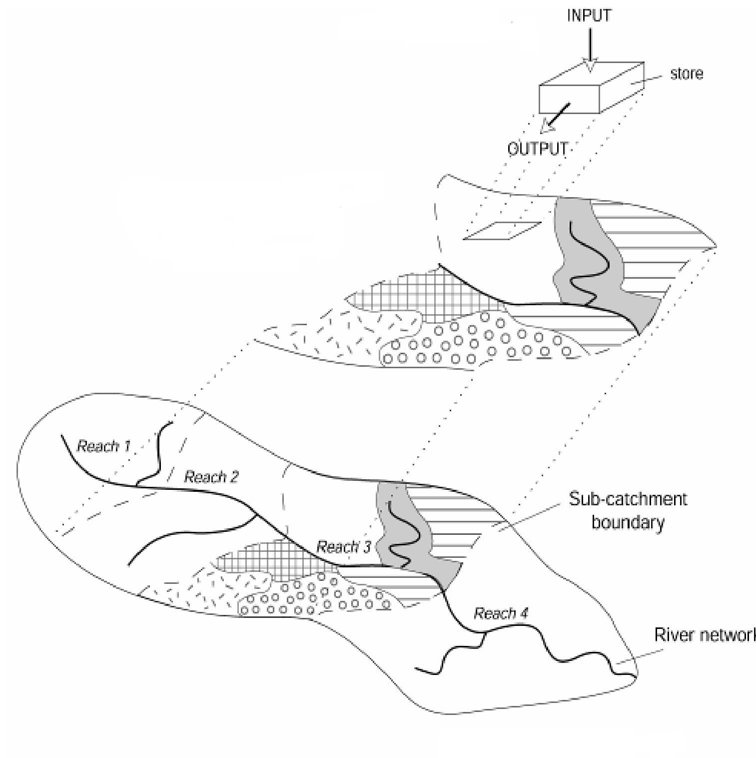

Figure 2.1. Visual Representation of Semi Distributed Cellular Model Structure (MIKE SHE Users Guide)

The conceptual framework of modeling fluvial hydraulics has largely relied on experimental flume studies and computational fluid dynamics (CFD) (Brasington and Richards, 2007). Recent advances in modeling techniques such as remote sensing and the used of Digital Elevation Models (DEM) have led to the development of novel spatial and cellular algorithms, efficient discretization methods and an increasing reliance on high quality topographic data. In fluvial geomorphology, cellular models use simplified or ‘relaxed’ versions of the complex flow equations used in CFD models (Coulthard et al., 2007). The basic principles of cellular modeling are that landforms are represented by a grid of cells and that the interactions between cells (e.g. the routing of water, chemicals or sediments) are treated using simple rules based on simplifications of the governing physics. From this point of view, a cellular modeling approach provides the potential to model a wide range of fluvial and geomorphic processes within one framework (Coulthard et al., 2007).

Complex problems call for hydrological models which can make a distinction between different water transport mechanisms within a catchment, and which can account for spatial variability of terrain properties in the area of interest. Incorporation of detailed process descriptions in the model structure, and allowance for spatial variability of landscape and land use characteristics, easily result in overwhelming data requirements and poorly identifiable model parameters (Beven 1989 and Grayson 1992). In the literature semi-distributed approaches to hydrological modelling have been proposed for circumventing some of these problems.

Previous modeling studies focused on various aspects of stream hydrology evolution ranging from hydrological models such as rainfall-runoff modeling, to hydrodynamic models that account for various transport mechanisms such as sediment transport or models of river morphodynamics. Most of the existing models focus on simulating a single aspect of the fluvial system such as runoff, sediment transport, or river morphologic development. Mathematical modeling of rainfall-runoff processes has a long history (e.g. Beven and Kirkby, 1979; Iberal, 1990). Unlike models that use lumped parameter values; spatially distributed hydrologic models, especially when supported by GIS applications, have the capability to incorporate a variety of spatially-varying land characteristics and precipitation forcing data, are thought to have great potential for improving hydrologic forecasting (Carpenter and Georgakakos, 2006). Spatially distributed hydrological models integrating both surface and subsurface hydrological processes include MIKE SHE, which was developed by the Danish Hydraulic Institute (DHI, 2005) and successfully applied to a number of watersheds in Denmark (Madsen, 2003; Henriksen et al., 2003; and Vazquez and Feyen, 2007) and Storm Water Management Model (SWMM) developed by Environmental Protection Agency of United States and applied to many studies worldwide (e.g. Smith et al., 2005). Zhang et al. (2008) developed an integrated surface-subsurface flow model to assess in the management of a watershed in China. Kavvas et al. (2004) developed the Watershed Environmental Hydrology (WEHY) Model which is based on up-scaled conservation equations. WEHY approaches the modeling of the hydrological processes considering the heterogeneity within the watersheds. Chen et al. (2004) applied the WEHY model for Shiobara-Dam watershed. Abu El-Nasr et al. (2005) tested the performance of two different models, the fully distributed MIKE SHE model and the semi-distributed SWAT model to examine if both models were equally able to describe the different phases in the hydrologic cycle of a catchment, given the availability of hydrologic data in the catchment.

Most of the hydrological processes include spatially heterogeneous processes that depend on a large variety of influencing factors such as climate, land cover and land use. Therefore, detailed physically-based distributed models are useful tools for understanding the interactions of the processes involved in hydrological modeling and need to be adopted for modeling the complex processes at the scale of basins. However, usually because of the scarcity of data, mostly lumped models have been used to model rainfall runoff process in catchments. Such models may produce reasonable results, but because of the distributed nature of hydrological properties like soil type, slope and land use, these models cannot be expected to accurately fully represent the catchment conditions (Shrestha, 2003).

Recent studies revealed the advantages of conceptual semi-distributed models for runoff estimation in comparison to lumped ones (Boyle et al., 2001; Ajami et al, 2004). Such an approach allows a satisfactory representation of catchment heterogeneities and provides the required level of detail for reasonable simulation, while being computationally efficient (Efstratiadis et al., 2008). The first step in developing a semi-distributed hydrological model for a selected catchment is to decide which sub-catchments should be modeled separately and which could be lumped together, and this decision is usually made based on the available hydro-meteorological data (Schumann, 1993). GIS enables to generate, manipulate, store, integrate and retrieve spatial data which can be used for distributed and semi-distributed modelling of a water catchment.

One of the most important factors in determining river hydrology and type is climate. Depending on the amount of precipitation, rivers will be epharmal, intermittent, or perennial, and as the hydraulic geometry relations indicate, the more water the larger the channel (Schumm, 2005). Investigation of large scale, long term impacts of climate and land use change on channel dynamics is important to understand and characterize the behavior and evolution of river and catchment systems. The changes in land use significantly affect the hydrograph peak and total volume of runoff for a given amount of rainfall by altering interception of rainfall by the canopy. For example, urbanization can substantially alter a catchment's hydrologic regime by reducing the infiltration of precipitation into the subsurface, since urban development typically involves the removal of trees and the replacements of soils and vegetation with impervious surfaces (Nelson et al., 2006).

2.1.1. Rainfall-runoff Phenomenon

Surface runoff is the water flow that occurs when soil is infiltrated to full capacity and excess water from rain, meltwater, or other sources flows over the land. According to Horton (1933) this is a major component of the water cycle. A land area which produces runoff that drains to a common point is called a watershed. When runoff flows along the ground, it can pick up soil contaminants including, but not limited to petroleum, pesticides, or fertilizers that become discharge or nonpoint source pollution.

2.1.2. Common Processes in Catchment Hydrological Modeling

Studying hydrological modeling each subcatchment surface is treated as a nonlinear reservoir and a catchment requires the integration of the various individual components of the hydrologic cycle, including overland flow, channel flow, infiltration, depression storage, evaporation, interception, subsurface flow, and base flow (Singh and Woolhiser, 2002). Inflow comes from precipitation and the runoff from any designated upstream subcatchments. Outflows consist of infiltration, evaporation, and surface runoff.

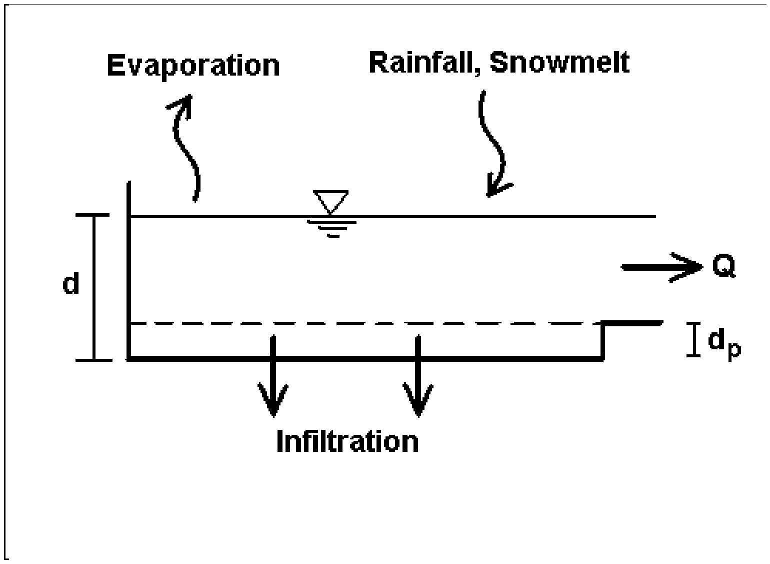

Figure 2.2. Representation of the Subcatchment Processes

The capacity of this "reservoir" is the maximum depression storage, which is the maximum surface storage provided by ponding, surface wetting, and interception. Surface runoff (Q) occurs only when the depth of water d in the "reservoir" exceeds the maximum depression storage, d_p, in which case the outflow is given by Manning's equation where W is the subcatchments characteristic width, *S* its slope, and n is Manning roughness value:

$$Q = W\frac{1.49}{n}(d - d_p)^{5/3} S^{1/2} \tag{2.1}$$

Depth of water over the subcatchment is continuously updated with time by solving numerically a water balance equation over the subcatchment and in order to calculate infiltration, Horton Method is used:

$$f = f_\infty + (f_0 - f_\infty)e^{-\alpha t} \tag{2.2}$$

where, f is infiltration rate (L/T), f_∞ is minimum infiltration capacity (L/T), f_0 is infiltration capacity for dry soil (L/T), t is time (T) and α is constant (1/T).

2.2. Use of Geographical Information Systems in Catchment Modeling

A geographic information system (GIS), or geographical information system, is any system that captures, stores, analyzes, manages, and presents data that are linked to location. In the simplest terms, GIS is the merging of cartography, statistical analysis, and database technology. GIS systems are used in cartography, remote sensing, land surveying, utility management, natural resource management, photogrammetric methods, geography, urban planning, emergency management, navigation, and localized search engines. During the study of hydrological analysis of the Göksu Basin in Mersin, Turkey; geographical information system techniques are used in order to formulate and statistically analyze the data with geographic and spatial importance.

Printed maps which could be defined as the major elements of cartography until some decades ago have left their places to the digital or digitalized maps. Turning into digital, cartography has leaped a major step just like any other branch of science: digitalized data could be archived, analyzed in deeper complexity and in a smaller piece of time, and some calculations and statistical analyses which could not be done with orthodox cartography can now be done in computer speed. Nowadays studying a branch of science according to a spatial reference without the use of computers and GIS technology has become obsolete.

During the acquisition of the data needed for the hydrodynamic analysis of Göksu Basin spatial information availability of the data was checked and -if available- the data later integrated into the project system with geographic reference. This integration procedure enhances the project by bringing together a very rich, multilayered map with various data on various layers. This map of data with spatial reference is and will be the major information database of the project.

Physics-based distributed hydrologic models (DHMs) simulate hydrologic state variables in space and time while using information regarding heterogeneity in climate, land use, topography and hydrogeology (Freeze and Harland 1969; Kollet and Maxwell 2006). Because of the large number of physical parameters incorporated in the model, intensive data development and assignment is needed for accurate and efficient model simulations. A Geographic Information System (GIS) has the ability to handle both spatial and non-spatial data, and to perform data management and analysis. However it lacks the sophisticated analytical and modeling capabilities (Maidment 1993; Wilson 1996; Abel et. al. 1994 and Kopp 1996). On the other hand from the physical model perspective, they generally lack data organization and development functionalities, therefore a combinational use of these tools must be accomplished in order to represent reality in a computer model.

2.3. Hydrological Modeling with SWMM

SWMM model was selected as the main modeling tool because of its free availability and easy to use interface. Also input parameters needed to model with SWMM were in accordance with the data we have obtained although other more complicated model were not superior with it most of the time.

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Smith et al., 2005). The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps. The storm water management model (SWMM), which was originally developed by the EPA between 1969 and 1971 (Metcalf and Eddy Inc. 1971), has been widely used to simulate all aspects of urban hydrologic and quality cycles, including rainfall, snowmelt, overland flow, flow routing through a drainage network, and urban nonpoint pollution concentrations (Huber and Dickinson 1992, Yang et al. 2007). It continues to be widely used throughout the world for planning, analysis and design related to storm water runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well. The current edition, Version 5, is a complete re-write of the previous release. Running under Windows, SWMM 5 provides an integrated environment for editing study area input data, running hydrologic, hydraulic and water quality simulations, and viewing the results in a variety of formats. These include color-coded drainage area and conveyance system maps, time series graphs and tables, profile plots, and statistical frequency analyses.

SWMM accounts for various hydrologic processes that produce runoff from urban areas. These include:

- time-varying rainfall
- evaporation of standing surface water
- snow accumulation and melting
- rainfall interception from depression storage
- infiltration of rainfall into unsaturated soil layers
- percolation of infiltrated water into groundwater layers

Spatial variability in all of these processes is achieved by dividing a study area into a collection of smaller, homogeneous subcatchment areas, each containing its own fraction of pervious and impervious sub-areas. Overland flow can be routed between sub-areas, between subcatchments, or between entry points of a drainage system.

3. METHODOLOGY

The methodology behind the model aimed here is to describe the catchment hydrological behavior by using a semi-distributed, physically-based model and GIS. Physically-based models can be described as abstract representations of the systems under investigation, usually in the form of mechanistic equations describing numerous transport and transformation processes, and they are commonly used in the modeling of river and catchment transport mechanisms. These kind of models are typically derived by combining mathematical statements of mass and momentum conservation with one or more empirical equations. The model presented in this thesis tends to express the relations between the system's variables and represents the response of a physical system (catchment hydrology) to external stimuli (precipitation). Parameters that are going to be used are presented below in Table 3.1:

Table 3.1.Table of Parameters

State Variables		**Forcing Functions**
Subcatchment Parameters	**Hydraulic Parameters (River)**	**Climatology of the Area**
Area	Length	Precipitation
Width	Channel roughness	Temperature
% Slope	Initial flow	Evapotranspiration
% Imperviousness	Channel Slope	Snowmelt
Land Use/Cover	Max Depth	

Schematic representation of the methodology is presented below as figure 3.1:

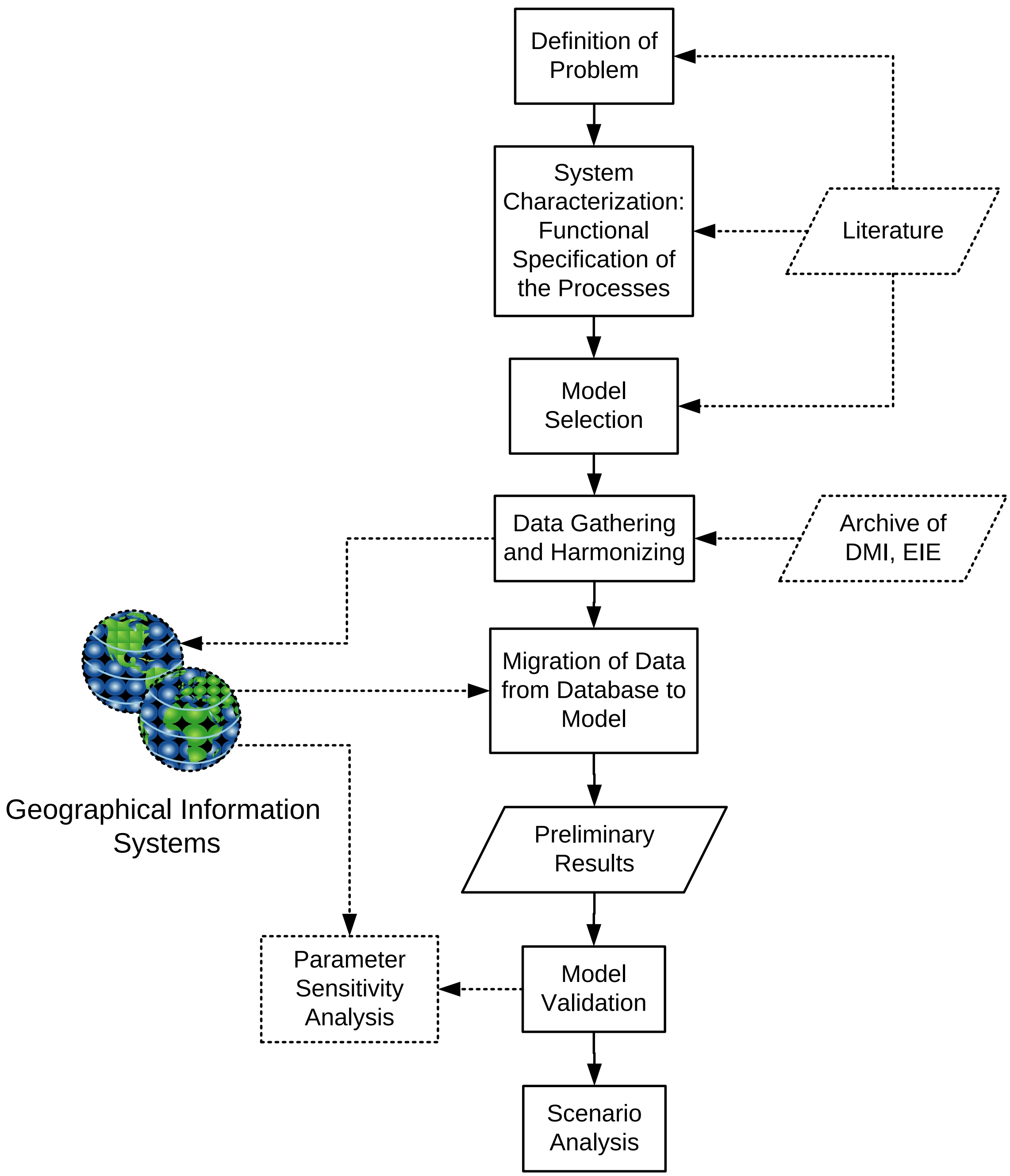

Figure 3.1. Methodology Scheme

3.1. Study Area

Göksu River -which was called ‘Cleadnos’ during the archaic ages- is one of the most important rivers that flow to Mediterranean Sea from Anatolia. As can be seen from the figure 3.2 river rises from Taşeli Plateau and flows through a deep canyon between Toros Mountains. River is fed by tributaries from Geyik Mountains and finally end in Silifke Delta which empties into Mediterranean Sea. River is more than 250 kilometers long with a drainage basin larger than 10,000 kilometer square.

Göksu River has two main tributaries called Hadım Göksuyu and Ermenek Göksuyu; these two branches join near Mut Village and flow to Mediterranean as Göksu River. Snow melts and rains in the area cause the river to display irregular flow regimes; while, the flow rate of the river is highest during month of April caused by snow melting, flow rate drops to lowest values in between months of September and December. Average flow rate of the river is 130 m^3s^{-1} (Turkish Environmental Protection Directorate, 1998).

