DEVELOPMENT OF INTEGRATED TOOLS FOR RIVER BASIN MANAGEMENT DRRSM AND GIS APPLICATION

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by
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ABSTRACT

The use of computerized hydrologic models is increasing in water resources research for purposes of establishing a technical base to estimate the results of management decisions and to identify the underlying mechanism of the real hydrologic systems in watersheds. The developments in data collection and manipulation systems such as digital sampling equipments, remote sensing technologies (RS) and geographical information systems (GIS) feed back the current hydrologic modeling systems to integrate them with the new complex algorithms and computation techniques. As new developments occur, new problems arise, such as over parameterization of the models and the difficulty in the use of complex models due to comprehensive data requirements.

In this thesis, the basic concepts in hydrologic modeling systems are reviewed, and problems in watershed modeling studies are expressed. Then, as a new trend, the distributed hydrologic modeling systems are discussed in detail. In addition, a simple conceptual distributed hydrological model is introduced as developed in the scope of this thesis for simulating daily runoff, using only the daily rainfall and evaporation data which are commonly found everywhere. The developed model is called DRRSM (Daily Rainfall Runoff Simulation Model) and uses the spatially distributed watershed data such as land cover and soil types by integrating GIS algorithms. Hydrologic computations are carried out on Hydrological Response Units (HRU), which are obtained by overlaying rainfall, land cover and soil type distributions of the watershed. DRRSM computes surface, sub-surface, groundwater and total runoff components of a watershed as a continuous time series at the outlet of the watershed. The runoff generations are based on simple linear discharge-storage relationships, which may be changed to non-linear structures by the user, if desired, since the DRRSM is developed by means of Object Oriented Programming techniques (OOP).

The application of the DRRSM is demonstrated on Demirci watershed, which is a sub-watershed of the Gediz River basin. After the calibration processes of the DRRSM, the verification of the model is realized. The results of the application in Demirci watershed shows that the developed model DRRSM can be used to simulate daily mean discharges of a watershed where comprehensive data do not exist. The simple forms of the equations in the hydrologic computations are shown to be satisfactory when the spatial distribution of the data are considered.

ÖZET

Su kaynaklarının yönetiminde, yönetim kararlarının teknik ve bilimsel temellere oturtulması amacıyla kullanılan bilgisayar destekli hidrolojik modeller, oldukça geniş ve önemli kullanım alanları bulmuştur. Geleceğe yönelik tahminler ve havza hidrolojisinin açıklanmasında kullanılan bu modeller, gelişmiş ülkelerdeki planlamacıların vazgeçilmez yardımcıları haline gelmiştir. Kullanılan modeller, sayısal veri toplayıcılar, uzaktan algılama (UA) ve coğrafi bilgi sistemleri (CBS) gibi yeni bilgi teknolojilerinin sayesinde sürekli kendilerini yenilemekte; bu yenileme ise, model yapısına, hesap yöntemlerine ve kullandığı veri çeşitliliğine yansımaktadır. Ancak bu gelişmelere paralel olarak, model yapısının karmaşıklığı, model parametre sayıları ve modelin kullanılabilmesi için ihtiyaç duyulan minimum veri gereksinimi de artmaktadır. Bu durum ise, hidrolojik modellemede çözülmesi gereken yeni sorunlar olarak karşımıza çıkmaktadır.

Sunulan tez çalışmasında, ilk olarak hidrolojik modeller konusundaki temel kavramlar ve tanımlamalar açıklanmakta, bunu takiben havza modellemesinde ortaya çıkan mevcut problemler özetlenmektedir. Hidrolojik modellemede yeni bir eğilim olan yayılı hidrolojik modeller de bu tez kapsamında incelenmekte ve detaylı bilgiler verilmektedir. Bunlara ilaveten, sunulan tez kapsamında geliştirilen ve sadece günlük toplam yağış ve tava buharlaşması verilerine gereksinim duyan basit, kavramsal ve yayılı tipte bir model olan Günlük Yağış Akış Simulasyon Modeli (DRRSM) tanıtılmaktadır. Geliştirilen model CBS ile entegre edilerek, havzanın alansal dağılım gösteren yağış özellikleri, arazi örtüsü ve toprak özelliklerini de alansal dağılımlarıyla birlikte dikkate almaktadır. Model içindeki hidrolojik hesaplamalar, alansal dağılım gösteren yağış, arazi örtüsü ve toprak özelliklerinin CBS teknikleriyle üst üste bindirilmesi suretiyle bulunan homojen Hidrolojik Birimler (HB) yardımıyla gerçekleştirilmektedir.

Geliştirilen model, yağış sonucunda bir havzadan gelebilecek yüzeysel, yüzey altı ve yeraltısuyu akım bileşenlerinin havza çıkışında oluşturacağı günlük akış değerlerini modelleyebilmektedir. Akım bileşenlerinin hesaplanmasında basit doğrusal debi-depolama ilişkilerinden yararlanılmıştır. Fakat model nesne bazlı yazılım geliştirme tekniği ile geliştirildiği için, model kullanıcısı basit doğrusal ilişkiler yerine doğrusal olmayan karmaşık ilişkiler de tanımlayabilmektedir.

Geliştirilen modelin bir uygulaması Gediz havzasının bir alt havzası olan Demirci havzasında gerçekleştirilmiştir. Model kalibrasyonu ve verifikasyonunun da sunulduğu bu uygulama sonucunda, geliştirilen modelin sadece yağış ve buharlaşma gözlemlerinin bulunduğu kısıtlı veriye sahip havzalarda rahatlıkla kullanılabileceği ve basit debi-depolama ilişkilerinin bile, alansal dağılımlı verilerin model içine alansal dağılımlarıyla entegre edilmeleri halinde iyi sonuçlar verdiği görülmüştür.

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CHAPTER ONE
INTRODUCTION

1.1 General

The hydrological cycle of precipitation, evaporation, percolation and runoff occurs continually around the world. This is the cycle from which the water for irrigation, energy, freshwater etc. are obtained. As humans alter the earth's environment, the hydrological cycle is also altered to some degree. It is difficult to quantify the amount of alteration in the hydrologic cycle because of the inherent complexity of the system. The result is arbitrary, ineffective, or overly extreme planning, management, and decision making regarding anthropogenic impacts on water resources. In an effort to provide managers with decision making tools that effectively quantify human impacts on the hydrologic cycle, computer models simulating the cycle have been developed.

Computer simulations of the hydrologic cycle have been performed since the advent of the Stanford Watershed Model (SWM) (Linsley, 1967). With the inception of the SWM, Linsley stated that the Stanford Watershed Model (SWM) does not yet represent the ultimate point in precipitation-runoff relationships, but indicates the development for digital hydrological simulation. The ultimate goal was a completely portable hydrologic model which could be applied to any catchment or basin given the appropriate observed hydrometeorological data. Over time, the SWM, as it is represented in other models such as HSPF (Hydrological Simulation Program-Fortran) and SWMM (Storm Water Management Model), has incorporated more complex algorithms, land cover specific parameterizations, additional components such as nutrients, and time specific anthropogenic impacts. With these developments, however, the crucial problem which is the detailed data need of such models have arisen with respect to complex algorithms and parameterization.