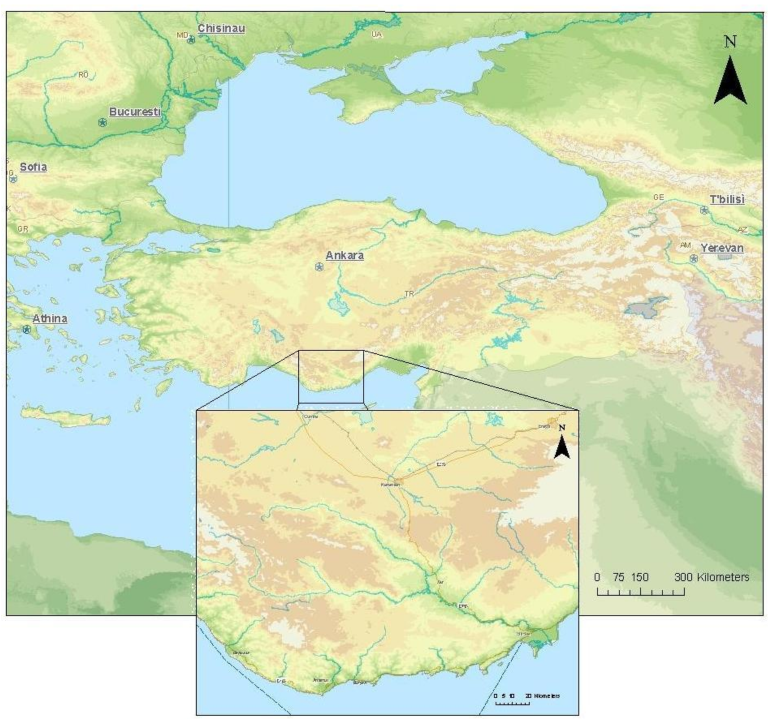

Figure 3.2. Location and Map of the Study Area

Göksu Delta is the most important wetland of the Mediterranean Anatolia (Ocakverdi, 1998). It is 164 km^2 in area and stretches towards the sea for 10 kilometers. Delta and the lakes present on it are natural habitats for many animals and plants, some of which are endemic for the area. The delta has been designated as Natural Protection Area by the 9th article of the Environment Law on the 2nd of March 1990 by the governing commission. Also, the delta has been confirmed as an important place for water birds by RAMSAR Convention

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3.2. Model Structure

The “structure” of a system can be defined as “the totality of the relationships that exist between system variables” (Saysel, 2010); and SWMM conceptualizes a drainage system as a series of water and material flows between several major environmental compartments. These compartments and the SWMM objects they contain include:

- The Atmosphere compartment, from which precipitation falls and pollutants are deposited onto the land surface compartment. SWMM uses Rain Gage objects to represent rainfall inputs to the system.

- The Land Surface compartment, which is represented through one or more Subcatchment objects. It receives precipitation from the Atmospheric compartment in the form of rain or snow; it sends outflow in the form of infiltration to the Groundwater compartment and also as surface runoff and pollutant loadings to the Transport compartment.

- The Groundwater compartment receives infiltration from the Land Surface compartment and transfers a portion of this inflow to the Transport compartment. This compartment is modeled using Aquifer objects.

- The Transport compartment contains a network of conveyance elements (channels, pipes, pumps, and regulators) and storage/treatment units that transport water to outfalls or to treatment facilities. Inflows to this compartment can come from surface runoff, groundwater interflow, sanitary dry weather flow, or from user-defined hydrographs. The components of the Transport compartment are modeled with Node and Link objects.

Not all compartments need appear in a particular SWMM model. For example, one could model just the transport compartment, using pre-defined hydrographs as inputs.

3.2.1. Conceptualizing the System

The basic principles of cellular modeling in geomorphology are that landforms are represented by a grid of cells and that the interactions between cells (e.g. the routing of water, chemical or sediment) are treated using simple rules based on simplifications of the governing physics. From this point of view, the cellular modeling approach provides the potential to model a wide range of fluvial and geomorphic processes within one framework (Coulthard et al., 2007).

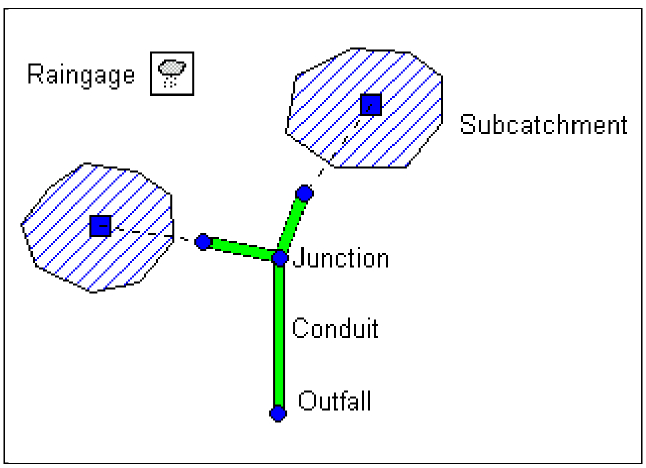


Figure 3.3. SWMM Visual Objects

Figure 3.3 depicts how a collection of SWMM's visual objects might be arranged together to represent a stormwater drainage system. These objects can be displayed on a map in the SWMM workspace.

Detailed descriptions of the objects used in SWMM modeling are presented in Appendix A.

3.2.2. Assumptions

In order to model a concept, some assumptions are to be made (Weverberg et. al., 2011), and the major assumptions for this study are:

- No water crosses the borders of the catchment
- Rainfall amount at any time for a subcatchment is equal to the closest weather station observation at that time
- River cross sections at each portion of the map are identical and river depth is enough to carry any flow
- Imperviousness values of areas are based on averages of the type of land cover (forest, urban, plantation…)
- Snowmelt pattern is identical every year

3.3. Setting the Boundaries and Backdrop Map Setup

A backdrop map is a 'dumb' map or image whose primary use is to provide context visually. It contains no other intelligence or attribution other than what is needed to provide the background. Creating a backdrop map researcher focuses on a region where the study will be carried on (Carpenter and Georgakakos, 2006). Extends of the backdrop map of this study are selected as illustrated below:

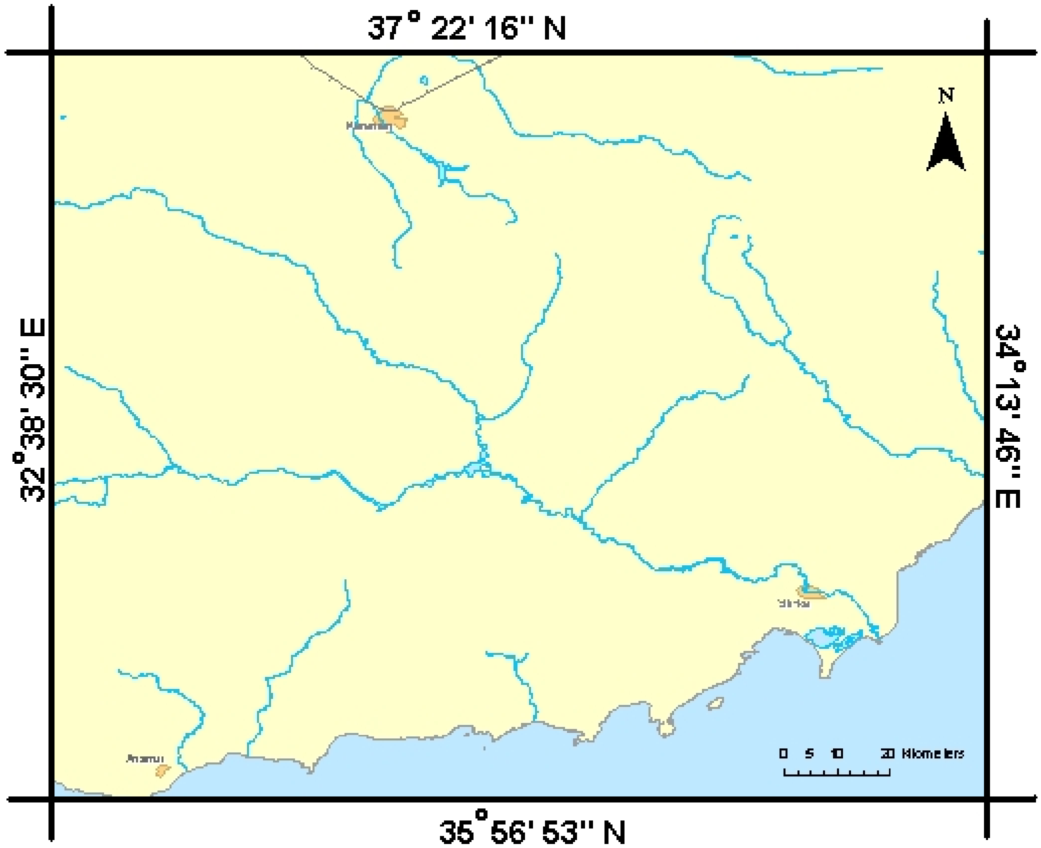


Figure 3.4. Backdrop Image and Geographical Extends

Latitude and longitude values can be based on several different geodetic systems or datums, the most common being WGS 84, a global datum used by all GPS equipment; therefore WGS 84 datum was also used for this study, meaning all the digital maps use the same datum to be compatible.

This backdrop image will act as a bookshelf for the data that are going to be brought together. All calculations, all representations and all visualizations will be done over this backdrop map along with given extends, in other words it defines the boundaries of our system.

3.4. Spatial Database Setup for Göksu River Basin

A spatial database is a database that is optimized to store and query data that is related to objects in space, including points, lines and polygons. This spatial indexing mechanism highly eases the research in which geographical features are used (Carpenter and Georgakakos, 2006).

Models of hydrological processes rely on representing characteristics of the earth's surface that affect components of the water balance, therefore watershed hydrological modeling is a subject that holds much input or output parameters with spatial significance, therefore it is most common to use geographic information systems (GIS) while studying on such major (Freeze and Harland 1969; Kollet and Maxwell 2006); GIS has strong spatial analysis function, which can be used in hydrological model construction. It is common practice to use GIS to explore the relationships between urbanization and hydrology. Application of GIS to urban storm water modeling includes storing, manipulating, analyzing, and displaying data in a geographical context (Seth et al. 2006).

During the study GIS acts not only as a spatial database, but also as a calculation tool, visualization tool, analysis tool and mind-mapping mechanism. All the data gathered in order to model the rainfall-runoff phenomenon has been harmonized and sometimes analyzed using geographic information systems during this particular study and ArcGIS programme version 9.3 has been used as a geographic information systems interface. ArcGIS lets the user to create their own maps; info layers, helps in performing advanced GIS data analysis and helps in creating-managing personal geodatabases.

3.4.1. Hydrological Data

In order to validate our model, obtaining flow data near the end of the river which collects the water from all catchment was crucial. That way the model would be evaluated if it fitted into the real life observations. General Directorate of Electrical Power Resources Survey and Development Administration (Elektrik İşleri Etüd İdaresi – EİE) has been gathering flow data from various rivers around Turkey to survey their electrical potential. These surveys usually are sold to companies with dam building plans, but this time they were used for scientific research. However, administration wasn't willing to give out free data even though it will be used for scientific purposes. Therefore, flow data of Göksu river near Silifke Town was bought from the organization with funding from the Boğaziçi Üniversity – Scientific Research Project Unit (Modeling the Effect of Climate Change on River Morphology).

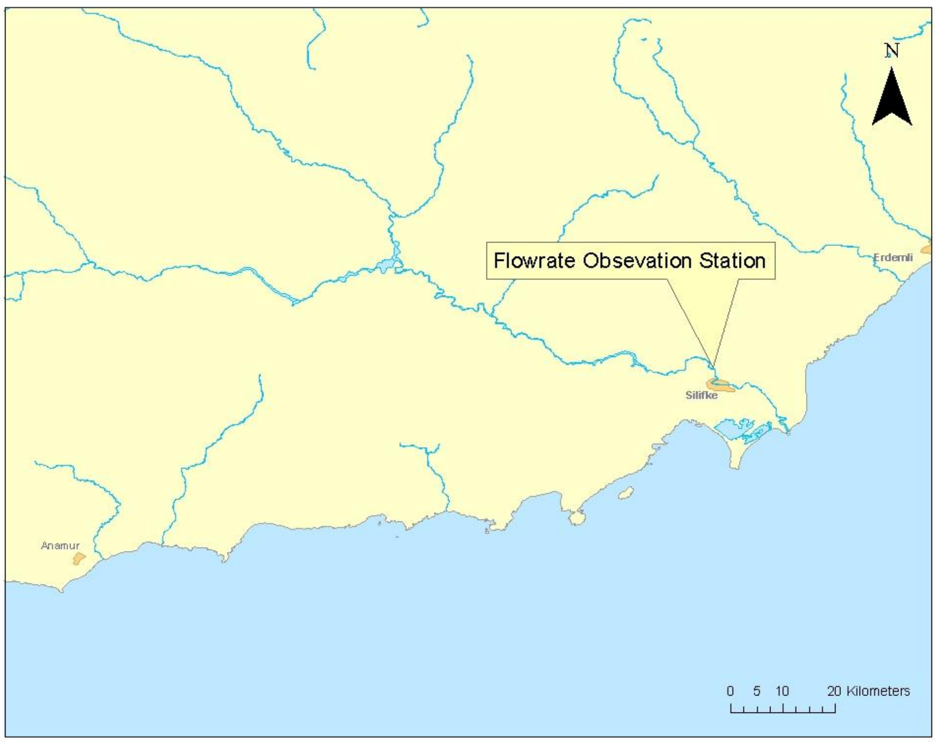


Figure 3.5. Flowrate Observation Station on Map

Data obtained covered the average daily flowrate for the years between 1961 and 2008 while representing the overall outfall of the Göksu Basin since the flowrate measurement station was located near the delta of Göksu River.

3.4.2. Meteorological Data

Rainfall intensities are the most important meteorological data in hydrological modeling along with the evapotranspiration as a minor output from the model. Both parameters are among the major climatic data that are collected by meteorology stations worldwide and are collected by Turkish Meteorological Service stations as well.

Turkish Meteorological Service is the major meteorological data supplier for the national geography. It has more than 100 stations nationwide observing meteorological parameters such as temperature, cloudiness, rainfall and evapotranspiration. Stations are well distributed along the country, however many of them are closely located in city centers rather than rural areas.

Locations of all stations around the country are well known by their latitudes and longitudes with accuracy down to geographic seconds, therefore it is easy to locate them on the backdrop map. There are no stations in the domain of the Göksu River Basin, however three of the stations are relatively close: Silifke, Karaman and Alanya. It was decided to use these three stations as meteorological representatives of the basin and therefore past rainfall data from these stations were obtained. This data included cumulative daily rainfall for the years 1965 to 2004 and average evapotranspiration with respect to months of the year.

Figure 3.6. Map of Silifke, Karaman and Alanya Meteorological Stations

Rainfall data format of Turkish Meteorological Service is not very user-friendly; it had to be converted into a usable format to be used in the simulation. For this reason a ‘Microsoft Visual Basic Script’ was written in order to pull the necessary data columns from various sheets and paste them on a separate sheet; this kind of scripts were written and used extensively to save time. An example script is given in Appendix B.

After the rainfall data were arranged into the necessary format it was saved on GIS database as data points on backdrop map to be used during the modeling step.

3.4.3. Topographical Data

Topographical parameters such as area, slope, width, elevation are among the most important parameters for determination of catchment characteristics and to be used during catchment discretization (Coulthard et al., 2007). All these data are highly available in digital maps, which are open for common use on the Internet; but in order to analyze these data, digital elevation maps have to be used along with other data layers such as precipitation and land cover (Wilson, 2011). In order to sustain interaction between various layers, digital elevation map files must obtained and must be laid over backdrop map using relevant information systems programme (e.g. ArcGIS, GRASS…) (Boyko and Treebushny, 2006).

Elevations maps of Turkey are prepared and served by 'General Command of Mapping' which is a sub-division of the Turkish Military. National digital elevation maps are prepared by this organization and sold even to the research institutes; therefore, default digital elevation models (DEMs) of ArcGIS software are used. These maps are raster (grid based) models with a cell size of 750 meters. Although sensitivities of these models are not high enough to represent reality in small subcatchments, they are useful in representing catchments with size of several thousand hectares.

Digital elevation model of the area has been prepared as a layer in GIS software and projected on the backdrop with a transparency value of 50%. Overall image of the backdrop and DEM is presented in figure 3.7:

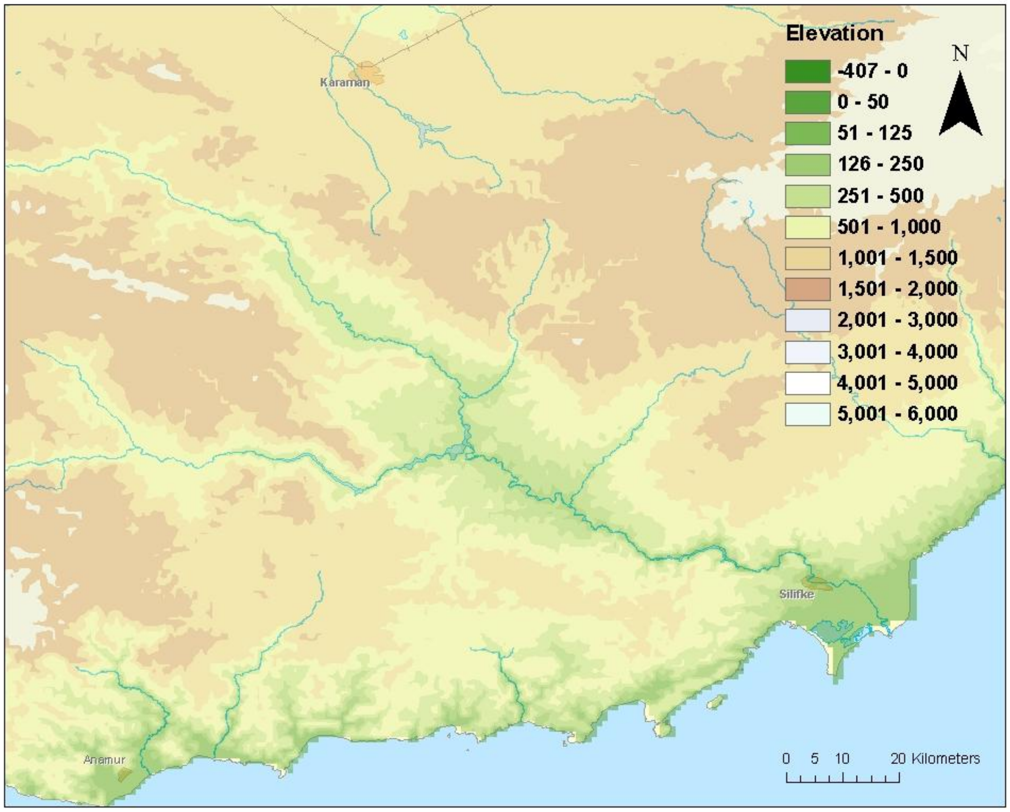


Figure 3.7. Backdrop with DEM Overlay

It is important to note that, since the dimensioning of the map has been defined, any length or area can be calculated by using this map. Secondly, although the image looks just like a regular classified topographical map, this created map holds elevation information of every pixel making it a more useful representation of the reality. Furthermore, it is possible to design algorithms using these pixel values. In order to represent the detail of digital map another map is created with a gradual topographical representation as in Figure 3.8.

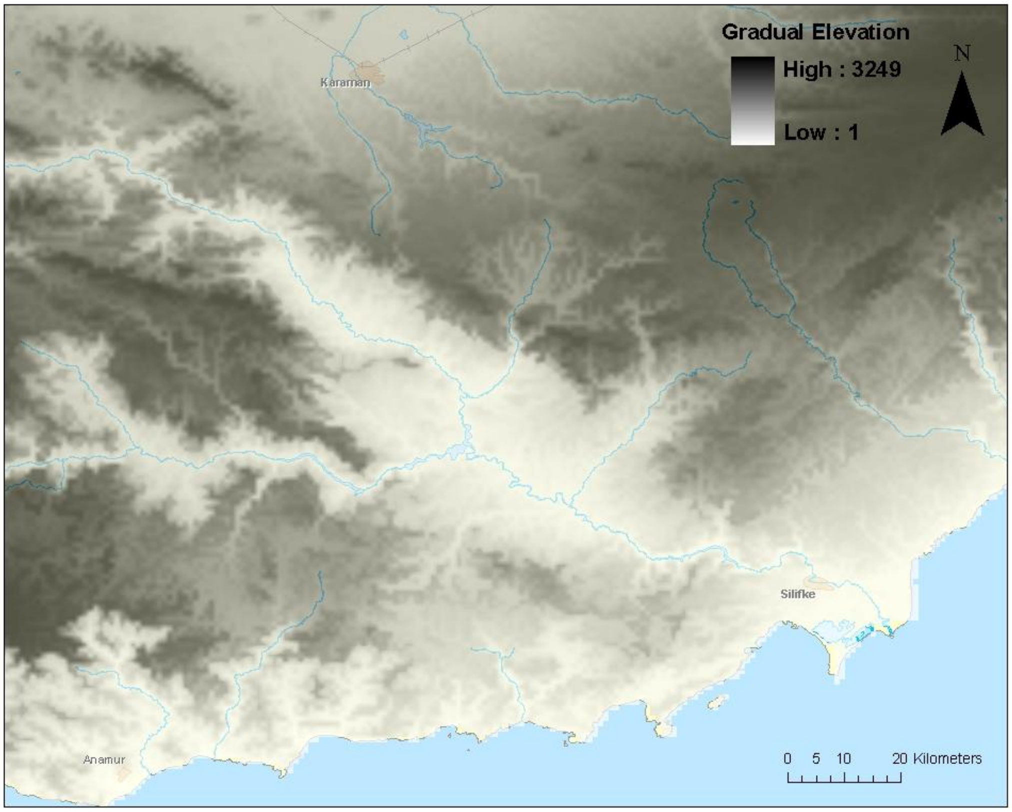


Figure 3.8. Map with Gradual Topographic Representation

As the representation has been changed from the classified to gradual, the intensity of the topographical differences appear more vividly. This digital intensity allows the user to observe more from just a topographical image: Using the spatial analysis tools present in the information systems programme defaults, slope map has been created from the digital topographical map; outcome map has been presented in figure 3.9 as stretched (gradual) representation.

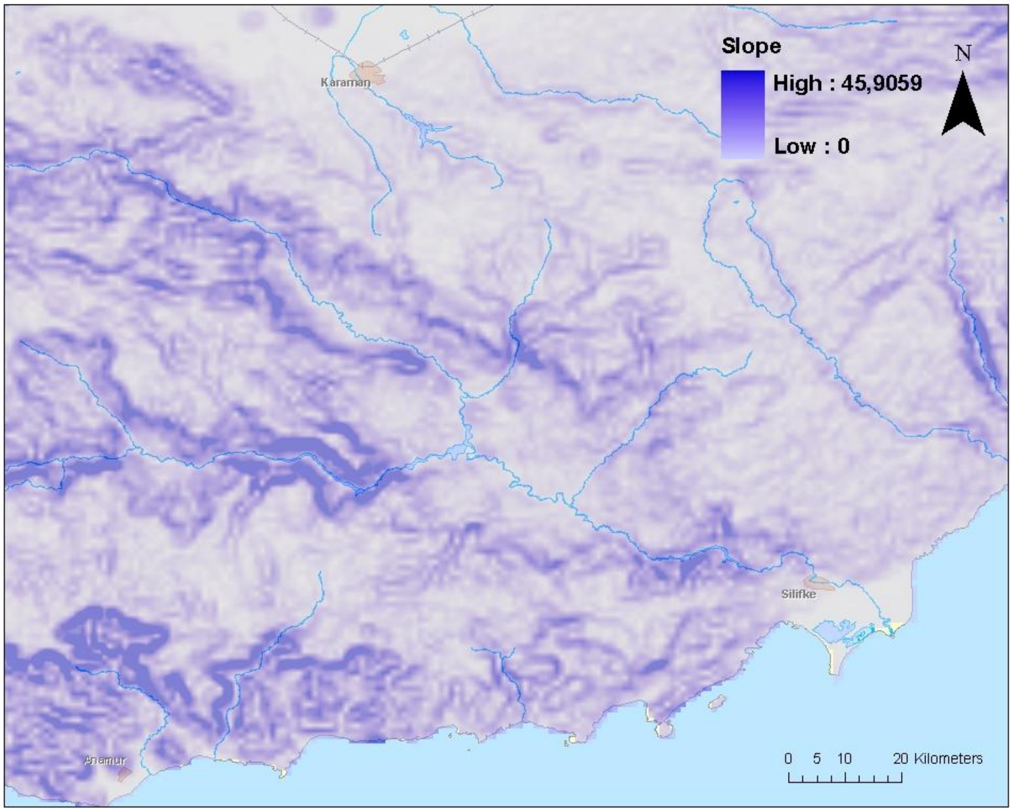


Figure 3.9. Slope Map of the Area

Using the maps created various parameters can be determined precisely, such as: elevation at any point, slope at any point, slope between any two points, area of any region, slope of any region etc. All these parameters will be used as inputs soon during the modeling process.

3.4.4. Catchment Discretization

Most of the control parameters can be extracted automatically from GIS layers; however, a well-established automatic catchment discretization approach based on GIS or other technologies does not exist. Some researchers have used grid-based meshes derived from GIS data as distributed subcatchments for distributed rainfall- runoff simulation (Yu et al. 2001; Du et al. 2007).

Slope map uncovers many features of the area which were not clearly visible on the topographical map. As plains and plateaus unfold as light blue areas, steep areas become more visible as being dark blue colored. In order to better understand the geography another overlay has to be applied: As presented in figure 3.10, slope map with transparency was projected over the elevation map:

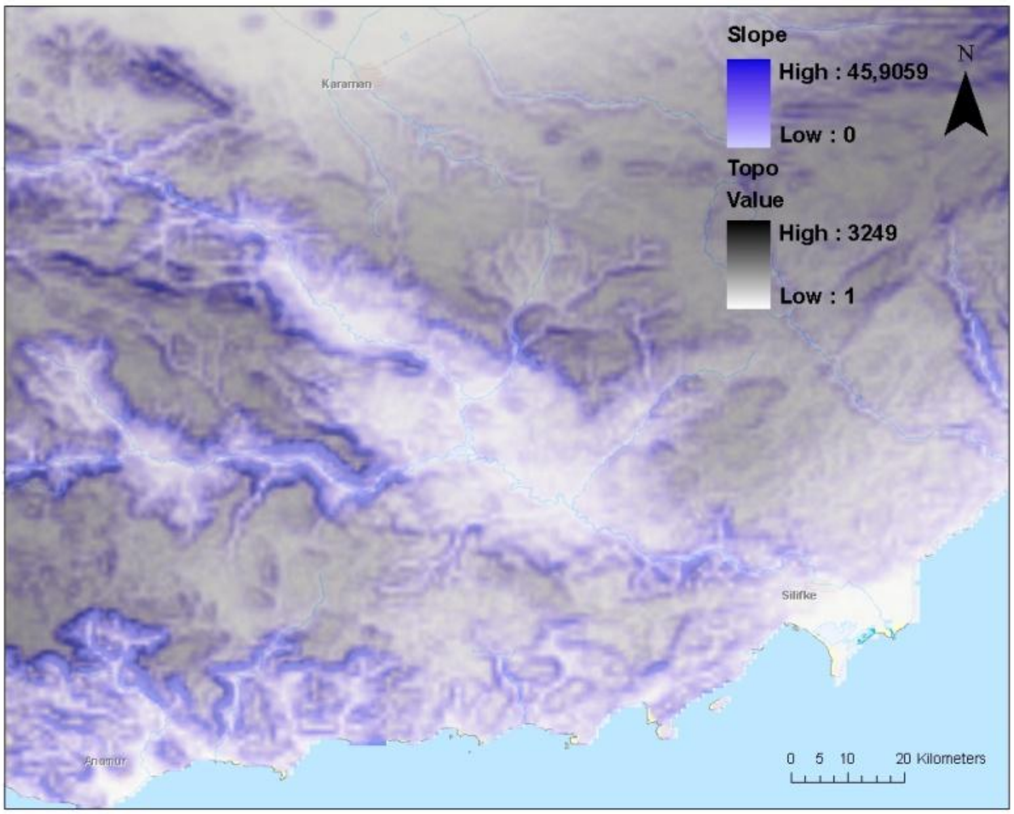


Figure 3.10. Combined Topographical and Slope Map

Slope and elevation overlay offers a very clear view of the topography. Plateaus, plains and valleys become highly visible: Plains are light grey areas without much blue coloring; plateaus are dark grey areas without much blue coloring and valleys are corridors with dark blue (high slope) sidewalls.

Looking at the image above, another thing that became visible is the catchment of the Göksu River. The bowl that feeds the river stand at the middle of the map, in order to highlight it more all subcatchment areas had been highlighted and presented below:

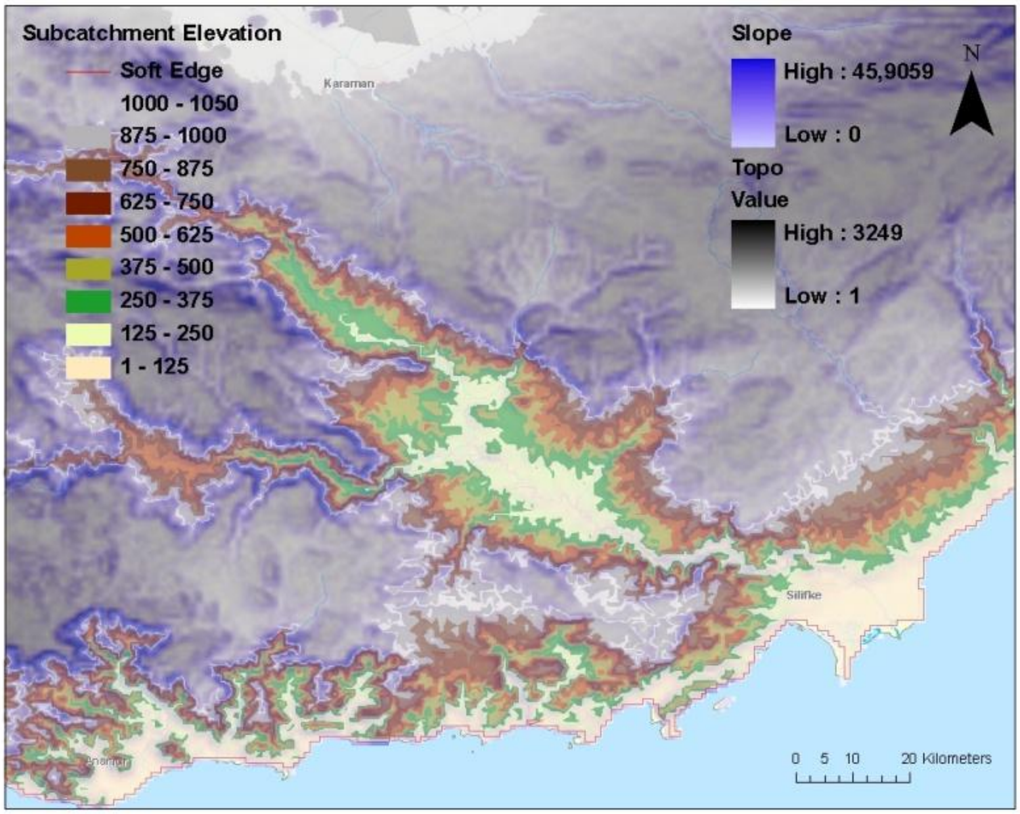


Figure 3.11. Catchment Highlighted with Elevation Properties

In this research, the DEM was used to extract basins using the Flow direction and Basins division tools in the ArcGIS hydrological-analysis toolbox. The direction of flow is determined by the direction of steepest descent from each cell. Basin tools are used to analyze the flow-direction raster to find all sets of connected cells that belong to the same drainage basin.

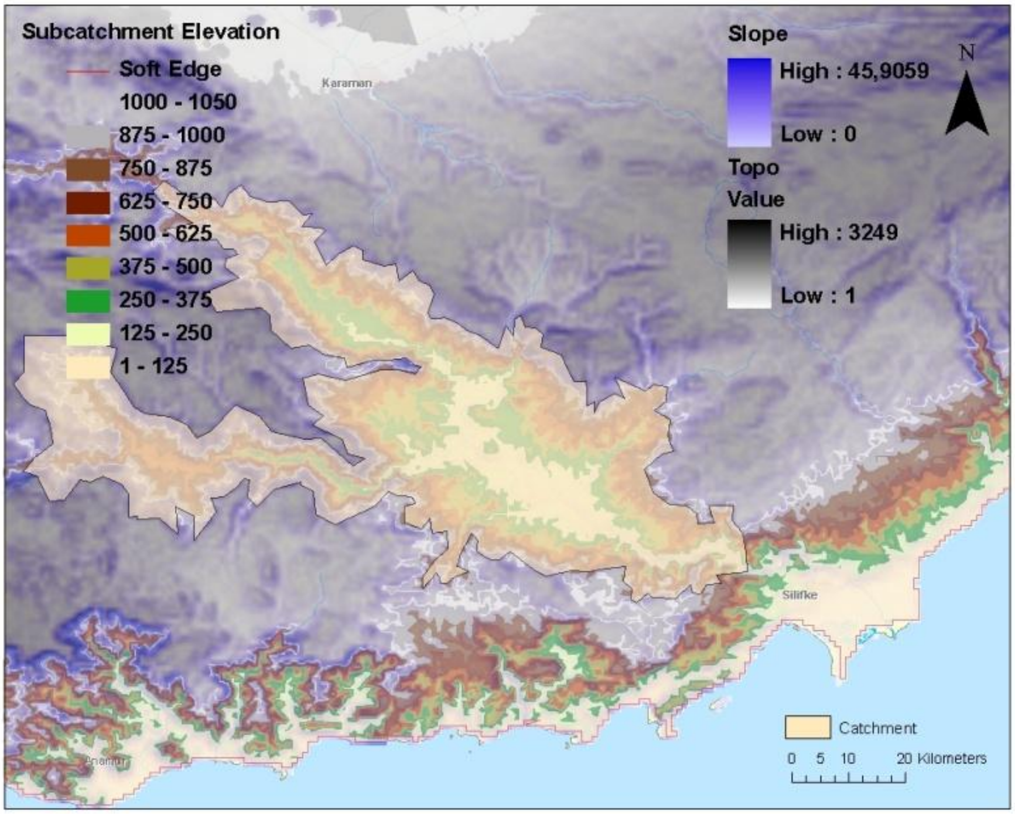


Figure 3.12. Discretizated Catchment

3.4.5. Creation of Stream Network

After catchment boundaries were drawn, the bed that water will flow through should be created digitally. This means that river coordinates, elevations, widths and slopes of sections should be determined and converted into digital data in order to be used in the upcoming steps of the study. First of all, the aspects of the subcatchments must be known and implemented into the model to define which way the runoff will run. This procedure has also been done by another spatial analysis tool present in the ArcGIS software and output map is presented below:

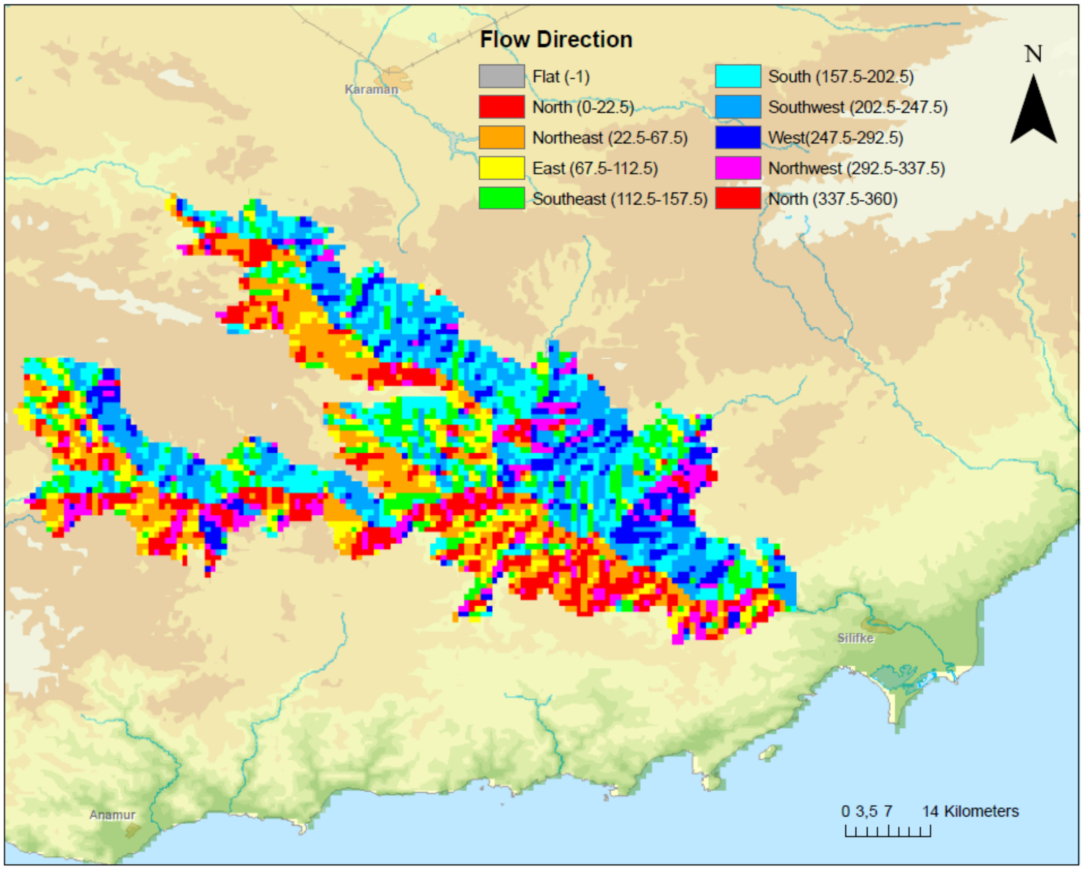


Figure 3.13. Flow Direction Map of the Catchment

Secondly, river track was determined over the flow direction map and satellite image and a polyline was created over it to represent it. Then, by using the topographical analysis tools present in the ArcGIS software polyline and elevation map were associated accordingly, giving elevation values to the points on the polyline. During this step the width of the sections were also determined and saved respectively.

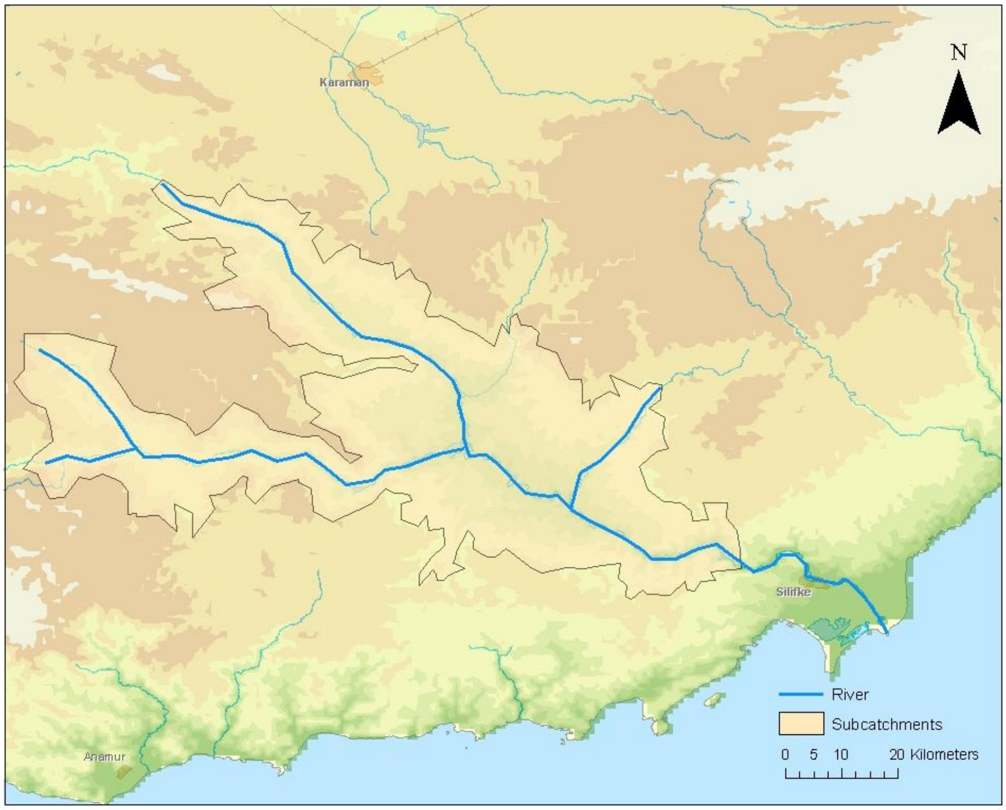


Figure 3.14. River Polyline Illustrated on Elevation Map

3.4.6. Land Cover Data

In order to better simulate the catchment hydrological modeling the catchment had to be divided into many subcatchments (Coulthard et al., 2007). This division increases the sensitivity of the model since smaller partitions better represent the reality of the partition. The type of partitioning selected for this study is gridding: the map was divided into 400 grids (20 on each axis) with 100 grids holding subcatchment parameters as presented in figure 3.15.