One of the shortcomings of hydrologic simulations is that they typically do not take into account the spatial distribution of different land surface features when performing calculations. Instead, they employ spatially averaged, or "lumped", parameters which represent the generalized characteristics of the basin. Soil properties, slope and land use/land cover usually vary significantly in any particular basin, but they are represented by a single spatially averaged parameter in the typical hydrologic model. The result is that the simulation does not often suit purposes of detailed management and decision making problems in water resources. Land cover locations are not explicitly represented, either. To more accurately simulate the movement and transformation of water across the landscape, the relative spatial locations of surface features must be taken into account. The development of spatially distributed hydrologic models by having the hydrologic process model operate within a simulation environment which can accurately represent spatial location of surface features, namely a Geographical Information System (GIS), makes this possible.

1.2 The Objectives of the Thesis

As mentioned in the above section, the current hydrologic models have very complex structures which increase the number of model parameters and data needs for model applications. In addition to that, the current integration of the GIS and hydrologic models brings another dimension, which is the need for spatially distributed data for the model run. Although the problems stated here are still crucial and current, trends in the design of modeling systems are in the direction of increasing complexity and parameterization since the data collection and manipulation systems are growing in the developed countries.

The differences between applications of advanced models in developed and developing countries, such as Turkey, are increasing regarding the complexity of models and the availability of data sufficient in both quantity and quality. These problems in developing countries make the use of advanced models impossible or unreliable. The solution to the problem has two aspects. On one side, there are the additional efforts to increase the quality and quantity of the data which has to be collected for the modeling studies and thus to prepare a technical base for water resources management decisions. This side relates to governmental policies and the economy of the country. On the other side, there are scientific efforts to develop and apply the new models which are suitable for use with the current data sets of the country. This side relates to the national research institutions and the universities.

In this thesis, it is aimed to develop a simple hydrologic model for simulating daily runoff by using the existing daily rainfall and evaporation data which are commonly found at the meteorological stations of Turkey. The developed model is called DRRSM (Daily Rainfall Runoff Simulation Model) and uses the spatially distributed watershed data such as land cover and soil types by integrating GIS algorithms. Hydrologic computations are carried out on the Hydrological Response Units (HRU) which are obtained by overlaying rainfall, land cover and soil type distributions of the watershed. By means of HRU concepts, the spatial variability of the watershed properties are considered in the hydrologic computations. DRRSM computes surface, sub-surface, groundwater and total runoff components of a watershed as a continuous time series at the outlet of the watershed. The runoff generations are based on simple linear discharge-storage relationships which may be changed to a non-linear structure by the user since the DRRSM is developed by means of Object Oriented Programming techniques (OOP). The current equations are developed as linear structures in order to test the performance of the model in using spatially distributed data. The application of the DRRSM is realized to test the model performance and the results in the Gediz River basin, for which some spatially distributed data are obtained from the internet sources.

Chapter 2 summarizes the classification of watershed models and gives some basic concepts and terminology in watershed modeling and the use of GIS in modeling studies. Chapter 3 focuses on the details of distributed watershed models and their constraints. Chapter 4 gives information about the construction, calibration and verification of hydrologic models and the uncertainties of modeling studies as a whole. Chapter 5 expresses the problems in both hydrologic modeling and the current status of modeling in Turkey. The objective of the thesis is also given in that chapter. The details of the developed hydrologic model DRRSM as technical notes and information are given in Chapter 6. Finally, the application of the DRRSM in the Gediz River basin with calibration and verification analyses are given in Chapter 7. Chapter 8 reviews the results of both the application of the DRRSM and the thesis.

CHAPTER TWO

WATERSHED MODELING

2.1 Modeling for Integrated Water Management

Air, soil, and water constitute the environmental continuum, and are vital components for sustaining life on earth. These components are interactive and interactions among them are complex. In other words, a management change imposed on one component of the environmental continuum has effects that propagate to other components, and some of these effects are unknown and cannot be quantified. This interactive nature requires that the environment is managed and protected as a cohesive whole (or system). This can be accomplished through an integrated approach to environmental management that clearly has to be interdisciplinary. Such an approach may entail management of individual components with proper accounting of their interactions and dependencies. The management of air, soil, and water is to be integrated as well.

Worldwide, environmental systems are rarely managed as a cohesive whole. That is partly because air, soil, and water resources have been and continue to be managed by independent organizations having little interaction among them. For example, there are a host of organizations in Turkey that have the authority to manage nation's water resources at the local, regional, and national level. The Ministry of Environment, and the Ministry of Energy and Natural Resources are two of the state institutions with broad authority for water resources management. Then, there are the departments of water resources, natural resources, or environmental quality at the state level having authority to manage water resources in their individual area.

The integrated water management should be accomplished within a spatial unit called watershed through the instrument of modeling. The integrated water management can be viewed as a three or more dimensional process centered around the need for water, the policy to meet the needs and the management to implement the policy. Water elements encompassing physical, chemical, and biological aspects of water quantity and quality may constitute the first dimension. Water uses, including agriculture, water supply, energy generation, industry, fish production, recreation, transportation, etc., may constitute the second dimension. Clearly, these water uses have to be accomplished following a well-defined management policy balancing the demand for water among different uses. The strategy to implement this policy may form the third dimension. The management must be dynamic and evolve with time, in response to changing needs and objectives. Thus, the fourth dimension may be formed by these needs and objectives.

The water elements, their interactions, and the effects on them of natural as well as external constraints, as shown in Figure 2.1, constitute the foundation on which the practice of integrated water management is to be built. External constraints such as economic, demographic, transportation and other forms of development directly influence one or the other water elements. Likewise, climatic vagaries, climatic change, and climatic extremes, and a host of natural hazards are some of the natural causes that greatly influence the water elements and have significant impact on the integrated water management.

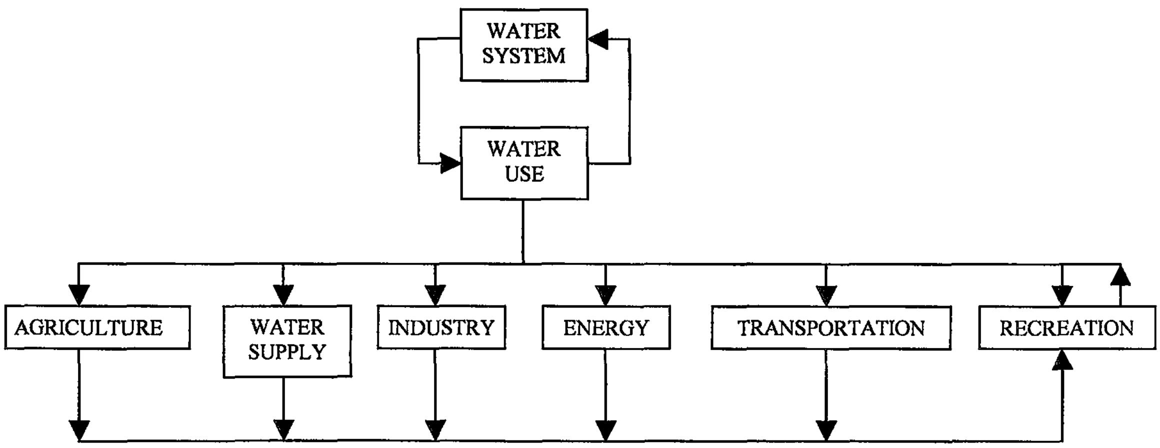


Figure 2.1 Elements of a water system and their interactions (Singh, 1995).