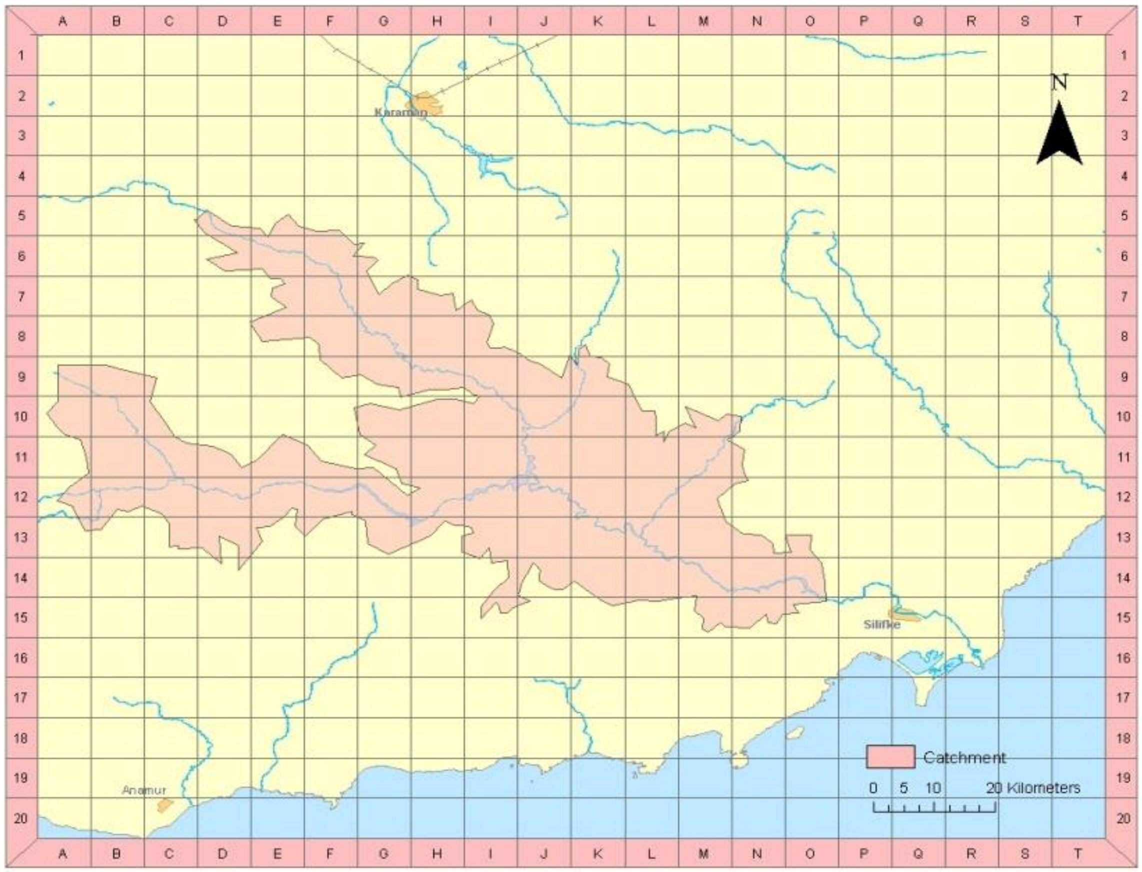


Figure 3.15. Gridded Base Map

Many parameters needed in order to do hydrological modeling such as area of subcatchment, slope of subcatchment, width of subcatchment etc. were determined for each grid with simple ArcGIS commands since the programme has the ability to calculate grid properties with respect to any given layer present. But in order to calculate more advanced parameters such as land use and land cover more developed techniques were used such as remote sensing of the area, which basically means taking high definition images of the area from satellites or high altitude balloons and doing photogrammetric analysis on them. Basically speaking, if an area appears green on the satellite image, it means that area is covered by plants and its imperviousness is low.

Although professional use satellite images from IKONOS, LANDSAT, QuickBird are very expensive and it was not possible to access to any for this study, regular and common use satellite images of the globe are readily available nowadays through Google, Yahoo, Microsoft and ESRI. During the study maps supplied by ESRI and Google are used and a map layout of the area with relevant satellite image is presented below:

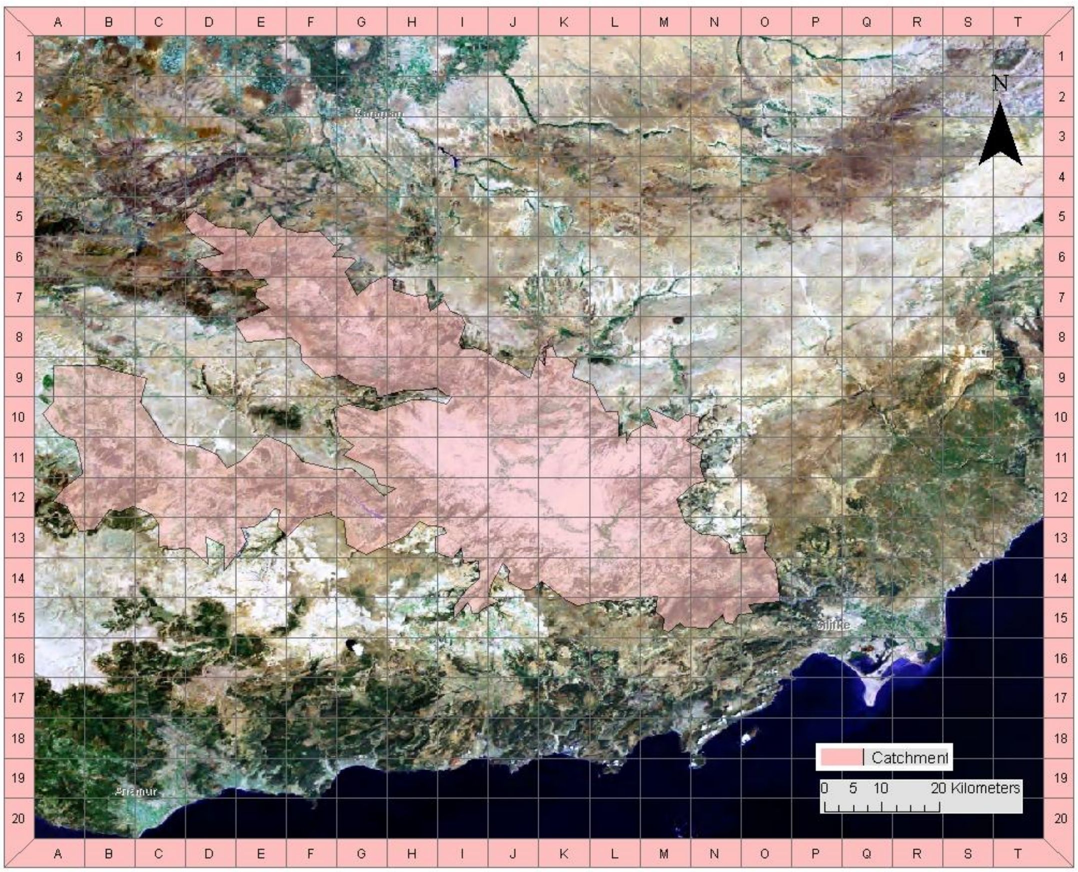


Figure 3.16. Gridded Satellite Image Overlay

Professional remote sensing research is done by computer algorithms which examine the area under many light spectrums and via sensitive calibration and then output the land cover characteristics. However, a straight-forward technique was used during this study and human eye scan was done on grids in order to define land cover parameters.

Every grid was magnified to a full screen view and analyzed visually for forested (f), residential (u), rock-soil covered (r) and agriculture (p) area percentages of it. This analysis gave percentage imperviousness results for various areas in one grid and in combination an average imperviousness value for the whole grid. Below, detailed examination of one grid (K11) is presented:

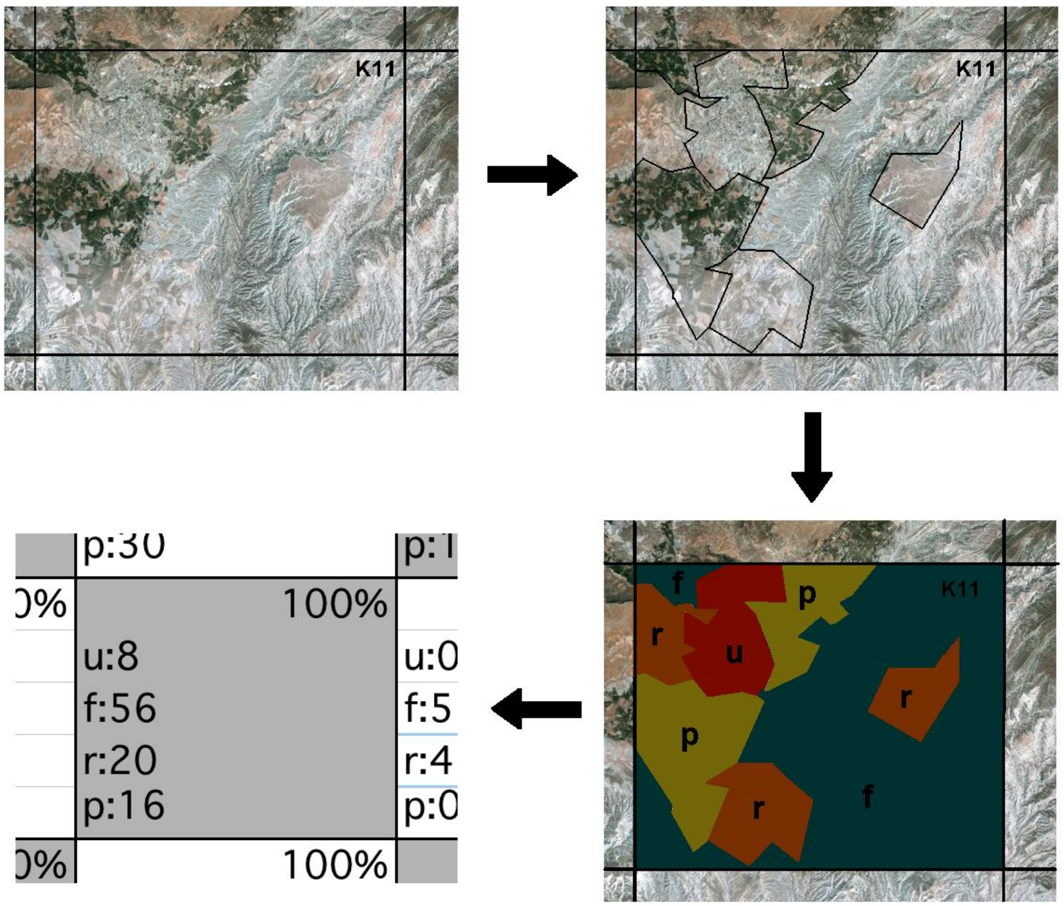
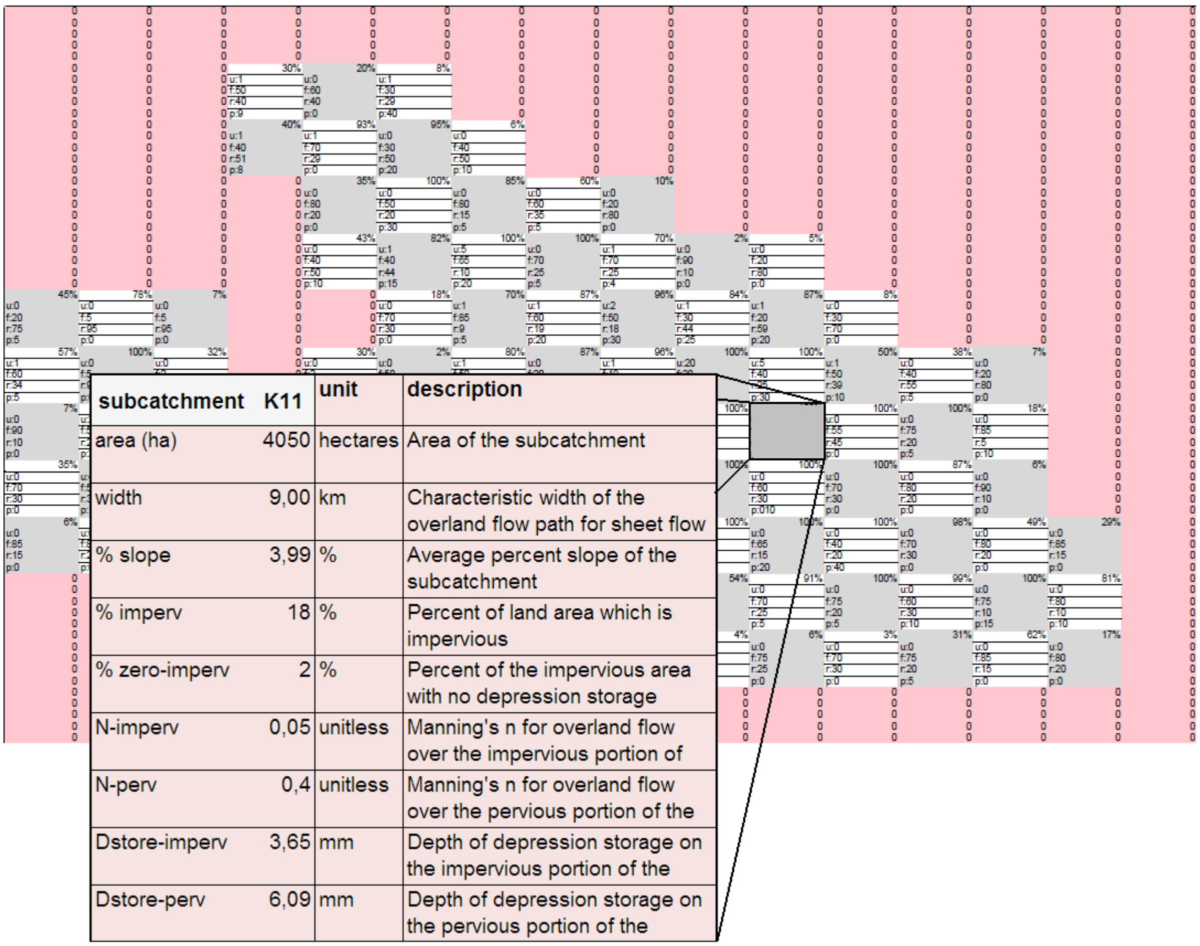


Figure 3.17. Grid Examination for Land Cover

After the land cover determination process was over a more detailed table of every grid from the properties gathered is created. This table included every property that is going to be used in the modeling process. Grid area, grid width and average grid slope has been calculated using the gridded base map on ArcGIS software; percent imperviousness and percent zero imperviousness has been calculated from the recently analyzed land cover data using the values supplied along with the imperviousness module of SWMM programme (Alley, 1983; Arnold, 1996; GVRD, 1999; May, 1997; Resources Inventory Committee, 1996; Schueler, 1994; USDA, 1986). Manning's coefficient and depression storage depths are also obtained from literature respectively (McCuen, 1996; ASCE, 1992).



subcatchment	K11	unit	description
area (ha)	4050	hectares	Area of the subcatchment
width	9,00	km	Characteristic width of the overland flow path for sheet flow
% slope	3,99	%	Average percent slope of the subcatchment
% imperv	18	%	Percent of land area which is impervious
% zero-imperv	2	%	Percent of the impervious area with no depression storage
N-imperv	0,05	unitless	Manning's n for overland flow over the impervious portion of
N-perv	0,4	unitless	Manning's n for overland flow over the pervious portion of the
Dstore-imperv	3,65	mm	Depth of depression storage on the impervious portion of the
Dstore-perv	6,09	mm	Depth of depression storage on the pervious portion of the

Figure 3.18. Representation of Grid Properties Table

The table and content representation presented above is the grid based data map of the whole catchment and hold all the necessary values and parameter to implement a modeling study on the catchment (Singh and Woolhiser, 2002)..

Overall map which holds all the information generated during spatial database setup step will act as a backdrop for the next step, all the associated digital data are present either in the table created for grids or in the maps that are projected together; with all this well organized information, migration from geographical information systems to the modeling interface will not be very hard.

3.5. Migration of Spatial Data into Hydrological Model (SWMM)

Spatially distributed hydrological models integrating both surface and subsurface hydrological processes include MIKE SHE, which was developed by the Danish Hydraulic Institute (DHI, 2005) and successfully applied to a number of watersheds in Denmark (Madsen, 2003; Henriksen et al., 2003; and Vazquez and Feyen, 2007) and Storm Water Management Model (SWMM) developed by Environmental Protection Agency of United States and applied to many studies worldwide (e.g. Smith et al., 2005).

Stormwater Management Model (SWMM) is a rather easy to understand and operate model with a spatial interface. Therefore a backdrop map of gridded subcatchment was used in order to visualize the area of interest and hydrological elements were created over it manually. SWMM model has more analytical capabilities for hydrological modeling procedure than GIS systems (Maidment 1993; Wilson 1996; Abel et. al. 1994 and Kopp 1996).

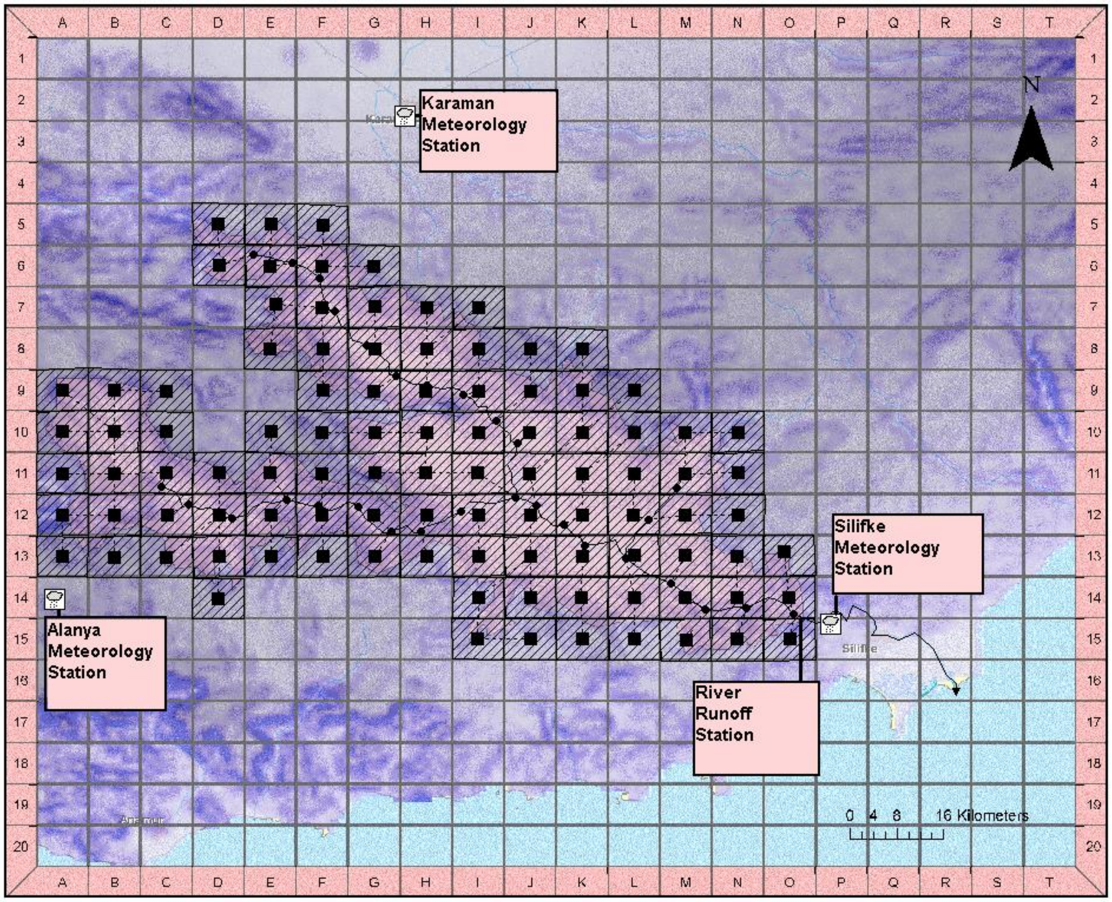


Figure 3.19. SWMM Layout Map with All Elements Placed

As seen from the figure 3.19, the subcatchments were created on every grid; this subcatchment selection will allow the use of parameters generated for the grid to be used without any change also in the modeling programme.