The need for water is derived from a variety of activities in which it is used as shown in Figure 2.2. These activities are vital for human society- its existence and development. Because usable water is limited in its availability, it has an economic value. Furthermore, different activities require water of differing quality. For example, for domestic use, water of high quality is needed. Clearly, all uses of water cannot be supported to the fullest extent and a management policy has to be developed that can prioritize water use following established criteria. There may be conflicts and interactions among different water uses, and these, in turn interact with water elements. The management policy has to incorporate all of these considerations.

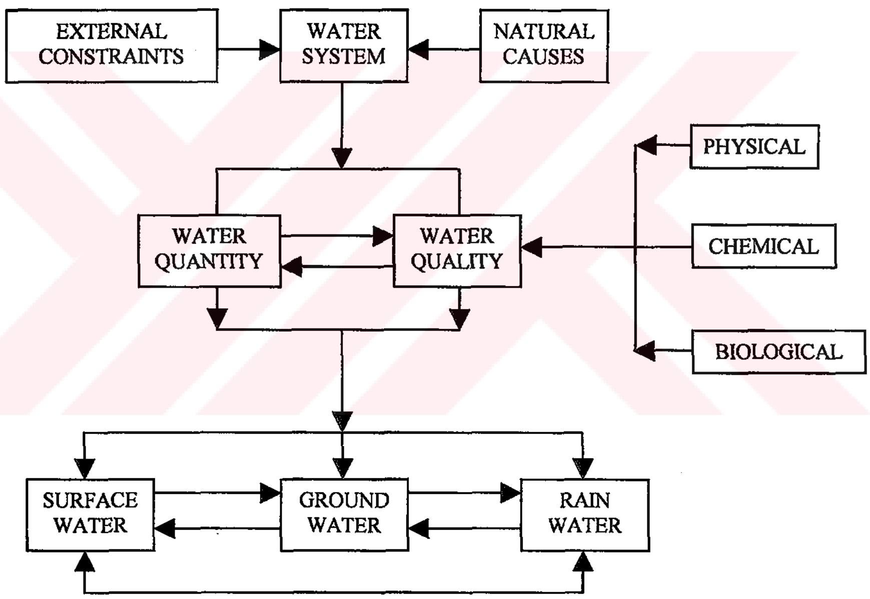


Figure 2.2 Water use and its interactions with water system (Singh, 1995).

The criteria, as shown in Figure 2.3, that form the foundation of the management policy must be developed following such considerations as cost effectiveness, economic efficiency, environmental impact, ecological and health considerations, and socio-cultural aspects. The criteria must be practical, implementable, and must be acceptable to the society at large. Furthermore, they must be capable of responding to changing needs of the society. The resulting policy must satisfy such interactive social goals as equity, efficiency, environmental quality, etc.

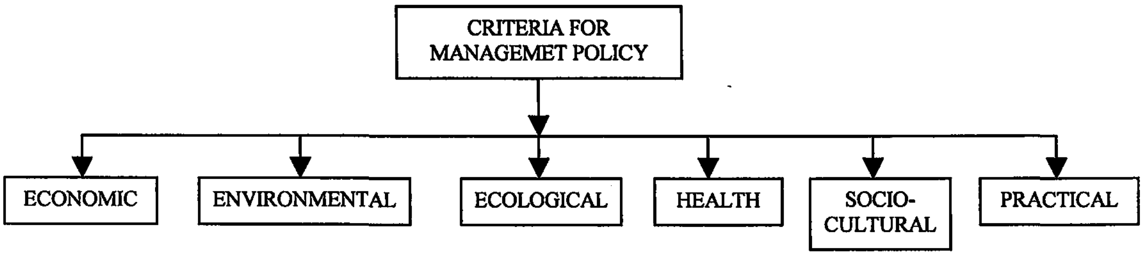


Figure 2.3 Criteria for information of a management policy.

Once a management policy is established, a strategy, including administrative infrastructure, has to be employed to undertake the integrated water management as shown in Figure 2.4. The components of integrated water management are interactive, and hence the administrative set up must be flexible and be responsive to changing goals. Thus, the integrated water management requires integration of the various components discussed earlier—physical, biological, chemical, social, economic, ecological, health, and environmental. This can be accomplished through development and application of mathematical models. The physical, chemical, biological, environmental, and ecological components and their models must be embedded in the development of comprehensive watershed models.

A model for integrated water management helps develop implementable solutions to water resources problems by combining into an optimization scheme all essential component models. The model incorporates or accumulates all of the interactive forces or influences. Thus, it aids the decision-making process and keeps the policy results within the intersection of the social goals of the management policy and the legal constraints.

Fundamental to integrated water management is watershed modeling. The watershed models are abundant in hydrologic literature (Singh, 1989), and the state of art of watershed modeling is reasonably advanced, especially when viewed in the context of practical application.

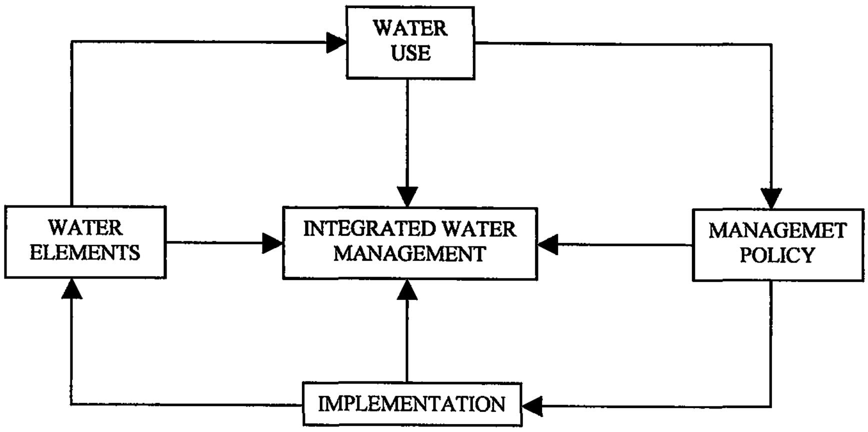


Figure 2.4 Integrated water management (Singh, 1995).

However, these models have yet to become common planning or decision-making tools. To that end, two milestones will have to be achieved. First, these models will have to be transformed and packaged at the level of a common user who is not necessarily a hydrologist. For some models, this has already begun to occur. Second, these models will have to be integrated with social, economic and management models yielding information that is easily interpreted or understood by the user.

A majority of watershed models simulate watershed response either without consideration of water quality or inadequate consideration thereof. These models will have to be made more versatile and more comprehensive to include biological as well as chemical aspects of watershed response. If these models are to be used for environmental or ecological modeling, then this versatility becomes an essential attribute of the models. A decision maker wants to know as much about a watershed as he can, not just water-quantity information.

In the past few years, with the revolution in information and communication technology, new technologies have unfolded that watershed models have not taken full advantage of. Examples include remote sensing and satellite technology (RSST), GIS, artificial intelligence, and risk and reliability analysis. The RSST is a powerful technology for data acquisition over extensive and even for data management—data retrieval, manipulation, organization and the like—that may be entirely suitable for development of distributed models. Artificial intelligence allows one to make watershed models user friendly and usable by nonhydrologists. Risk and reliability analysis allows for providing information on the accuracy of model results that the user wants to know about. It is this information that in many cases becomes crucial in selection of a model and determines the economic worth of data as well as of the model (Harmancioglu et al., 1998).