Other than subcatchments, the conduits representing the river and branches were drawn; the meteorological stations and river flow data collecting station were placed. All created elements in SWMM have a long list of input parameters needed for the model to work properly. During next step all these parameters are inputted from the tables created during the previous steps supplying the programme with real life information for subcatchments on their size, slope, percent imperviousness…, conduits on their length, width, elevation and rain gages with real life historical data.

3.6. Assessment of Model Sensitivity

The structure and parameters of the most mathematical models developed for environmental systems are based on physical, chemical or biological processes. Such mathematical models, which use traditional scientific descriptions of component processes, may contain many ill-defined parameters (Hornberger et al., 1980). It is not always possible to fully utilize a mathematical model because of the lack of data. If the problem of interest shows similarities with those that have been reported in the literature, sufficient amount of information may be gathered and, the parameters of the model can be specified via a priori statistical distributions (Hornberger et al., 1981).

Sensitivity analysis was done for the preliminary analysis of environmental systems and to identify the critical uncertainties of mathematical models for the direction and planning of future research. This technique also reveals the parameters or processes that have little influence on the simulated outputs of the model.

The assessment of model sensitivity was based on the ratio of the relative variation in model output to the relative variation in model input. For each variation increment, the relative variation in model input and model output were calculated as follows (Dubus et al., 2003):

$$\text{Input variation} = \frac{I - I_{\text{BC}}}{I_{\text{BC}}} * 100 \qquad (3.1)$$

$$\text{Output variation} = \frac{O - O_{\text{BC}}}{O_{\text{BC}}} * 100 \qquad (3.2)$$

where I is the value of the input parameter, I_{BC} is the value of the input parameter for the base-case scenario, O is the value of the output variable, and O_{BC} is the value of the output variable for the base-case scenario. The ratio of variation (ROV) can be defined as follows:

$$\mathrm{ROV} = \frac{\text{Output variation}}{\text{Input variation}} \tag{3.3}$$

$$\mathrm{ROV} = \frac{O - O_{\mathrm{BC}}}{I - I_{\mathrm{BC}}} * \frac{I_{\mathrm{BC}}}{O_{\mathrm{BC}}} \tag{3.4}$$

The ratio can be either positive or negative. It takes negative values if a decrease in an input parameter results in an increase in the output value or if an increase in an input parameter results in a decrease in the output value. The sign of the ratio is not critical when the aim is to classify input parameters according to their influence on model output. Hence, the absolute value of ROV (|ROV|) was considered for classification purposes.

4. RESULTS and DISCUSSIONS

Before the model was set up, it was already understood that the rainfall data collected did not fully represent the rainfall that catchment faced, correlation between rainfall and runoff was given in table 4.1. There was no meteorological station located exactly in the catchment to collect representative data from.

Table 4.1. Correlation between Rainfall and Runoff

Formula	Silifke Rainfall (mm/day)	Karaman Rainfall (mm/day)	Alanya Rainfall (mm/day)	Runoff-real (cms/day)
$Correl(X,Y)=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$	**0,23763806**	**0,21696199**	**0,19257101**	**1**

A positive correlation value indicates that the simulated values describe the trend of the measured data better than the mean of the observation values, while a negative value indicates that the corresponding model output is dissimilar to the behavior of the studied system (Sourisseau et al. 2007; Arabi et al. 2007). Obviously, a higher correlation value (close to 1) means a better fit of the predicted hydrograph to the observed one. Model simulations with negative correlation values are considered ‘‘unacceptable’’ (Santhi et al. 2001). Correlation likelihood values are used in this paper for model calibration, and the objective is to maximize their values.

As the correlation table above shows the correlations between the collected rainfall values and runoff were low, this low correlation can also be seen from a random year graph of the rainfall and runoff as presented below.

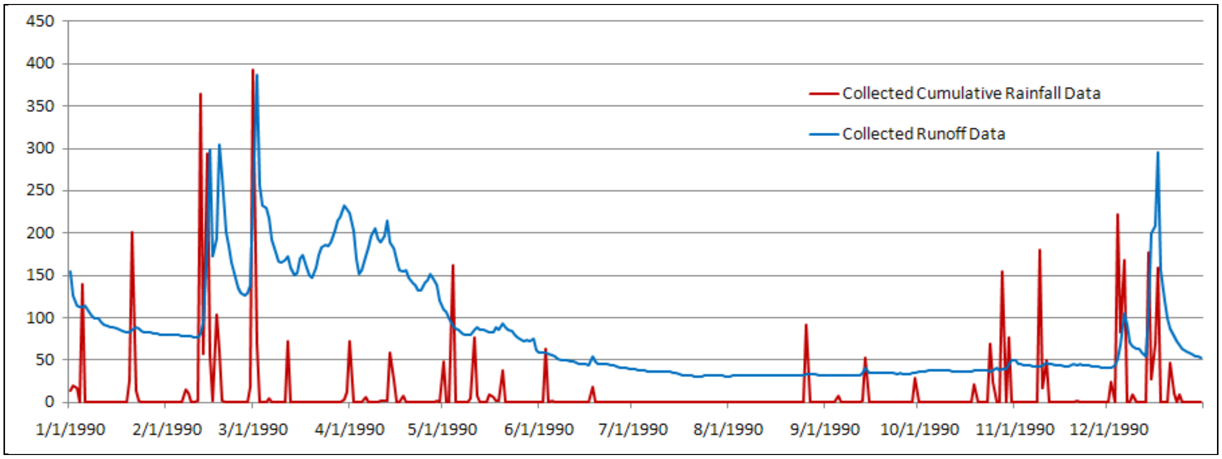


Figure 4.1. Graph of 1990 Collected Rainfall (cms) vs Collected Runoff (mm)

As some rainfall peaks have a counter on the runoff curve, some do not have any counter at all; furthermore the base flow that runoff has do not have any resemblance with runoff values causing a low correlation in general.

4.1. Preliminary Results and Base River Flow Calibration

Parallel to the rainfall data, preliminary outputs from the SWMM model come out with a low correlation with observed runoff data:

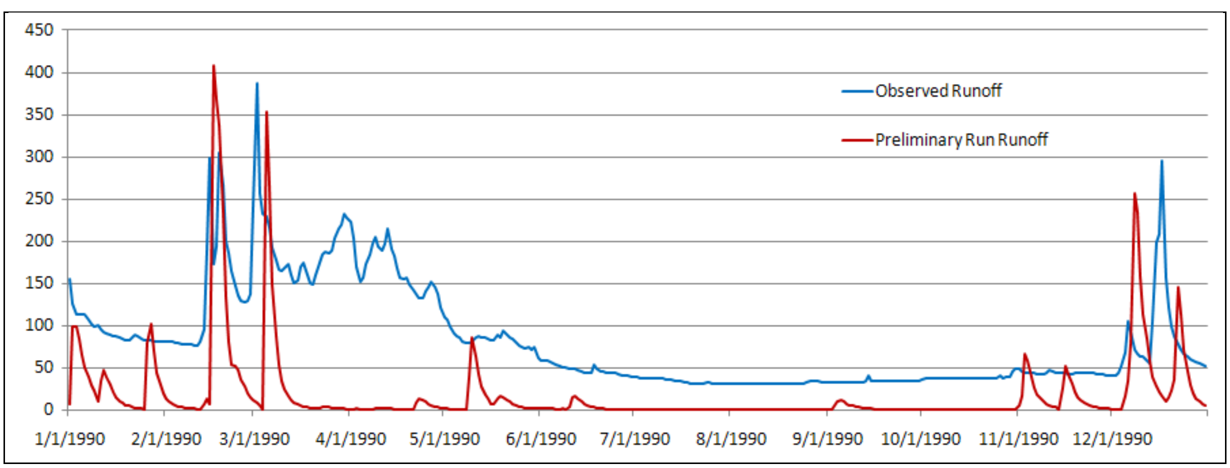


Figure 4.2. Graph of 1990 Observed Runoff (cms) vs Preliminary Run Runoff (cms)

The main reason behind this low resemblance was the lack of snowmelt factor and basic calibration. An average snowmelt flow was added to the model by the use of flow data from the past years and also calibration was done by the use of integrated calibration tool of the SWMM programme to better fit it. The base flow caused by the snow melt is given below and the same snowmelt pattern is going to be used for all years.

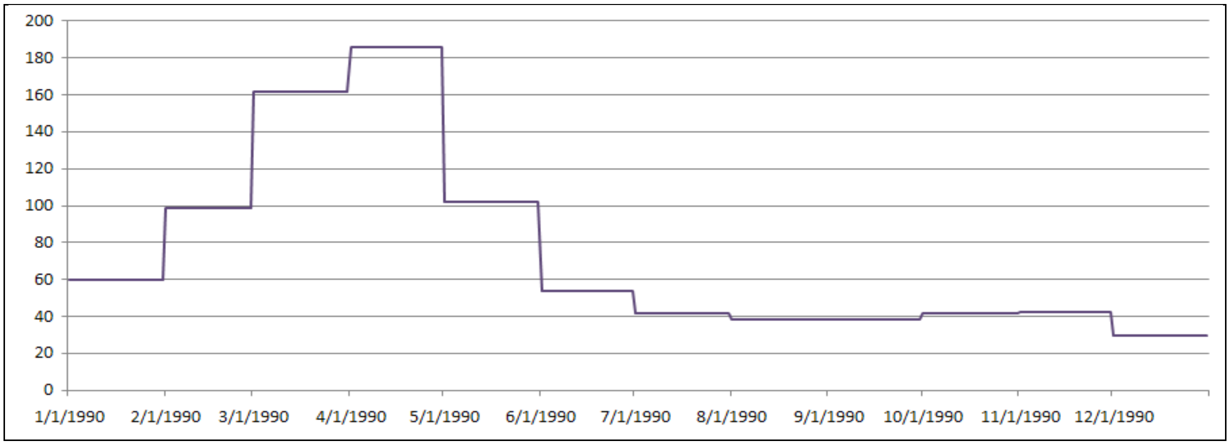


Figure 4.3. Snowmelt Pattern (mm)

Although the pattern was called snowmelt, it obviously holds some percentage of groundwater flow within it. SWMM having a groundwater flow tool present did not output anticipated flow pattern during the time with no rainfall, therefore it must be understood that snowmelt pattern has some groundwater component present within it.

These arrangements resulted in a better outcome from the model and with a better fit. Comparison of the runoff outcome and observed runoff are given below for the same year (1990).

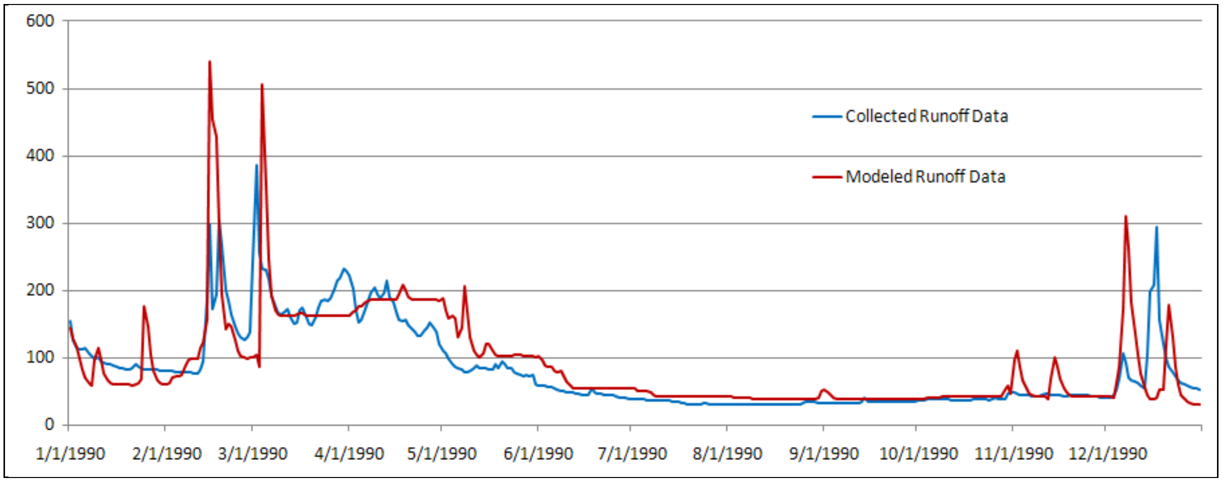


Figure 4.4. Graph of 1990 Collected Runoff Data (cms) vs Modeled Runoff Data (cms)

All the correlation values in between are presented below and the model which takes into account the snowmelt pattern has the highest coefficient.

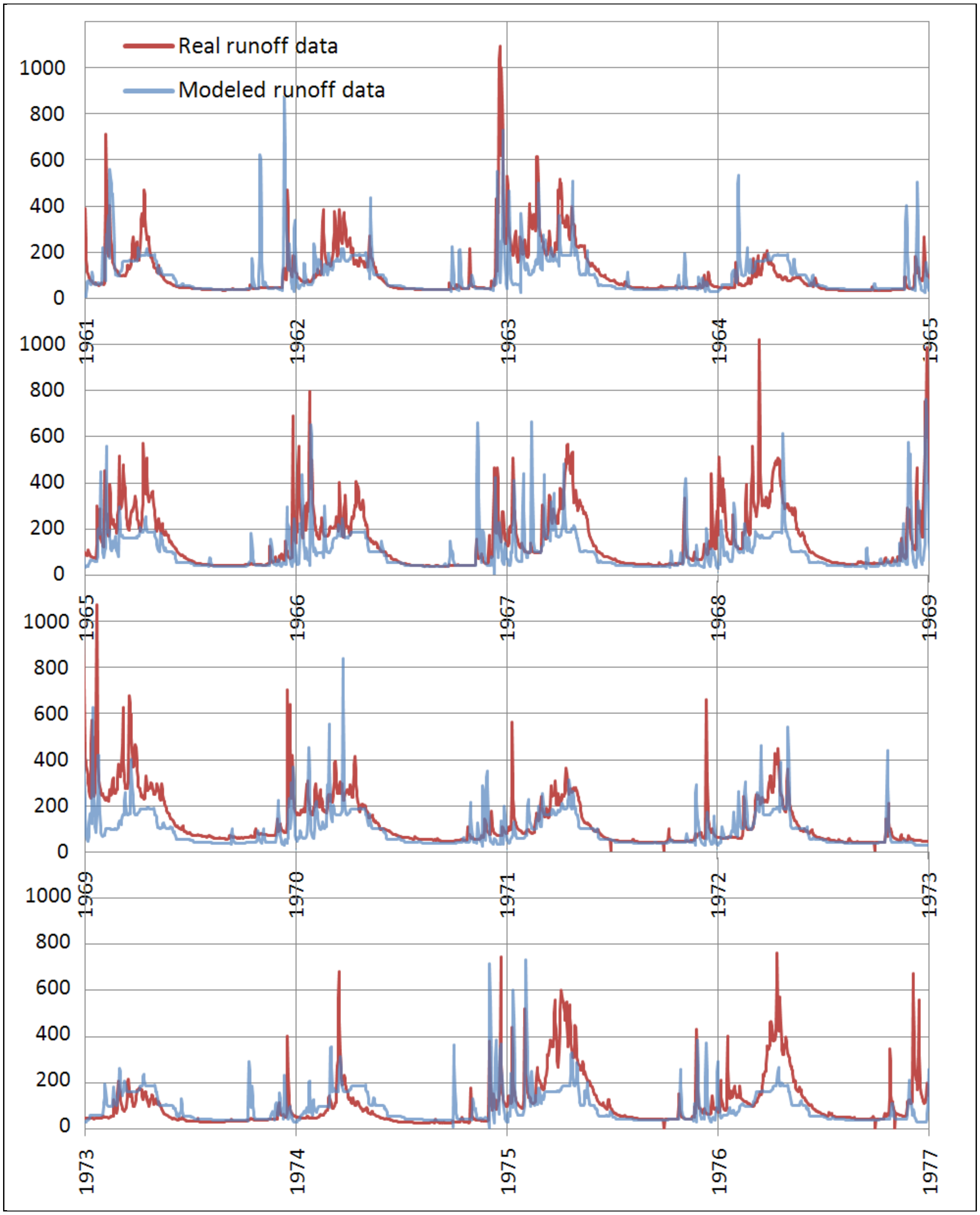
Table 4.2. Table of Correlation Values of 1990 Modeled

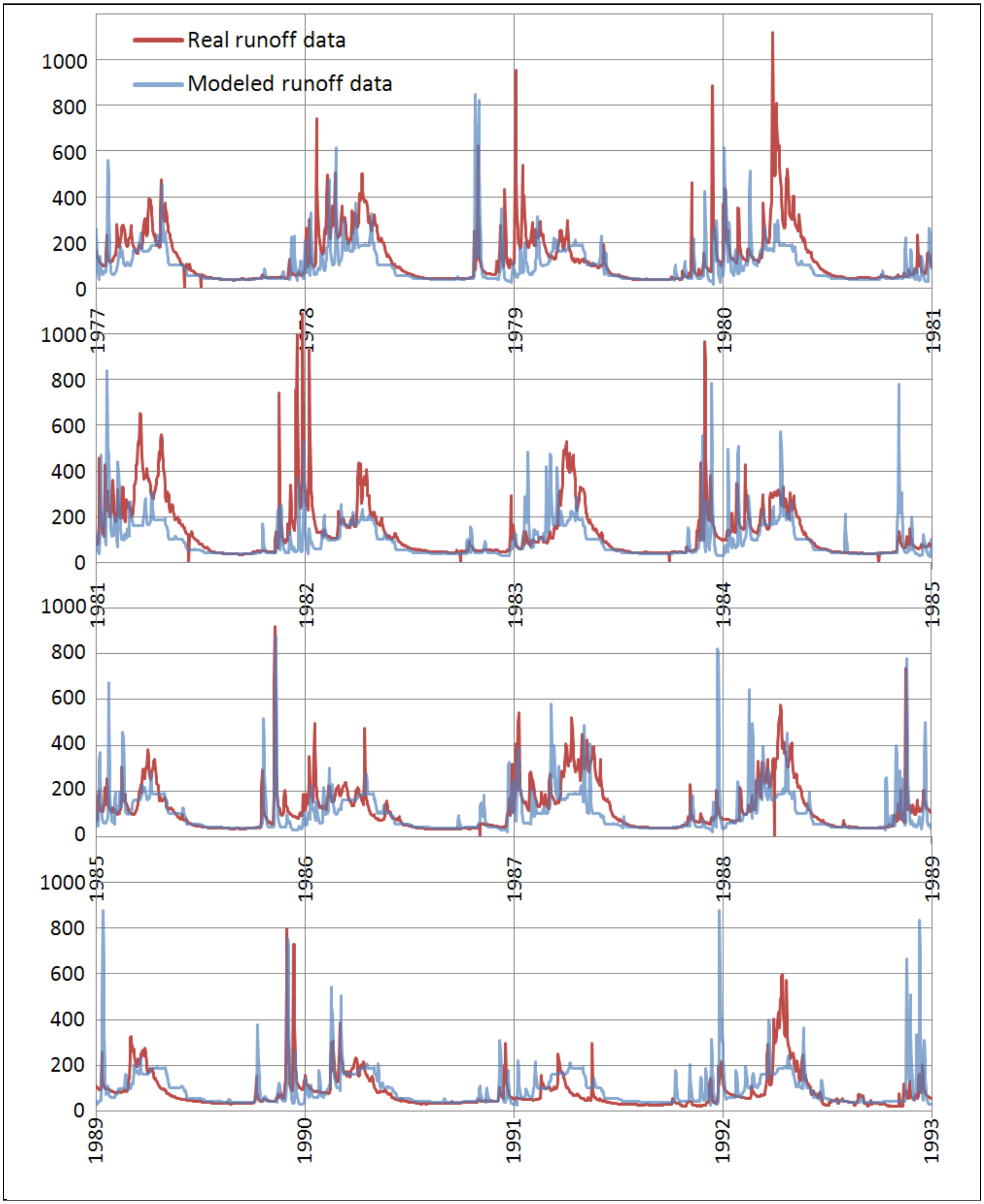
	Silifke Rainfall (mm/day)	Karaman Rainfall (mm/day)	Alanya Rainfall (mm/day)	Model Runoff without Snowmelt (cms/day)	Model Runoff with Snowmelt (cms/day)	Runoff-real (cms/day)
$Correl(X,Y)=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$	0,1513	0,1879	0,1844	0,3173	0,7361	1,0000

Effect of base river flow on the flow output is enormous; during the modeling of other years same techniques and same path will be followed.