2.2 Terminology in Watershed Modeling

Before classifying watershed models, it is appropriate to mention some terminology, in order to make this classification clear. No unique and general accepted terminology is presently used in the hydrological community. Therefore, definitions of some of the most common terms used in hydrological modeling are given in the following:

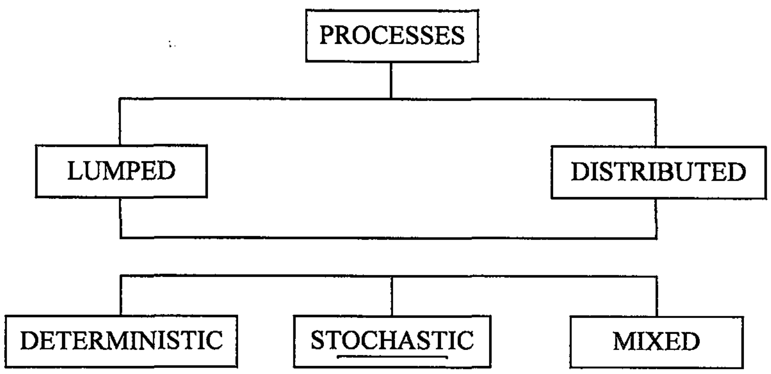
- The *natural system* that is considered here is the hydrological cycle or parts of it as we currently conceive it.
- A *hydrological model* is a simplified representation of the natural system. A *mathematical model* is a set of mathematical expressions and logical statements combined in order to simulate the natural system.
- *Simulation* is the time-varying description of the natural system computed by the hydrological model. A simulation may be seen as the model's imitation of the behavior of the natural system.
- A *Routine*, a *component*, or a *submodel* is part of a more comprehensive model, e.g. the snowmelt simulation part of a model for the complete land phase of the hydrological cycle.

- A *parameter* is a constant in the mathematical expressions or logical statements of the mathematical model. It remains constant in virtual time. A *variable* is a quantity which varies in space and time.
- A *deterministic model* is a model where two equal set of input always yield the same output if run through the model under identical conditions. A deterministic model has no inner operations with a stochastic behavior.
- A *stochastic model* has at least one component of random character which is not explicit in the model input, but only implicit or "hidden". Therefore, identical inputs will generally result in different outputs if run through the model under, externally seen, identical conditions. This notation can be extended to models in which the input has a direct stochastic character.
- *Catchment* is conceived as a region of physical space over which flows occur that are collectively of concern to us. A catchment is thus an object towards which the universe of discourse of hydrology becomes directed.
- A *lumped model* is a model where the catchment is regarded as one unit. The variables and parameters thus represent average values for the entire catchment. Thus, the virtual world is reduced to just one object.
- A *distributed model* takes account of spatial variations in all variables and parameters.
- A *physical process* is a representation in our own minds of an event occurring in our outer world of sense experience.
- A *black box* or an *empirical model* is a model developed without any consideration of the physical processes that we otherwise associate with the catchment. The model is merely based on analyses of concurrent input and output time series.
- A *conceptual model* is one that is constructed on the basis of the physical process observed in the catchment. In a conceptual model, physically sound structures and equations are used together with semi-empirical ones. A conceptual model, which is usually a lumped-type model, is often called a *grey box model*.

- A *physically-based model* describes the natural system using the basic mathematical representations of the flows of mass, momentum and various forms of energy. For catchment models, a physically-based model in practice also has to be fully distributed. This type of model, also called a *white box model*.

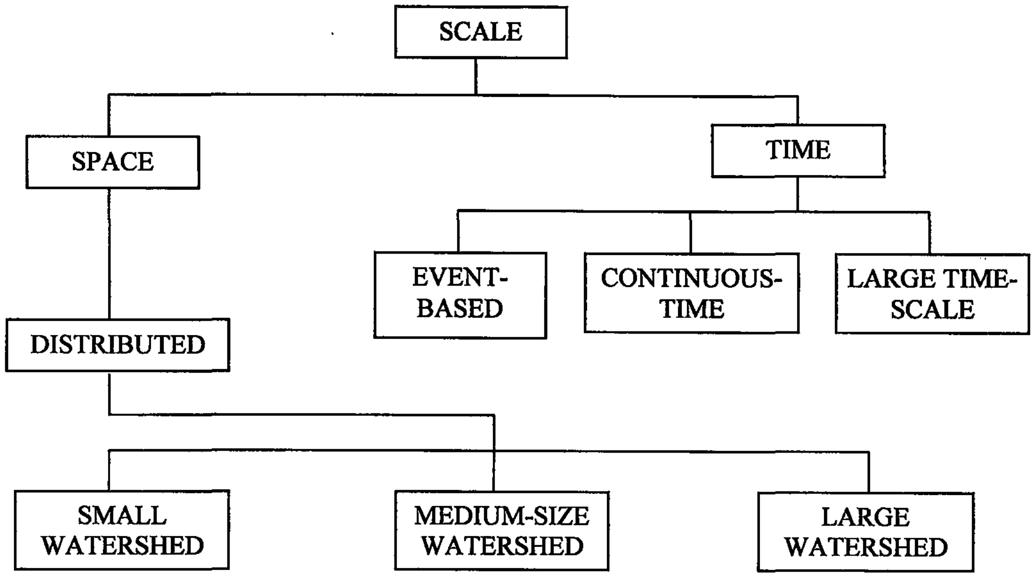
2.3 Classification of Watershed Models

Since the development of the Stanford Watershed Model in 1966 by Crawford and Linsley, there has been a proliferation of watershed models (Renard, et al., 1982; James, et al., 1982; Singh, 1989). The models are of different types and were developed for different purposes. Nevertheless, many of the models share structural similarities, because their underlying assumptions are the same, and some of the models are distinctly different. The watershed models can be classified, as shown in Figure 2.5, according to different criteria that may encompass (a) process description, (b) scale, and (c) technique of solution.



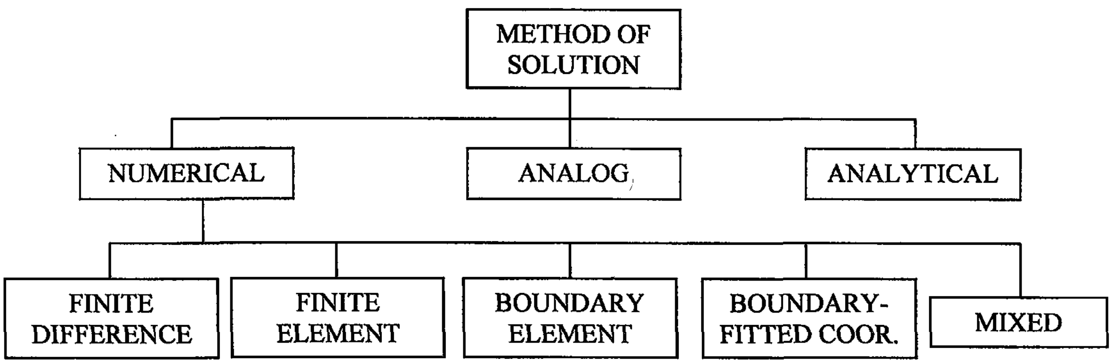
a) Classification of models based on process description.

Figure 2.5 Classification of watershed models (Singh, 1995; Harmancioglu et al., 1998).



b) Classification of models based on space and time scales.

Figure 2.5 (Continued)



c) Classification of models based on solution technique.

Figure 2.5 (Continued)

2.3.1 Process-Based Classification

A model, as shown in Figure 2.6, has five components, including: (1) system (watershed) geometry, (2) input, (3) governing laws, (4) initial and boundary conditions, and (5) output (Harmancioglu et al., 1998). Depending upon the type of the model, these components are variously combined. The processes include all of the hydrologic processes that contribute to the system (watershed) output. Based on the description of those processes, in conjunction with the system (watershed) characteristics, the model can be described as lumped or distributed, deterministic or stochastic or mixed.

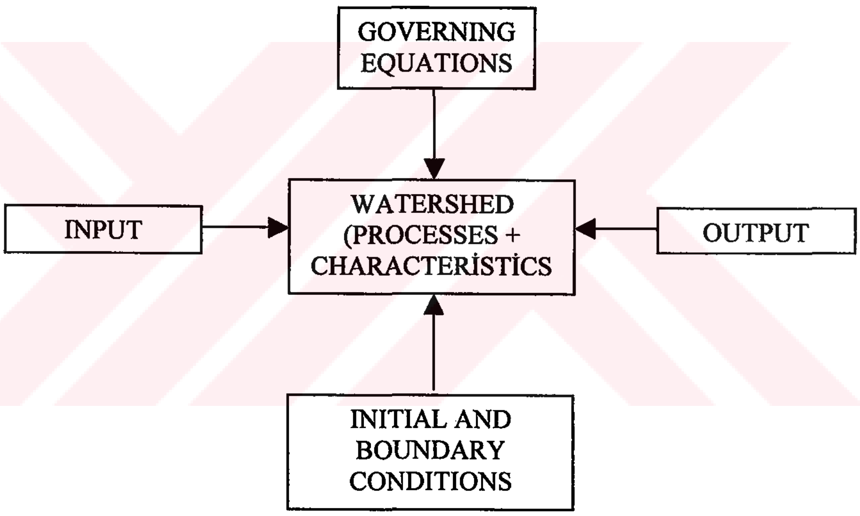


Figure 2.6 Model components.

A lumped model, as shown in Table 2.1, is general by expressed by ordinary differential equations taking no account of spatial variability of processes, input, boundary conditions and system (watershed) geometric characteristics. In most lumped models, some processes are described by differential equations based on simplified hydraulic laws, and other processes are expressed by empirical algebraic equations. Examples of lumped models are HEC-1 (Hydrologic Engineering Center, 1981), HYMO (Williams & Hann, 1972), RORB (Laurenson & Mein, 1983), SSARR (U.S. Army Engineer, 1972), tank model (Sugawara, et al., 1984), among others.

Distributed models, as shown in Table 2.1, take an explicit account of spatial variability of processes, input, boundary conditions, and/or system (watershed) characteristics. Of course, in practice, a lack of data—field or experimental (laboratory) – prevents such a general formulation of distributed models. In a majority of cases, the system (watershed) characteristics are lumped, many of the processes are lumped, the input is lumped, and even some of the boundary conditions are lumped, but some of the processes that are directly linked to the output are distributed, as for example, rainfall-runoff process. These models are not fully distributed; rather they are quasi-distributed at best. Examples of distributed models are SHE (Abbot, et al., 1986a, 1986b), IHM (Morris, 1980), SWMM (Metcalf and Eddy, Inc., et al., 1971), NWSRFS (Hydrologic Research Laboratory, 1972), amongst others.

Table 2.1 Lumped and distributed models (Harmancioglu et al., 1998).

INPUT	SYSTEM CHARACTERISTICS	COMPONENT PROCESSES	GOVERNING EQUATIONS	OUTPUT	MODEL TYPE
Lumped	Lumped	Lumped	ODE	Lumped	Lumped
Lumped	Lumped	Distributed	PDE	Distributed	Distributed
Distributed	Distributed	Distributed	PDE	Distributed	Distributed
Distributed	Distributed	Distributed	PDE	Distributed	Distributed

The description of a process can be either deterministic, stochastic, or mixed. Depending upon the way the processes are described, the models can also be classified as deterministic, stochastic, or mixed (Singh, 1988). If all of the components of a model are deterministic, the watershed model is deterministic. If all of the components of the model are stochastic, the model is fully stochastic, and if only some components are stochastic then the model is quasi-stochastic. When the model components are described by a mix of deterministic and stochastic components, the model is a stochastic-deterministic or hybrid model. A vast majority of the models are deterministic, and virtually no model is fully stochastic. In some cases, only some parts of the model are described by the laws of probability, and other parts are fully deterministic. It is then fair to characterize them as quasi-deterministic or quasi-stochastic.

2.3.2 Time-Scale Based Classification

The watershed models can be classified based on the time scale of models. The time scale can be defined as a combination of two time intervals (Diskin and Simon, 1979). One of the time intervals is used for input and internal computations. The second is the time interval used for the output and calibration of the model. Based on this description, the models can be distinguished as a) continuous-time or event based, b) daily, c) monthly, and d) yearly models. This classification is dictated by the interval of computation. If the model components are available at shorter time intervals, such as hourly interval or shorter, the model will be a short-interval model. Of course, the choice of a time interval is often a function of model's intended use.

2.3.3 Space-Scale Based Classification

The spatial scale can be used as a criterion to classify models into small-watershed, medium-size watershed, and large watershed models. Of course, the definition of a small watershed is somewhat vague. Usually, the watershed with area of 100 km^2 or less can be called small, those with area of 100 to 1000 km^2 medium, and those with area of larger than 1000 km^2 large. Such a classification is arbitrary, and is experimental rather than conceptual and is governed by data availability rather than physical meaning. The essential point is the concept of homogeneity and averaging of hydrological processes. For consideration of runoff generation on these watersheds, two phases can be considered; land phase and channel phase. Each phase has its own storage characteristics. Large watersheds have well-developed channel networks and channel phase, and thus, channel storage is dominant. Such watersheds are less sensitive to short duration, high intensity rainfalls. On the other hand, small watersheds have dominant land phase and overland flow, have relatively less conspicuous channel phase, and are highly sensitive to high-intensity, short-duration rainfalls.

If all three types of watersheds are spatially uniform, then they will behave hydrologically similarly. Under this condition, classification of watersheds serves no useful purpose and becomes moot. If a watershed is homogeneous with respect to its characteristics, then it is called a small watershed. In reality, though, watersheds are seldom homogeneous, therefore, homogeneity is defined in an average or statistical sense. For example, for a subsurface environment if the average of logarithmic values of the hydraulic conductivity is the same, the aquifer may be considered homogeneous. Similarly, if the average system characteristics do not change, then the watershed may be considered small. For medium-size watersheds, the heterogeneity is present but it is in the medium range (± 2 standard deviation around the mean), whereas it is quite large for large watersheds. Even if a watershed is homogeneous in one characteristic, it may not necessarily be homogeneous in another characteristic. In that sense, both the soil and land use characteristics are important. Strictly speaking then no watershed may be small; all will be either large or medium.