4.2. Model Validation

In order to validate the model, comparison with the real life data was used. Below is graphical comparison of the model outputs and data collected from the flow observation station:




Real runoff data
Modeled runoff data
1000
800
600
400
200
0
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993

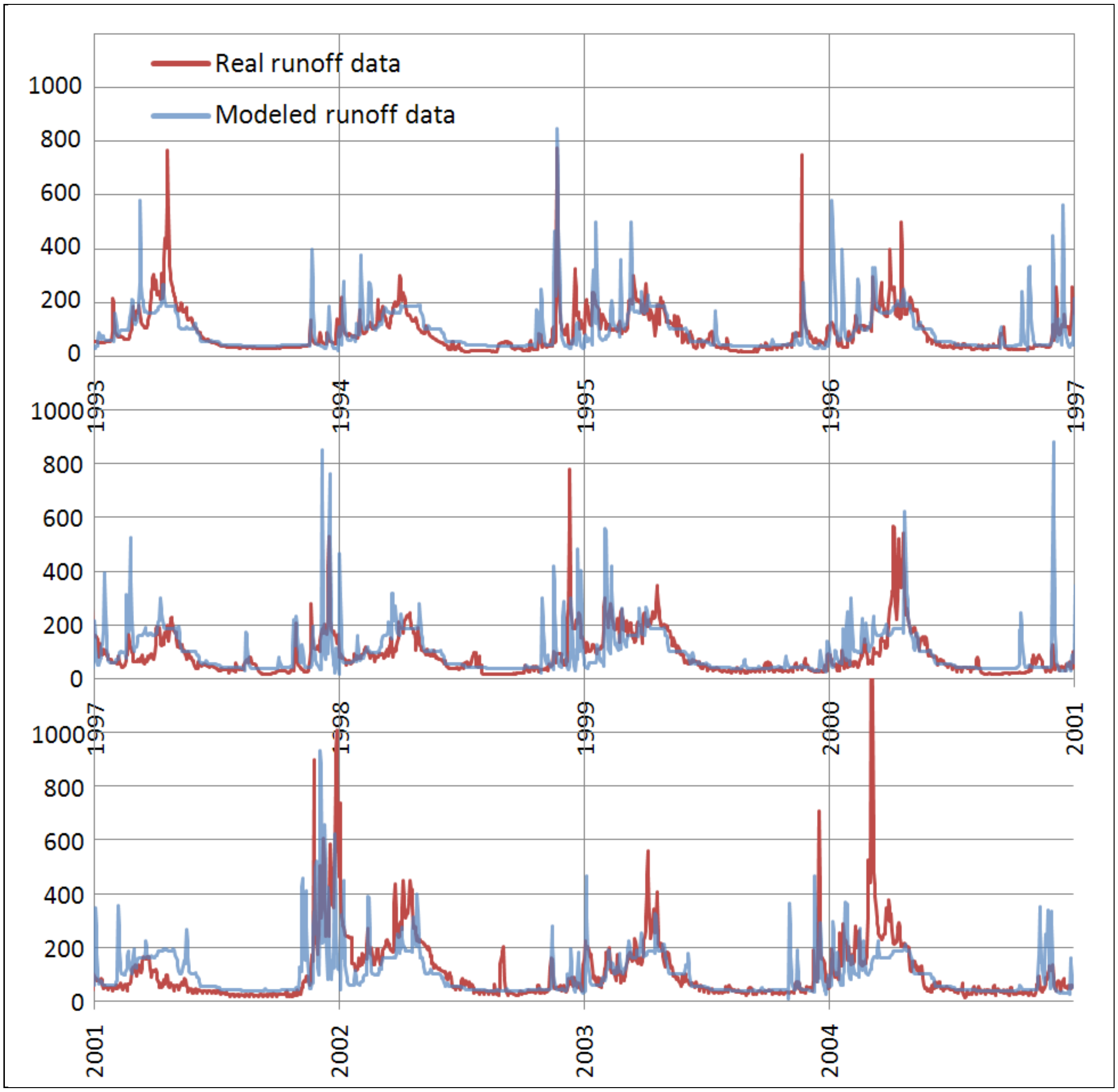


Figure 4.5. Comparison Graph of the Real Runoff (cms) and Modeled Runoff (cms)

Visual inspection of the model is presented in figure 4.5 on yearly basis, which shows that there are in good arrangement with observed runoff data and are satisfying visually. Although some of the peaks do not perfectly fit, rainy periods and dry periods are represented well in the model. In order to better evaluate the goodness of fit and statistical relationship between the modeled values and observed values Pearson Correlation has been done on arrays of data and outcomes are presented below.

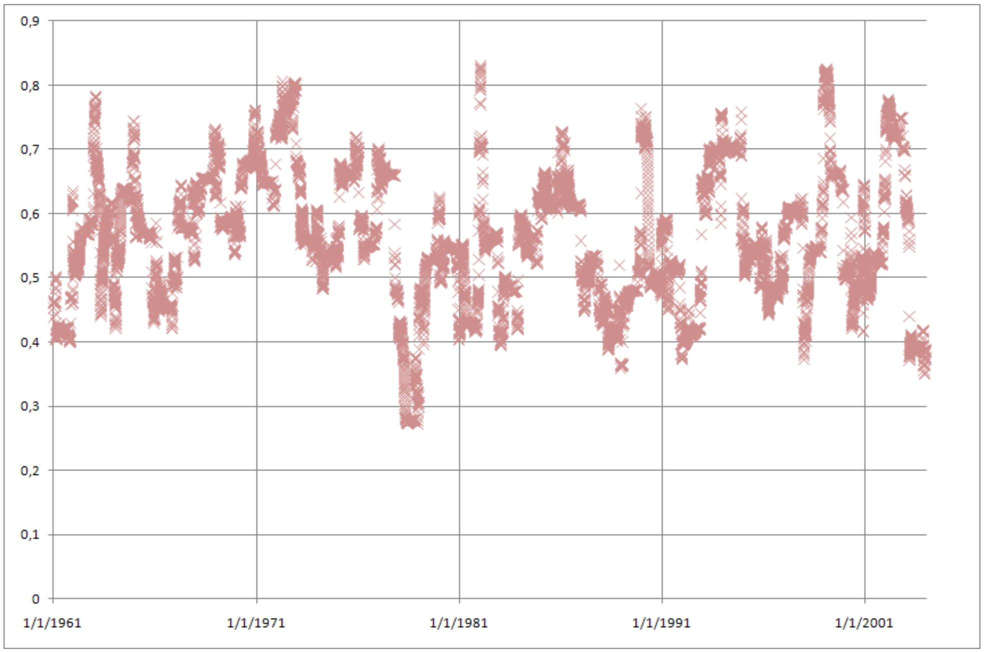


Figure 4.6. Pearson correlation coefficient with respect to time

Correlation coefficient versus time scatter plot presented in figure 4.6 is a good representation of model fit over the years. It shows very strong correlation during some years (over 0,8 in 1982) and some low ones (less than 0,3 in 1978) but data usually fall between 0,4 and 0,8. The reason of low correlation values might be the lack of high number of rainfall stations that represent the system.

Table 4.3. Representative Correlation Value Table of Overall Results

Correlation Formula	**Runoff-real (cms/day)**	**Modeled Runoff (cms/day)**
$Correl(X,Y)=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$	**1**	**0,511257313**

The Model has around 16000 points on the each correlation array and an overall Pearson Correlation value of 0,5; suggesting that there is strong correlation between the model output and the observed data. And the scatter plot of the model runoff outcomes versus observed runoff is also presented below:

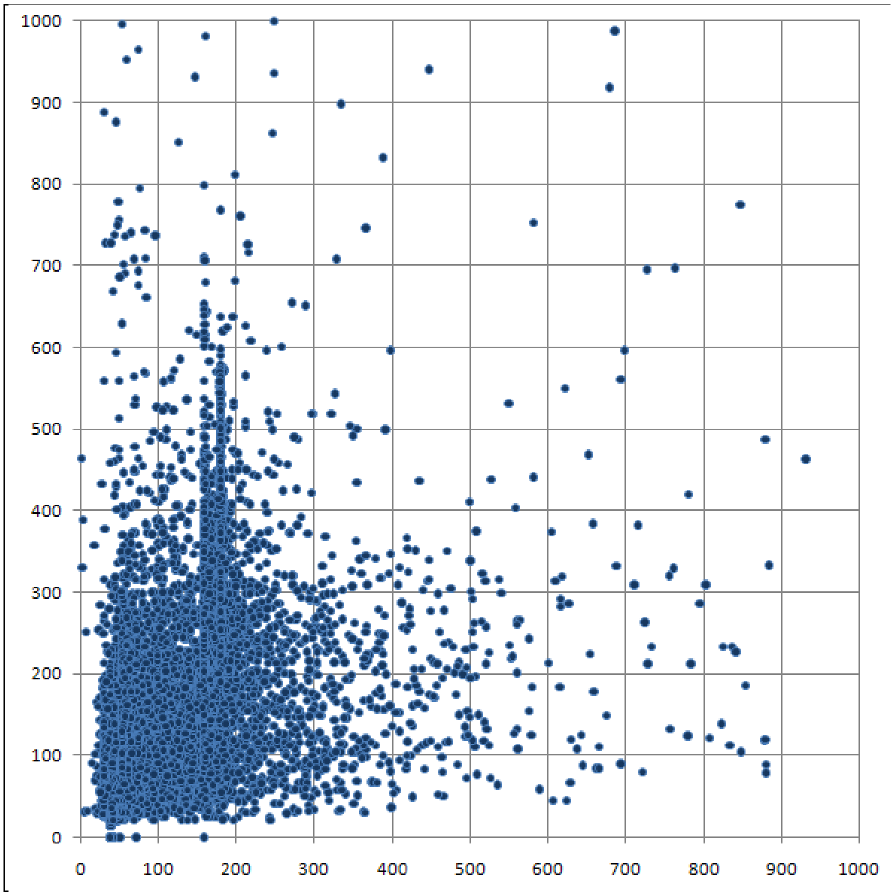


Figure 4.7. Observed Runoff (cms) vs Modeled Runoff (cms)

4.3. Parameter Sensitivity Analysis

Various parameters that have been used in the model were analyzed in order to find their influence on the result. A one at a time sensitivity analysis approach was undertaken for the modeling of a specific year, 2003. The value of each parameter was changed by 10% intervals within a range of 100%, from -50% to +50%. According to Mulligan and Wainwright, 2004, the main reason for carrying out such a method is to:

- Better understand the behavior of the model
- Ensure model parsimony by the rejection of parameters or processes to which the model is not sensitive

- Target field parameterization and validation pro grammes for optimal data collection
- Provide a means of better understanding parts of the whole system being modelled

The outcomes were projected on three dimensional hydrographs since outcomes of the model were already in 2 dimensions therefore the sensitivity multiplier becomes the third dimension. Scales of the graphs are same altogether, so the changes on representations totally reflect the sensitivity of the system to corresponding parameter. It must be kept in mind that these sensitivity analyses do not reflect the physical reality behind the phenomenon, but just the sensitivity of SWMM model to the various parameters.

4.3.1. Analysis of Area of Subcatchments

The area of subcatchment defines the area that collects rainfall, as the area of collection increases, output of the system increases.

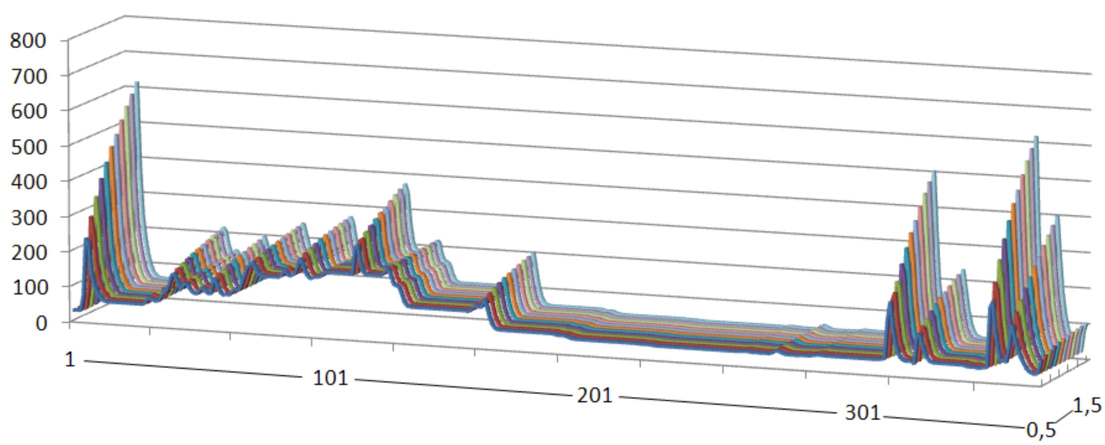


Figure 4.8. Model Output Hydrographs with Respect to Various Areas of Subcatchments (cms vs days vs multiplier)

4.3.2. Analysis of Width of Subcatchments

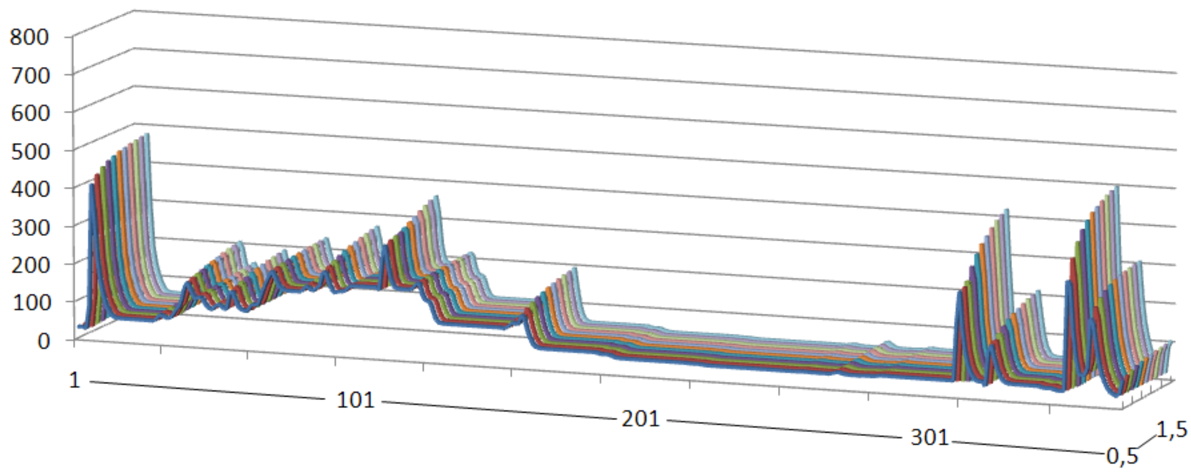


Figure 4.9. Model Output Hydrographs with Respect to Various Widths of Subcatchments (cms vs days vs multiplier)

The width parameter stands for the characteristic width of the overland flow path for sheet flow runoff in SWMM model. It is the major parameter that defines the shape of the subcatchments. It could be seen from the graph that the model is mildly sensitive to the changes in width parameter, as the width of the subcatchments increase the peaks of the hydrographs increase. This outcome is acceptable since with the increases of width of a subcatchment with constant area length, therefore, time spent to leave the area decreases. This decrease in time results in lower routing value and higher maximum flow (Yang et al. 2005).

4.3.3. Analysis of Percent Slope of Subcatchments

Average percent slope of the subcatchment –interestingly- has the same effect on hydrograph with width adjustment. This outcome is reasonable, since, with increasing slope, the time spent to leave the area decreases further decreasing routing value and increasing peak flow during the times of rain (Horton, 1933). Sensitivity of the model to the changes in slope of subcatchments is moderate.

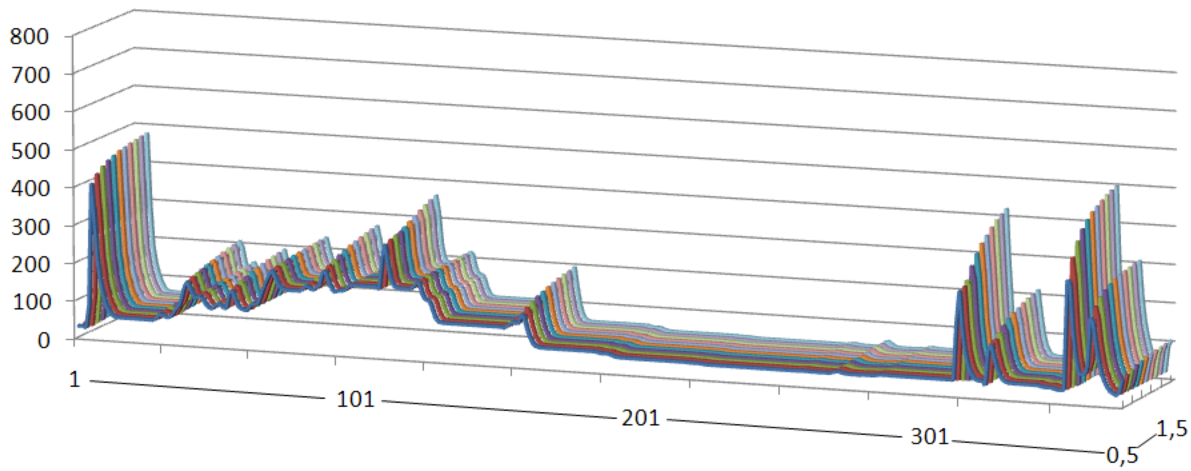


Figure 4.10. Model Output Hydrographs with Respect to Various Slopes of Subcatchments (cms vs days vs multiplier)

4.3.4. Analysis of Percent Imperviousness of Subcatchments

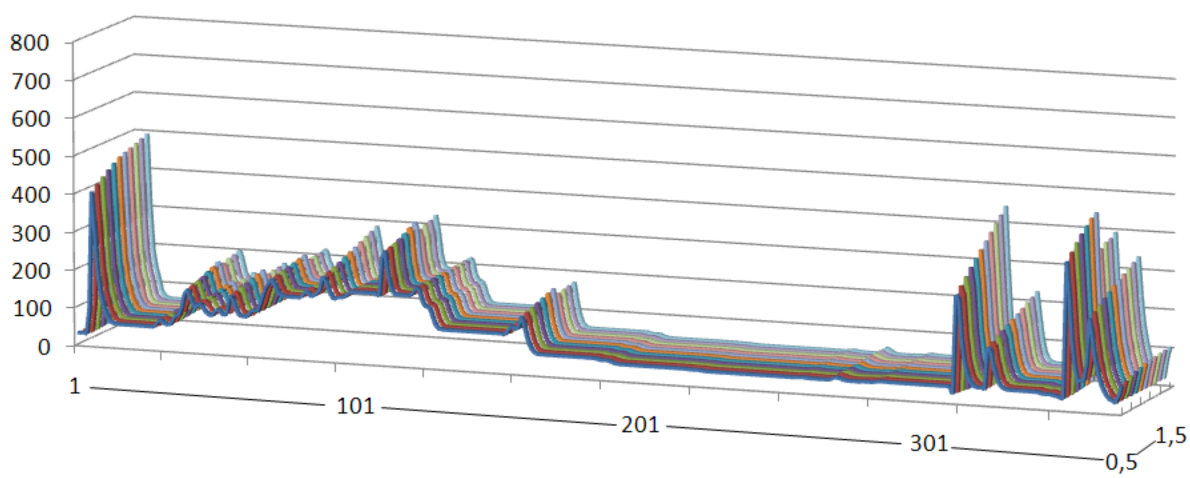


Figure 4.11. Model Output Hydrographs with Respect to Various Percent-Imperviousness Values of Subcatchments (cms vs days vs multiplier)

Percent of a subcatchment area which is impervious is another important parameter in our model, and as seen from the presented hydrographs, the model has an average sensitivity with respect to changing imperviousness. Maximum values of flow during the stormy periods are increased this increasing imperviousness values. This outcome is quite acceptable: with increasing imperviousness, amount of water which will not infiltrate, which will run off from the surface must increase (Yang et al. 2005).

4.3.5. Analysis of N-impervious of Subcatchments

N-imperviousness stands for Manning's n for overland flow over the impervious portion of the subcatchment. The system does not seem to be affected by the changes in this parameter at all, only minor changes can be observed from the graph below. This result could be explained by the area being a rural with high percent of forest cover, this high percentage of pervious cover decreases the effects that imperviousness parameters impose.

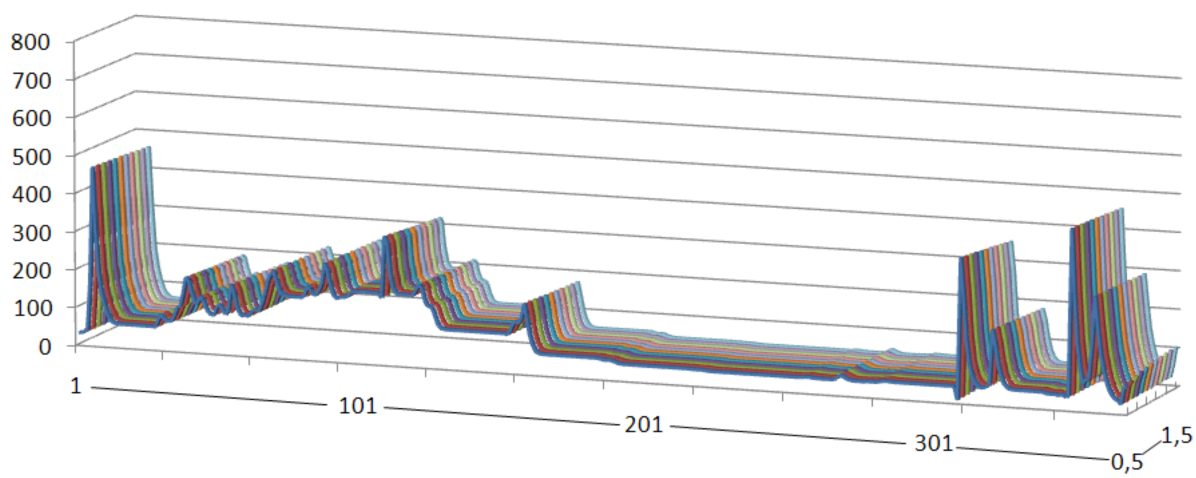


Figure 4.12. Model Output Hydrographs with Respect to Various N-impervious Values of Subcatchments (cms vs days vs multiplier)

4.3.6. Analysis of N-pervious of Subcatchments

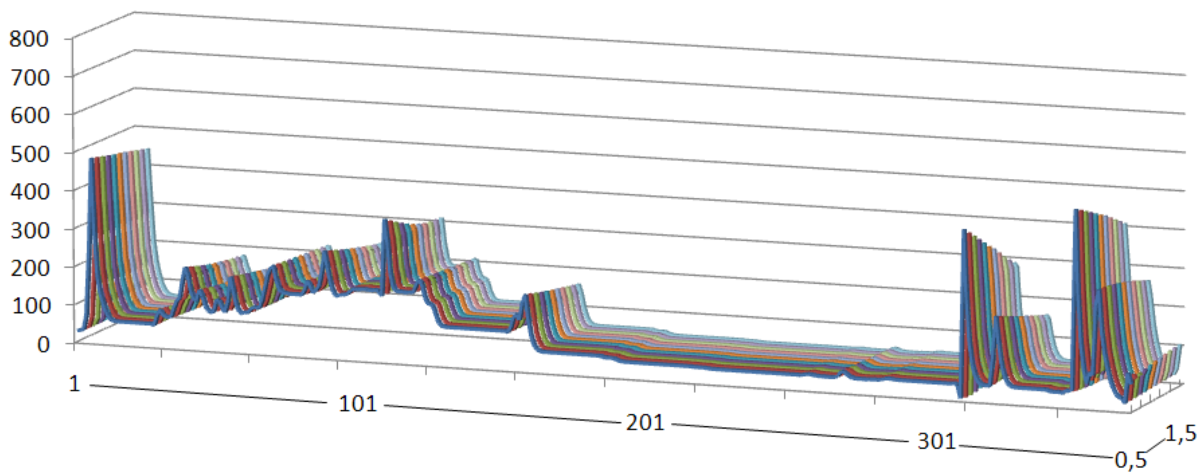


Figure 4.13. Model Output Hydrographs with Respect to Various N-pervious Values of Subcatchments (cms vs days vs multiplier)

Unlike N-impervious, Manning's coefficient for pervious areas (N-pervious) has some affect on outcome. As the Manning's coefficient increases the peaks of hydrograph increases; this result is parallel with the reality since Manning's Coefficient defines the area roughness. As roughness of an area increases the time for the runoff water to get through the system also increases, lowering the peak and expanding the base of the graph. The reason behind system being more sensitive for the changes in N-pervious is system area being a rural-forested area; there are more spaces for this coefficient to show effect.

4.3.7. Analysis of D-store Impervious Values of Subcatchments

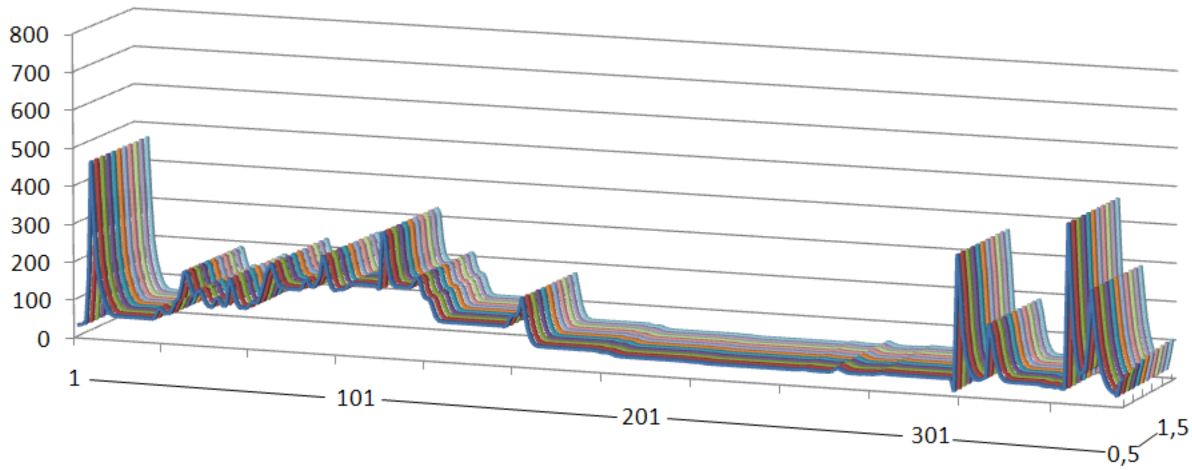


Figure 4.14. Model Output Hydrographs with Respect to Various D-store Impervious Values of Subcatchments (cms vs days vs multiplier)

D-store impervious stands for the depth of depression storage on the impervious portion of the subcatchment. Depth of depression storage capacity, in soil science, is the ability of a particular area of land to retain water in its pits and depressions, thus preventing it from flowing. However for this model we do not see the effect of change in this parameter which was assumed to be uniform in the model.

4.3.8. Analysis of D-store Pervious Values of Subcatchments

D-store pervious stands for the depth of depression storage on the pervious portion of the subcatchment. Just like D-store impervious, changes in this parameter do not affect the outcome of the model at all.

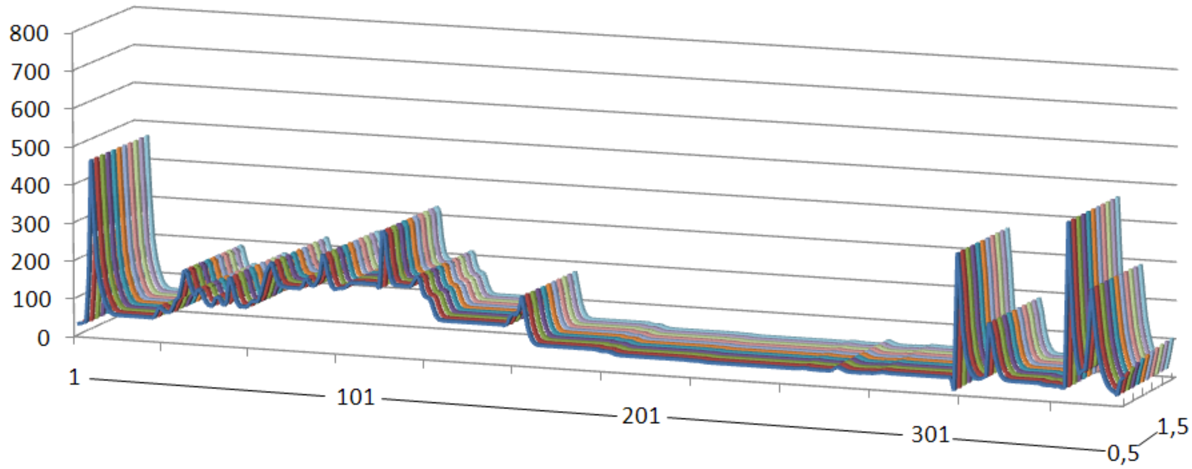


Figure 4.15. Model Output Hydrographs with Respect to Various D-store Pervious Values of Subcatchments (cms vs days vs multiplier)

4.3.9. Analysis of Max Depth of Conduits

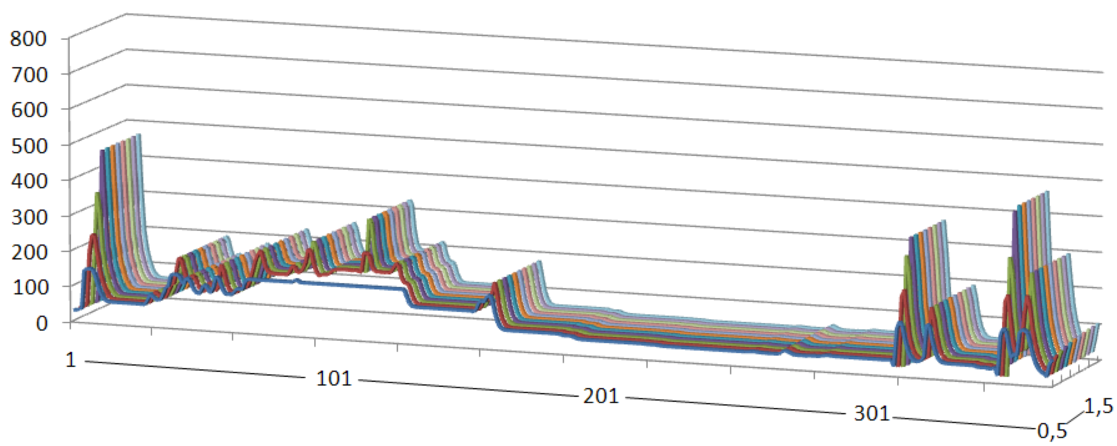


Figure 4.16. Model Output Hydrographs with Respect to Various Conduit Depth Values of Subcatchments (cms vs days vs multiplier)

Max depth of the conduits stands for the depth of the river in this study. From the graph, it has been seen that the max depth do not affect the outcome if it does not become the governing factor. But if the depth falls beyond a point where it does not have the carrying capacity, flooding happens and the outflow decreases significantly (Schumm, 2005). Water that has overflowed the river banks sporeads out over a large area infiltrating and evaporating: leaving the system via other forms of transport then river runoff.

4.3.10. Analysis of Length of Conduits

Length of conduits stands for the length of the river in general. As the length of the river increases the time for the running water to leave the system increases significantly resulting in a larger flow routing: the maximum values of the peaks decrease and the bases widen. This parameter has great affect on outcomes therefore must be determined carefully.

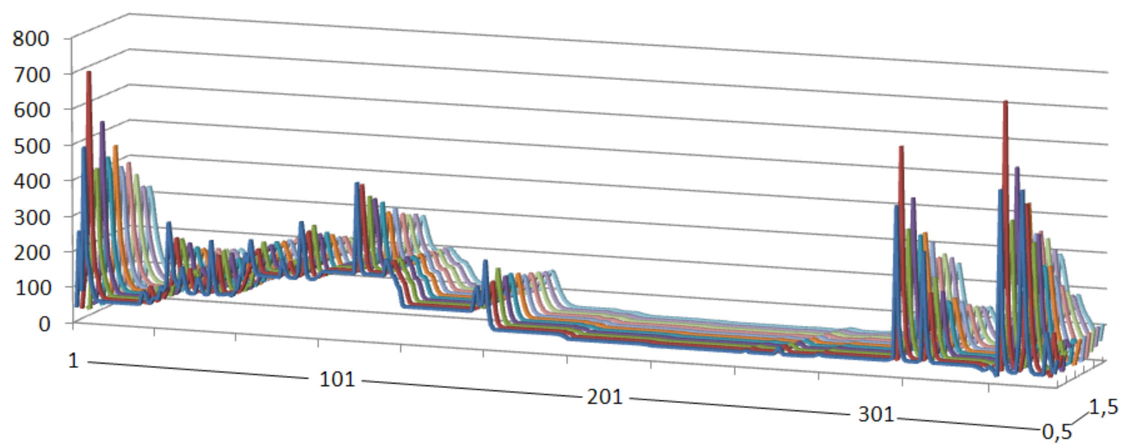


Figure 4.17. Model Output Hydrographs with Respect to Various Conduit Length Values of Subcatchments (cms vs days vs multiplier)

4.3.11. Analysis of Roughness of Conduits

Roughness of conduits parameter in this model stands for the Manning's Coefficient for the river. The parameter has been changed to various values to represent different channel types. During this sensitivity analysis it could be assumed as though we are testing a variety of channel types from concrete to natural channel with irregular section with pools. Concrete having a low roughness value put less resistance to water, hence maximum flows of stormy days are higher in concrete channels than in the natural channels (Horton, 1933).

During the urbanization of the areas, rivers or creeks go underground or are turned into concrete channels. This sensitivity analysis also show how this procedure reduces routing due to lowering roughness and with a lower routing capacity increases the change of area being flooded.

Table 4.4. Typical Roughness Values of Channels (ASCE, 1982)

Channel Type	**Manning n**
Lined Channels	
- Asphalt	0.013 - 0.017
- Brick	0.012 - 0.018
- Concrete	0.011 - 0.020
- Rubble or riprap	0.020 - 0.035
- Vegetal	0.030 - 0.40
Excavated or dredged	
- Earth, straight and uniform	0.020 - 0.030
- Earth, winding, fairly uniform	0.025 - 0.040
- Rock	0.030 - 0.045
- Unmaintained	0.050 - 0.140
Natural channels	
- Fairly regular section	0.030 - 0.070
- Irregular section with pools	0.040 - 0.100

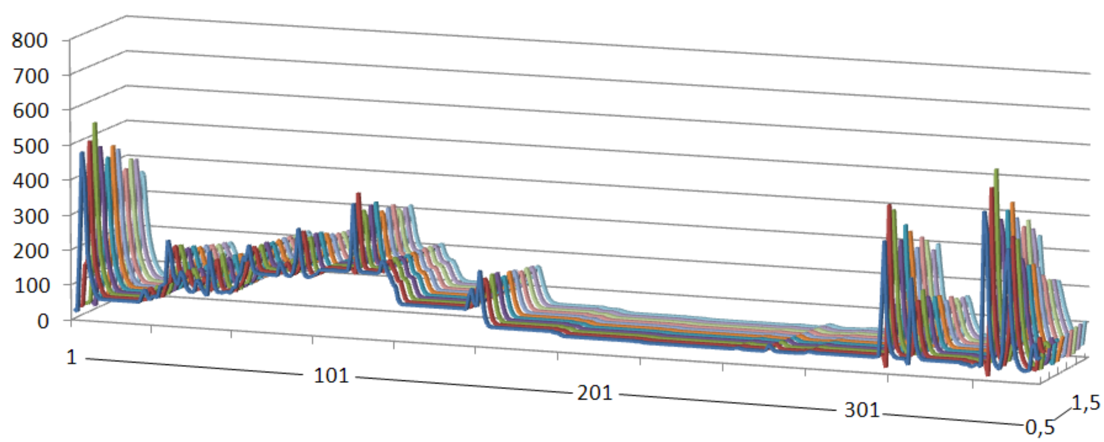


Figure 4.18. Model Output Hydrographs with Respect to Various Conduit Roughness Values of Subcatchments (cms vs days vs multiplier)

4.3.12. Analysis of Evapotranspiration

From the sensitivity analysis done on the parameter it can be seen that the parameter has low effect on runoff from the system: as the evaporation increases, the outcome decreases in small amount linearly. This outcome possibly does not represent the reality, in reality evapotranspiration must have a larger impact on hydrograph with such rapidly changing values.

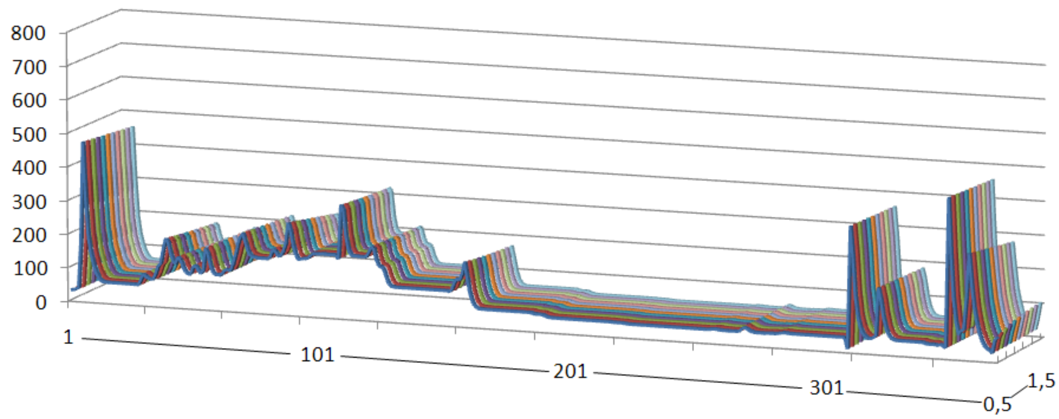


Figure 4.19. Model Output Hydrographs with Respect to Various Evapotranspiration Values of Subcatchments (cms vs days vs multiplier)

4.3.13. Analysis of Snowmelt

Snowmelt is one of the major parameters that influence the runoff amount from the catchment. The amount of influence varies from season to season since also the snowmelt happens mostly during the spring time when fresh snow on hills start melting (Fang et. al., 2007). Increase in flowrate due to an increase in snowmelt is linear, but the slope of increase is highly related with the base snowmelt amount.