2.3.4 Land-Use Based Classification

Based on land use, watersheds may be classified (Singh, 1992) as : a) agricultural, b) urban, c) forest and range land, d) desert, e) mountainous, f) coastal, g) wetlands, and h) mixed. In many cases, large or even-medium-size watersheds have mixed land use. These watersheds behave hydrologically differently, indeed so differently that they have given rise to different branches of hydrology. For example, treatment of agricultural watersheds constitutes what is called agricultural hydrology. Similarly, there is urban hydrology for urban watersheds, coastal hydrology for coastal watersheds, forest hydrology for forest watersheds, desert hydrology for desert watersheds, wetland hydrology for marshes and wetlands, and mountain hydrology for mountainous watersheds. The soils, geology, and vegetation are different for these watersheds. As a result, the hydrologic processes are different in their evaluation in these different watersheds, and hence their models are clearly different.

2.3.5 Model-Use Based Classification

Frequently, watershed models are classified on the basis of their intended use: a) planning models, b) management models, and c) prediction models. A comprehensive watershed model can be employed to accomplish a considerable array of analytical tasks for planning and management of water resources. It offers the opportunity for systematic analysis of a management policy. On the other hand, it becomes an increasingly valuable predictor of river-basin response to management strategies. For planning purposes, the model defines geographical and temporal trends that may not be accurate at specific sites in the river basin. Thus, the primary use of a planning model is for analyses of river systems management strategies. The larger issues related to basin-wide trends and plans need to be analyzed to determine if there exist site interactions. Once these interactions are determined, a site-specific analysis can be performed with greater accuracy, perhaps with use of a prediction model. Probably the most powerful feature of a planning and management model is the ability it offers planners and managers to replace past management indices with improved economic performance measures of potential decisions.

2.4 Scaling and Its Effects

Song and James (1992) reviewed five scales used in hydrologic simulation: 1) laboratory scale, 2) hillslope scale, 3) catchment scale, 4) basin scale, and 5) continental scale. The laboratory-scale models use hydrodynamic equations and are often one-dimensional. The hillslope-scale models combine surface and subsurface flows, may include preferential flow through soil pores, and may be two-dimensional or even three-dimensional. The catchment scale models add topography in simulation of surface runoff and geology in simulation of baseflow, and often divide larger catchments into smaller homogeneous parts. Basin-scale models employ storage and translatory routing schemes in combining catchment runoff. Continental- and global-scale models focus on atmospheric processes and their interactions with land-surface processes.

Scaling and its effects are tied to heterogeneity. At smaller scale, heterogeneity is small and it is large at large scale. Clearly, it is the greatest at the continental or global scale and the smallest at the laboratory scale. This heterogeneity can be traced to three sources. First, weather, climate, topography, soils and geology are the principal sources of heterogeneities. Hydrologic heterogeneity is further accentuated by the differences in the factors that control hydrologic processes of rainfall, interception, evaporation, infiltration, baseflow, and runoff. These factors may include physical properties such as trees, ridges in the ground surface, geometry of soil layers, and so on.

The hydrologic models use parameters to represent watersheds as a whole, whereas data on watershed characteristics are collected at a number of field locations and are difficult to transform into a collective measure. The question then arises as to scale that is best suited for hydrologic simulation. As the spatial scale changes from a small area to a large area, the watershed response becomes less sensitive to spatial variations of input as well as system characteristics. On the other hand, greater heterogeneity suggests smaller optimal scales. This spatial extent, however, is constrained by the differences in physical, vegetative, and topographic features that can cause the pattern of hydrologic response to vary. This, then, leads to defining a scale as the size of a unit or a subwatershed within which the hydrologic response can be treated as homogeneous. This scale must not be too small to be dominated by local physical features, nor so large as to ignore significant hydrologic heterogeneity caused by spatial variabilities of watershed characteristics. The optimal scale in a watershed is determined by the collective working of multiple processes that generate hydrologic response and the availability of hydrologic data.

2.5 Perspective on Model Building

Construction of a computer model of watershed hydrology may be driven by the need to solve a particular problem or the scientific pursuit of model building which may or may not be used for problem solving. Frequently, the type of a model to be built is dictated by the availability of data. Different models have different data needs. In general, distributed models require much more data than do lumped models. In most cases, needed data either do not exist or are not available in full. That is why regionalization and synthetic techniques are useful. Even if the needed data are available, problems remain with regard to incompleteness, inaccuracy, and inhomogeneity of data. Then, of course, storage, handling, retrieval, analysis, and manipulation of data have to be dealt with. If the volume of data required is large, data processing can be quite a sophisticated undertaking.

A watershed hydrology model is an assemblage of component models corresponding to different components of the hydrologic cycle. The time scale of model output (e.g., streamflow) greatly influences the type of the model or the details to be included in the model. For example, a monthly watershed model is quite different in its architecture and construction from, say, an hourly model. Thus, the elements of simulation differ with the model type. It remains an unresolved question as to the hydrologic laws operating at different time scales for different components of the hydrologic cycle. Solution of this question will greatly facilitate model construction and more clearly define the data needs.

After a model is developed, it needs calibration, verification, and an assessment of its reliability. Model calibration involves optimum parameter estimation subject to a specified error criterion. Usually the available data is split into two halves, one for calibration and the other for verification. The calibration set should encompass the full range of data variability that may be expected in verification. A range of fairly sophisticated parameter estimation techniques are available. However, it is not clear how a model's parameter changes with variation in the objective function. Furthermore, an error analysis of calibration results is to be performed. Through this analysis, it can be ascertained if the errors are due to errors in data, parameters, or model construction. Model verification and reliability of model results are essential to show if a model is any good.

2.6 Application of GIS

Geographical Information Systems (GIS) are computer based tools that store, analyze, retrieve, manipulate and manage large amounts of spatial data. They are spatial data-base management techniques. Originally these tools were developed to ease cartography, but are being used these days for inventory analysis, estimation, planning, and modeling (Fıstıkoglu, 1995).

Watershed modeling requires accurate and representative data. Collection, storage, and manipulation of the required data can be cumbersome for three reasons:

a) Spatial nature of hydrologic data,

b) Large volumes of data, and

c) Organization of data.

However, through the use of a geographic information system and the associated software, such data can be compiled and processed with relative ease. The watershed and hydrology are inherently spatial. The physical characteristics of the watershed such as soils, land use and topography vary spatially. In distributed watershed models, these characteristics can be used directly. However, the watershed will have to be spatially characterized into homogeneous sub-areas. To that end, the traditional data file structure is less than troublefree. Clearly, a general-purpose spatial data analysis and manipulation tool will be desired.

Distributed watershed models, especially numerical models, require large volumes of data. A hydrologic unit is characterized by many data, including those on topography, land use, soils, geology, climate, and so on. On the other hand, the various application programs may require the same data stored in different files, thus creating storage redundancy within the traditional file structure system.

Hydrologic data are arranged in a variety of formats and stored on various media. It is often difficult and tedious to transform and manage these data. Furthermore, because many models have different data requirements, a collection program tailored to the demand of a particular model can not be used for another with differing data requirements. Consequently, a separate collection program has to be developed and data transformation then has to be undertaken for each model. These data problems can be resolved through application of a GIS. Its ability to extract, overlay, and delineate watershed characteristics permits integration with watershed models. Design, calibration, modification, and comparison of these models can be significantly facilitated by use of the GIS. However, the application of GIS technology to watershed modeling requires careful planning and extensive data manipulation, involving three major steps:

1) Spatial data construction,
2) Integration of spatial model layers, and
3) The GIS and model interface

With ever increasing volume of data available from many sources, the first step is time consuming. The second step is becoming less tedious due to advancing GIS capabilities in that a series of spatial overlaying and/or projecting procedures can be derived yielding the final modeling layer. The last step involves actual programming for interfacing GIS with watershed models.

Although, large quantities of data can be efficiently manipulated in time by using a GIS, certain limitations need to be recognized. First, building the database is expensive and time consuming. Also, appropriate data may be another problem, and making up for deficiencies in data is quite difficult with a GIS. Unless the same database can be used in a variety of analyses or models, the use of a GIS may not be cost-effective. However, with increasing complexity of investigations or models involving more data and more complex data processing, a GIS may indeed be cost-effective. The PC based GIS innovations have greatly cut down the cost and are more affordable now. A successful GIS application calls for data accuracy, data integrity (also called referential integrity), and multiple attributes capability. A GIS package should have a relational database management system (DBMS) that provides both logic and physical data independence.

A GIS may be either raster-based or vector based. A raster based GIS is more storage efficient than a vector based GIS. The larger the coverage, the greater the storage space used by a vector based GIS. The processing speed of a vector based GIS is slower and can be an important consideration if extensive spatial processing is needed for a watershed model (Fistikoglu, 1995).

Construction of an appropriate GIS database is the most difficult and expensive undertaking for watershed modeling. There exist large volumes of data on soil, geology, land use, vegetative cover, and so on in digitized form. However, there are problems with many of the existing digital data bases:

1) They are in different formats,
2) They use different coordinate (projection) systems,
3) They are too coarse for in 2-D or 3-D watershed models.

Integration of GIS with watershed modeling accomplishes a number of significant hydrologic functions: designing, calibrating, modifying, and comparing watershed models. The use of a GIS permits subdividing a watershed spatially into hydrologically homogeneous sub areas. Depending upon the type of application requiring categorization of hydrologic properties, many combinations of spatial overlay can be performed. With this technique, it is possible to delineate areas of varying soil loss rates (Ventura, et al., 1988), identify potential areas of non-point source agricultural pollution (Schmidt, 1987; Fistikoglu, 1995), map groundwater contamination susceptibility (Whittermore, et al., 1982), and so on. GIS improves the ability to incorporate spatial details beyond the existing capability of watershed models. With much better resolution of terrain streams and drainage areas the ability to delineate more appropriate grid layers for a finite element watershed model is enhanced.

CHAPTER THREE

DISTRIBUTED WATERSHED MODELING

3.1 General

The physical environmental factors that control hydrological processes vary greatly across space. For example, hydrological properties of soil are characterized by a high degree of spatial heterogeneity across a broad range of spatial scales starting at the sub-meter scale. Precipitation, land cover, and topography also generally vary to different degrees over sub-watershed scales. As all of these factors impact hydrology, if their spatial distribution is explicitly incorporated into the simulation, the model should be more accurate.

Hydrological models have historically been developed independent of Geographic Information Systems (GIS), partly because of the relatively recent appearance of GIS and partly due to computational requirements (EPA, 1987). With the advent of GIS, software which uses topology to relate surface features in a geographic projection, a number of attempts have been made to link or integrate it with hydrological models.

3.2 Spatially Distributed Modeling

Nielsen et al. (1973) present findings from a study performed on a single 150 ha. field where the spatial variation of particle size, distribution and bulk density within the field was considered homogenous enough to be within the permitted limit of a single mapping unit. However, the steady infiltration rate varied considerably over the field with values ranging from 0.5 to 45.7 cm/day. And the steady hydraulic conductivity range was observed to be between 1 to 100 cm/day. They concluded that the use of hydrological parameters treating the field as a single unit was not appropriate.

Beckett and Webster (1971) showed that soil Nitrogen and Organic Matter, factors that are all affected by soil hydrological properties, vary considerably within a single field. Sharma et al. (1980) performed a series of twenty six infiltration tests in a single watershed. Results indicated that there was no obvious pattern of distribution of infiltration parameters according to soil type or location within the watershed. They conclude that, due to large variability within soil units of the watershed, delineation of hydrologically homogenous zones is not warranted. Rogowski (1972) stated that if the coefficient of variation exceeds 15% then spatially distributed parameters should be employed. Sharma et al., (1980) showed that coefficient of variation for the various soils tested never fell below fifteen percent for the soils tested. Thus, soils vary significantly at a scale well below that of the field. Being able to represent this spatial heterogeneity would improve the accuracy of detailed hydrological simulations.

Beven and Wood (1983) examined the effects geomorphology has on determining surface runoff. Employing a series of different runoff estimation functions that are keyed to different geomorphologies, they showed that runoff and flooding frequency can be very sensitive to model parameters especially when the catchment basin is geomorphologically complex. Wood et al. (1988) in a subsequent study showed that runoff estimates are very sensitive to the size of the area being averaged (irregular polygonal subbasins in their study, pixel size in the case of a rasterized database, or entire basins in the case of a spatially averaged model) because of topography effects. Rodriguez-Iturbe and Valdes (1979) and Hebson and Wood (1982) also illustrated the importance of accurately representing the geomorphology of the basin and developed a series of models that parameterize basins specifically on these factors. Given the sensitivity of models to physiographic parameters, representing complex basins in a spatially distributed manner should improve simulation results.

Using a land cover classification derived from remotely sensed data in conjunction with a relatively simple curve number based hydrological model, Blanchard (1975) improved runoff estimation. Tao and Kuowen (1989) compared a spatially averaged surface runoff model with a spatially distributed one with respect to land cover, all other factors held constant. The spatially distributed model had land cover derived from a classification of remotely sensed data. The distributed runoff model was shown to improve the estimation of flow when compared against observed data. Incorporating the spatial location of varying land covers yields better model results.

Perry and Shafer (1990) compared a spatially averaged hydrological model with a spatially distributed one with respect to precipitation, all other model parameters were held constant. The results of their study showed that spatially averaged rainfall is suitable for small basins only if discharge at the basin outlet is to be considered. If the interior basin hydrology is to be considered, which is usually the case for water resource management, then spatially varying precipitation data is considered more appropriate.

With hydrological properties that vary considerably at the field scale, the need to incorporate spatially distributed parameters into watershed scale models for management purposes becomes evident. While the typical soil experiences fifty percent of the coefficient of variation within a single square meter (Sharma, 1980), spatially explicit distribution offers an improvement over complete spatial averaging. Explicit consideration of the spatial distribution of soils, land cover, and precipitation are critical to developing more accurate hydrological models.