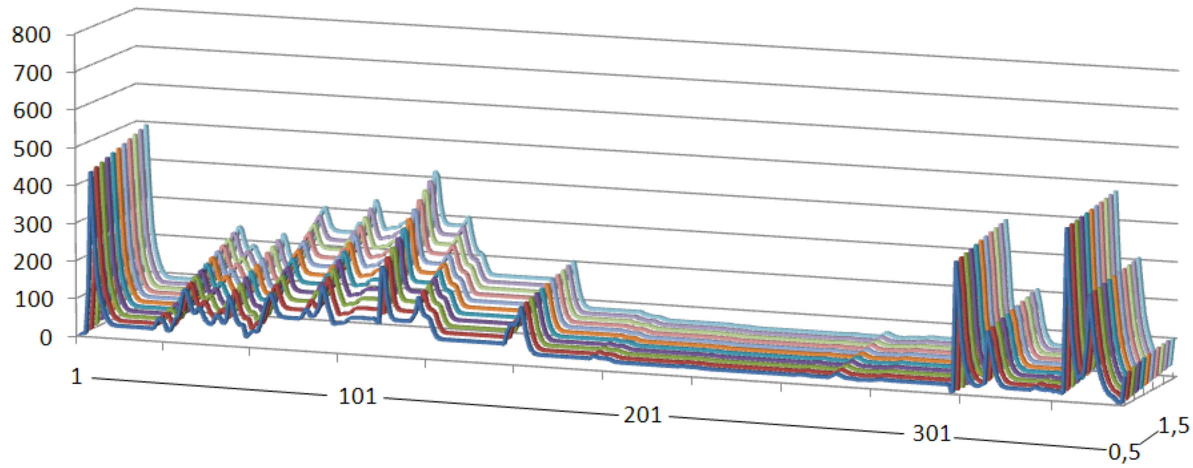


Figure 4.20. Model Output Hydrographs with Respect to Various Snowmelt Values of Subcatchments (cms vs days vs multiplier)

4.3.14. Analysis of Rainfall

Rainfall is the most important parameter. It has the highest influence on the outcome and runoff hydrograph (Horton, 1933). As the rainfall increase the flowrate at the output increases respectively.

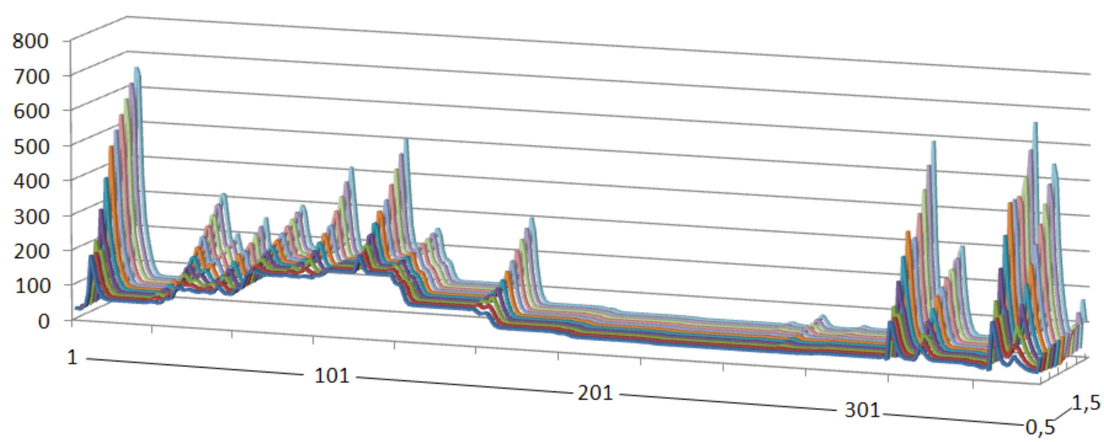


Figure 4.21. Model Output Hydrographs with Respect to Various Rainfall Values of Subcatchments (cms vs days vs multiplier)

4.4. Overall Sensitivity Analysis of Parameters

All the illustrated parameters and the models sensitivity to the changes in those are given above in the table 4.5 according to their ratio of variation, and their weights are consistent with the previous research done on the subject (Julien, 1990; Nearing, 1990).

Table 4.5. Sensitivity Comparison Table

Parameter	**Sensitivity Class (Proportion)**
Area of Subcatchments	Very High (Direct)
Rainfall	Very High (Direct)
Snowmelt	Very High (Direct)
Length of Conduits	High (Inverse)
Max Depth of Conduits	High (if governing) (Direct)
Width of Subcatchments	Medium (Direct)
Percent Slope of Subcatchments	Medium (Direct)
Percent Imperviousness of Subcatchments	Medium (Direct)
N-pervious of Subcatchments	Medium (Inverse)
Roughness of Conduits	Medium (Inverse)
Evapotranspiration	Very low (Inverse)
N-impervious of Subcatchments	Very low (Inverse)
D-store Pervious Values of Subcatchments	Very low (Inverse)
D-store Impervious Values of Subcatchments	Very low (Inverse)

In order to better present the sensitivity of parameters two graphs are presented below: Figure 4.22 holds every parameter but since the scale of some parameters are much smaller than parameters with high impact they are not represented clearly on the graph, therefore another graph has been plotted as figure 4.23 without rainfall, snowmelt and area of subcatchments parameters.

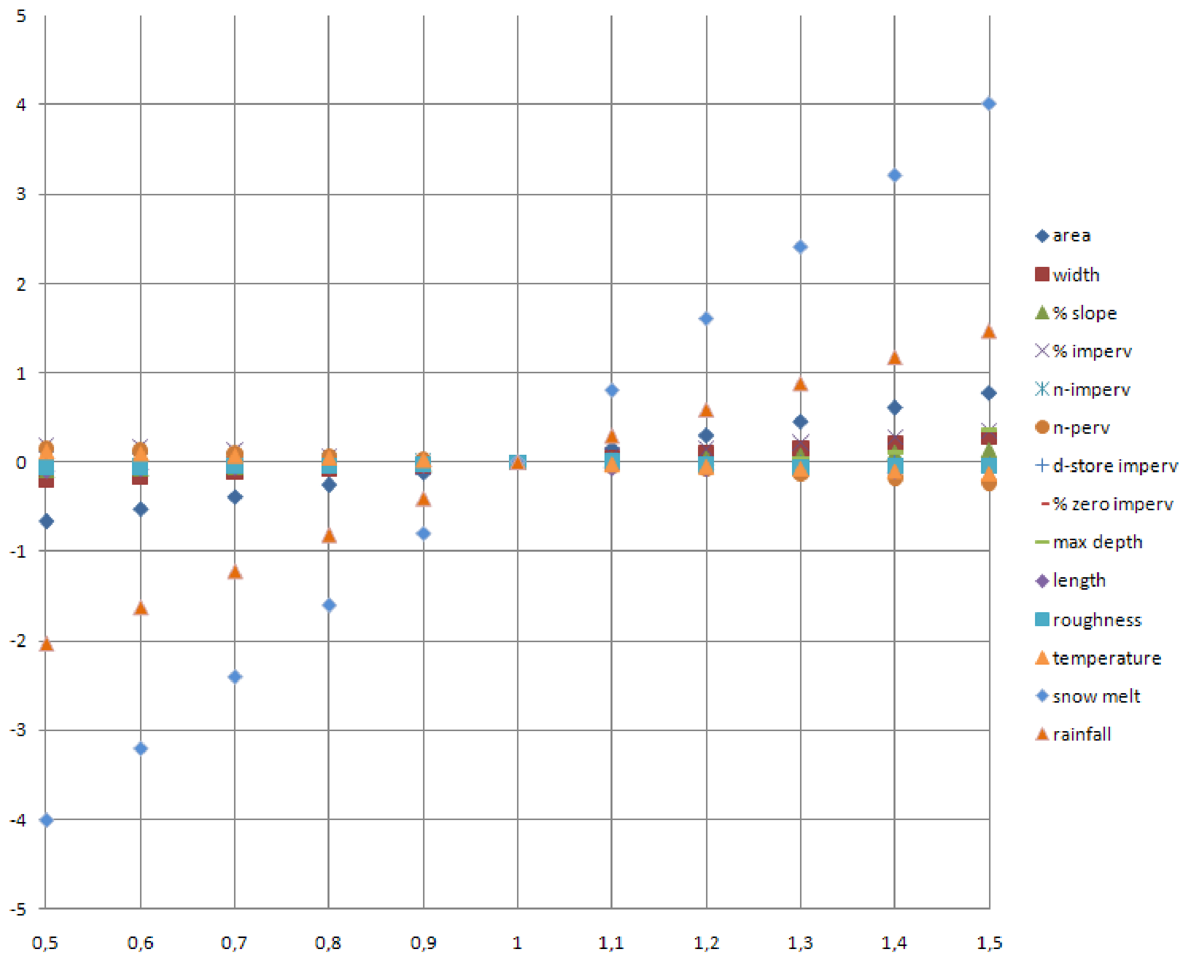


Figure 4.22. Parameter Sensitivities (Ratio of Variation vs Multiplier)

As the outcome of the sensitivity analysis suggests, some parameters are more important than other parameters. Highly influencing parameters in our case were obtained with rather good resolution during this study with the use of geographical information systems; on the other hand parameters with small influence were taken from literature. This resulted in better outputs from the model.

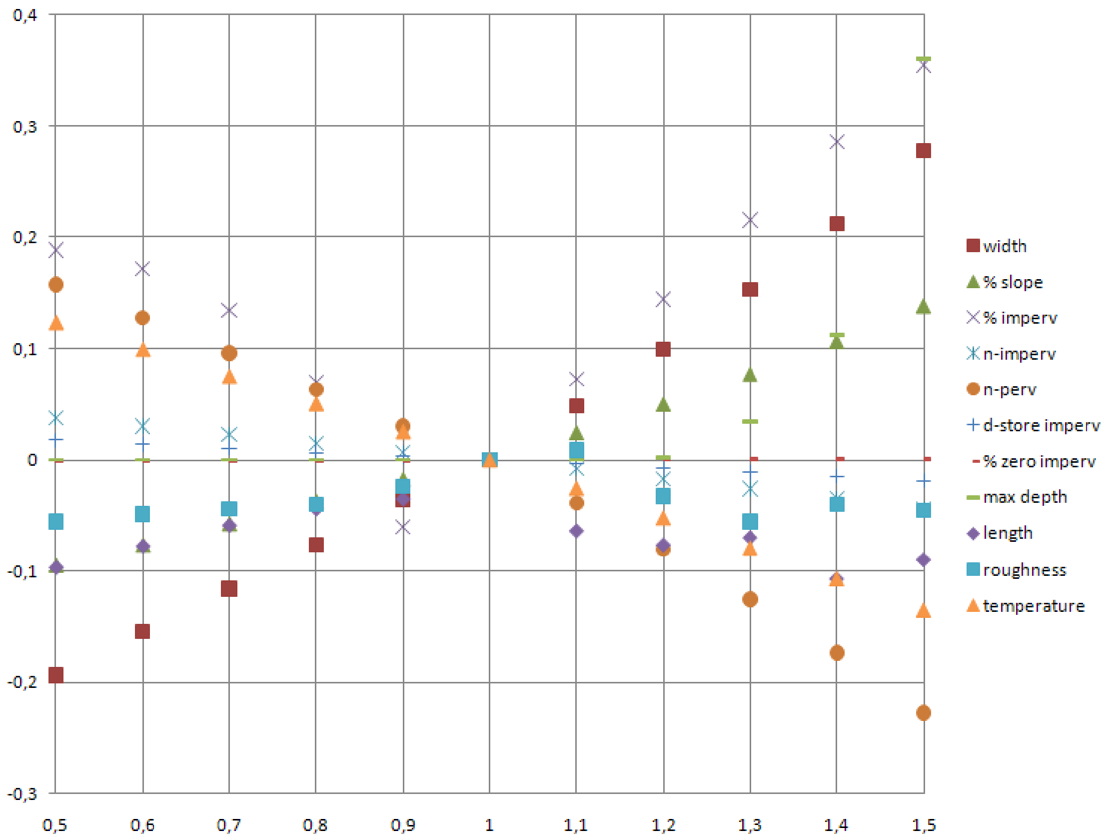


Figure 4.23. Parameter Sensitivities (Ratio of Variation vs Multiplier)

In reality, parameters that would change and affect the runoff in the future are area of catchments (dam building), percent imperviousness of subcatchments (deforestation), evapotranspiration and snowmelt (due to changes in temperature trends) and rainfall (due to precipitation trend changes). These affects must be kept in mind and catchment must be managed accordingly.

5. CONCLUSION and RECOMMENDATIONS

Although presented thesis covers a small part of the contemporary hydrological modeling techniques, it defines well a basis for understanding the rainfall runoff phenomenon using step by step instructions. Software programs, models or formulations used during the study might vary but the basics would be same in any similar research.

Unlike traditional maps, geographic or spatially referenced digital data can be aggregated, transformed, and shared; it is easily isolated and abstracted from the particular application in which it was developed and could be reused on a completely different media; it could also easily routed to become open for other potential communities. Old hierarchy of map distribution mechanism is completely inadequate to represent the multidirectional alternative information flows that are theoretically feasible now and eased by geo-standards and associated interoperability. However, benefits of this continuous data transaction cannot be realized without help from governments, thus, concept of asset management and interoperability in this case is closely linked to the governmental notion of a national infrastructure. In this respect, national geographic information assets have much in common with other types of infrastructure such as national road and railroad networks. In this process, governments will not only need to promote the diffusion of GIS technologies, but they will also have to take steps to overcome the institutional barriers that inhibit the potential use of GIS. These include a wide range of issues related to data availability and access.

National spatial data infrastructure implementation in Turkey is far from being completed although Turkish National Geographical Information System Action Plan was accepted in 1996 and appeared in the official journal (28/07/2006; no: 26242) with the objectives of: “Implementation of a national data infrastructure, respecting the technological development trends and INSPIRE Directives, and construction of a web portal by which state institutes and organizations will be sharing the standardized data they hold with users.” Nonetheless, if a minor category among the whole national data diversity: Spatial data requirements for a ‘Catchment Hydrology Modeling’ study were focused, lack of beneficial implementation becomes evident: Data are dispersed among many institutions; there are no standards of data format; data are not free even for public research institutes

As a methodological protocol, this study is uniquely applicable to rainfall-runoff analysis using SWMM and ArcGIS software. Integration of data file exchange was a critical link for this study. In this case, attribute tables for soil, land-use and virtual rainfall were generated by ArcMap and analyzed to develop the parameters for the input files for SWMM. SWMM and ArcGIS were chosen because of their relative popularity with many professionals.

It would appear that the discretization of the watershed did introduce volumetric differences into the models. The increase in data and parameters from lumped to grid scale modeling most likely became more representative of reality and less like a single parameter model. However, with the use of more sophisticated programs, representation resolution could have been altered a couple times.

Sensitivity analysis brings out the most important parameters (the parameters that affect the runoff more), during the data gathering more effort should be given on better defining these parameters and implementing these with higher fidelity in order to get better results from the rainfall-runoff models. As also discussed in chapter 4.4 highly influencing parameters in our case were obtained with rather good resolution during this study with the use of geographical information systems; on the other hand parameters with small influence were taken from literature. This resulted in better outputs from the model.

As brought out in introduction paragraph living further into the 21st century, sustainable management of water becomes more important day by day. Critical to any sustainable water management strategy is our understanding of the circulation of water, and our ability to assess, model and predict its availability, variability and quality. The need to understand and predict has become even more urgent in impending climate change scenarios which threaten to put increased stress on water resources (Lettenmaier et al., 1999; Milly et al., 2002; Milly et al., 2005). However, the characterization and modeling of water cyle processes are extremely challenging due to their closely coupled nature and because of their occurrence in disparate media (ground, land surface, atmosphere and plants) and over vast spatial scales (that can range from a few centimeters for infiltration, to tens and hundreds kilometers for groundwater flow) and time scales (that can extend from a few seconds, typical for evaporative fluxes, to the several years or decades for base flow). As noted by Intergovernmental Panel on Climate Change (IPCC, 2007), we still do not have an adequate understanding and ability to model and predict water cycle processes and the associated feedbacks. This study is just a brick in this tower of learning.

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APPENDIX A: DESCRIPTIONS OF THE OBJECTS USED IN SWMM

Rain Gages supply precipitation data for one or more subcatchment areas in a study region. The rainfall data can be either a user-defined time series or come from an external file. Several different popular rainfall file formats currently in use are supported, as well as a standard user-defined format.
The principal input properties of rain gages include:

- rainfall data type (e.g., intensity, volume, or cumulative volume)
- recording time interval (e.g., hourly, 15-minute, etc.)
- source of rainfall data (input time series or external file)
- name of rainfall data source

Subcatchments are hydrologic units of land whose topography and drainage system elements direct surface runoff to a single discharge point. The user is responsible for dividing a study area into an appropriate number of subcatchments, and for identifying the outlet point of each subcatchment. Discharge outlet points can be either nodes of the drainage system or other subcatchments.

Subcatchments are divided into pervious and impervious subareas. Surface runoff can infiltrate into the upper soil zone of the pervious subarea, but not through the impervious subarea. Impervious areas are themselves divided into two subareas - one that contains depression storage and another that does not. Runoff flow from one subarea in a subcatchment can be routed to the other subarea, or both subareas can drain to the subcatchment outlet.

Infiltration of rainfall from the pervious area of a subcatchment into the unsaturated upper soil zone can be described using three different models:

- Horton infiltration
- Green-Ampt infiltration

- Curve Number infiltration

To model the accumulation, re-distribution, and melting of precipitation that falls as snow on a subcatchment, it must be assigned a Snow Pack object. To model groundwater flow between an aquifer underneath the subcatchment and a node of the drainage system, the subcatchment must be assigned a set of Groundwater parameters. Pollutant buildup and washoff from subcatchments are associated with the Land Uses assigned to the subcatchment.

The other principal input parameters for subcatchments include:

- assigned rain gage
- outlet node or subcatchment
- assigned land uses
- tributary surface area
- imperviousness
- slope
- characteristic width of overland flow
- Manning's n for overland flow on both pervious and impervious areas
- depression storage in both pervious and impervious areas
- percent of impervious area with no depression storage

Junctions are drainage system nodes where links join together. Physically they can represent the confluence of natural surface channels, manholes in a sewer system, or pipe connection fittings. External inflows can enter the system at junctions. Excess water at a junction can become partially pressurized while connecting conduits are surcharged and can either be lost from the system or be allowed to pond atop the junction and subsequently drain back into the junction.

The principal input parameters for a junction are:

- invert elevation
- height to ground surface

- ponded surface area when flooded (optional)
- external inflow data (optional)

Conduits are pipes or channels that move water from one node to another in the conveyance system. Their cross-sectional shapes can be selected from a variety of standard open and closed geometries. Irregular natural cross-section shapes are also supported, as are user-defined closed shapes. The principal input parameters for conduits are:

- names of the inlet and outlet nodes
- offset depth or elevation of the conduit above the inlet and outlet node inverts
- conduit length
- Manning's roughness
- cross-sectional geometry
- entrance/exit losses
- presence of a flap gate to prevent reverse flow
- inlet geometry code number if conduit acts as a culvert

Outfalls are terminal nodes of the drainage system used to define final downstream boundaries under Dynamic Wave flow routing. For other types of flow routing they behave as a junction. Only a single link can be connected to an outfall node. The boundary conditions at an outfall can be described by any one of the following stage relationships:

- the critical or normal flow depth in the connecting conduit
- a fixed stage elevation
- a tidal stage described in a table of tide height versus hour of the day
- a user-defined time series of stage versus time.

The principal input parameters for outfalls include:

- invert elevation
- boundary condition type and stage description
- presence of a flap gate to prevent backflow through the outfall.

APPENDIX B: SCRIPT USED FOR DATA COLLECTION IN EXCEL

```
Sub ac_al()
Application.DisplayAlerts = False
For i = 1960 To 2005
Workbooks.Open"C:\arcgis\table\rainfall\yagis"&i&".xls"
For j = 1 To 256
If Worksheets("sheet1").Cells(5, j).Value = "SILIFKE" Then
Worksheets("sheet1").Range(Cells(6, j), Cells(372, j)).Copy
Workbooks("silifke.xls").Worksheets("sheet1").Paste
Destination:=Workbooks("silifke.xls").Worksheets("sheet1").Cells(2, i - 1959)
Workbooks("silifke.xls").Worksheets("sheet1").Cells(1, i - 1959).Value = i
End If
Next j
Workbooks("yagis" & i & ".xls").Close savechanges:=False
Next i
End Sub
```