3.3 Linking GIS and Hydrological Models

Some currently available linkages of GIS and hydrological models are arranged so that the GIS and the model are linked with a one way transfer of data where the GIS data are typically averaged by basin for input into the model (Cruise & Miller, 1993; Donigian et al., 1994, Greene & Cruise, 1995). GIS data are usually spatially averaged (values over the entire hydrological unit are averaged for the hydrological unit of interest to a single value) previous to transfer for the determination of parameter values for a model that runs independent of the GIS. More recent attempts do allow for the distributed GIS data to be input directly to the model without averaging. Beven and Kirkby (1979) presented an application of a variable contribution area model called TOPMODEL. This model uses rasterised elevation data to perform runoff estimations based on relatively simple calculations. Basin catchment area, precipitation volume and average slope are used to estimate basin mouth outflow volumes for runoff events. Spatially averaged parameters represent soil water response with a constant infiltration rate and an exponential subsurface store. The subsurface volume of water simply accumulates and is considered non-contributing to outflow volume for the period of the storm. While the parameters are spatially averaged, the model will allow the simulation of a series of sub-basins with independent parameters. An improvement on this model was subsequently presented by Beven and Kirkby (1983). The improvement incorporates contribution from subsurface flow, previously considered to be an insignificant source to storm peak flow.

The Systeme Hydrologique Europeen (SHE) is a physically based, spatially distributed hydrological model that simulates the complete hydrological cycle on a long-term basis for surface and subsurface flow (Abbott et al., 1986). SHE employs parameters to calibrate finite difference calculations for mass balances and estimates derived from empirical equations. However, it does not operate in conjunction with a GIS, and it relies on a standard rasterised neighborhood flow algorithm. The Florida Institute of Phosphate Research created a hydrological model and GIS integrated package where the GIS is used as a data input tool as well as model integrator (Ross and Tara, 1993). The model package incorporates a surface water runoff model and an independent groundwater flow model. The GIS acts as a spatial averaging tool for data input into the surface flow model segments. Surface flow model output is spatially averaged to the groundwater flow model resolution via the GIS. After a model run is completed, the GIS is then used to present the calculated output. In this case, the GIS is used for spatial averaging, data formatting and output visualization. The GIS is well integrated with the models, but calculations are performed on spatially averaged parameters and data. Models such as these are an improvement, but are still limited to the developers' dictates as the user has little or no control over which parameters and data sets are distributed or averaged. A complete integration of GIS and hydrological models also has the advantage of enabling the use of the GIS in a vertical (multiple stacked georeferenced data layers) as well as horizontal (iterative surface flow) manner.

GIS based models have also been developed independent of hydrological models such that hydrology is implicitly represented. These models use multiple data layers as input to regression estimates of surface runoff and their constituents. Tim et al., (1992) presented a vertical GIS model developed to estimate non-point pollution runoff without directly simulating the hydrological cycle. Various soil parameters are employed to estimate edge of stream sediment and adsorbed phosphorous loads under varying conditions. The spatially distributed parameters appear in a series of GIS data layers and are used in relatively simple, empirically derived equations. No surface flow, transportation, or neighborhood (horizontal) analysis are incorporated into the model; thus the model is vertically but not horizontally integrated. This type of GIS model is complementary to the stand alone hydrological model in that it takes into account spatial location but does not simulate horizontal flow, where the typical hydrological model does not take into account spatial location but does simulate horizontal flow.

Hydrological models and GIS are natural partners which have become increasingly connected over time. Single event, surface flow models have been completely integrated within a GIS for the purposes of flood prediction. All of these to date employ conventional surface routing techniques which yield unrealistic flow patterns. Some management and decision making models have become linked with GIS, using it as a data input or for visualization of output.

The complete integration of GIS and numerical simulation will allow hydrological models to branch into a new phase of applications in management and decision making. Rather than broadly generalizing surface features within watersheds as has previously been done, hydrological models will now be able to take full advantage of spatially distributed databases by allowing the user to set the spatial and temporal scale of input data and simulation. Managers will be able to test the efficacy of forest buffers, and the width necessary for a specific location to have the desired impact on runoff water quality. Land use changes under specific conditions can be simulated previous to development to test the relative impacts of various plans. Urban or agricultural best management practice applications can be tested based on soil types, surface slope, crop specifics and a host of other data currently available in GIS layers. The impact of various development plans on local hydrology can be vigorously tested before the decision to approve or reject the plan is made. Overall, it will allow managers to analytically compare proposals previous to decision making on issues that can be costly on many different levels. In addition, data processing and plotting tools are already available to the modeler through the GIS with a minimum of custom programming.

The complete integration of a multi-event, time variable, surface and subsurface flow, spatially distributed, hydrological model with realistic routing patterns with a GIS is the logical next step in the development of hydrological models.

3.4 Constraints For Applications of Distributed Hydrological Models

Nevertheless, in spite of two decades of modeling development, distributed hydrological models are today being used in practice only at a fraction of their potential. The reasons of this situation can be evaluated in the following headings.

3.4.1 Data Availability

The prerequisite for making full use of the distributed models is the existence and easy accessibility of a large amount of data, including detailed spatial information on natural parameters such as geology, soil and vegetation and man-made impacts such as water abstractions, agricultural practices, and discharge of pollutants.

In many cases, all such relevant data do not exist and even the existing data are most often not easily accessible due to the lack of suitable computerized data bases. A further complication in this regard is the administrative problem created by the fact that these models, in addition to the traditional hydrometeorological data, require and can make use of many other data sources, such as those arising from agricultural, soil science and geological investigations.

Thus, distributed models have had to work with such data as happens to be available, which are rarely if ever collected with a view to their compatibility with distributed hydrological modeling activities. Hence, most distributed model codes are able to run with different levels of data availability, and indeed in many cases (topographic data, vegetation maps, etc.) are only means whereby this data can be introduced directly into decision-making processes.

For many years, high expectations have been directed to remote sensing techniques for providing spatial data for use in distributed hydrological models.

However, so far, the operational use of remote sensing data are, with the exception of satellite-inferred snow cover data and land use/vegetation mapping, not common practice. With the launching of new satellites in recent years, improved possibilities arise and there are now good reasons to expect the long awaited break-through for large scale operational applications of remote sensing data jointly with distributed hydrological models.

3.4.2 Lack of Scientific-Hydrological Understanding

With the introduction of a new modeling paradigm and concurrent research in process descriptions, new shortcomings in the scientific-hydrological understanding have emerged, especially with regard to flow, transport and water quality processes at small scales and their up-scaling to describe larger areas. These scientific shortcomings have, on the one hand, constrained the practical applications of distributed hydrological models and, on the other hand, the existence and application of such models have put a new focus on some of these problems, thus contributing to advances in the scientific-hydrological understanding.

3.4.3 Traditions in Hydrology and Water Resources Engineering

The distributed model codes constituted a "quantum jump" in complexity as compared to any other code so far known in hydrology. Moreover, they used technologies, such as had been developed in computational hydraulics, with which few hydrologists were familiar. Although the numerical-algorithmic problems could be largely overcome by development of the codes into user-friendly fourth generation modeling systems with well proven algorithms, the problem was then shifted back to one of comprehending the fully integrated complexity of the physical system that was being modeled together with the constraints that were inherent in the modeling procedure. Very few professional engineers and managers were, and still are, educated and trained with the necessary integrated view of hydrological process in anything like their real physical complexity.

This difficulty is exacerbated by the very nature of hydrology itself, whereby most professionals posses only limited view on the totality of the physical processes. Soil physicists, plant physiologists, hydrogeologists and others usually have only a very partial view on the whole system, while there are few organizations that have available both the full range of such specialists and more broader-ranging professionals that are needed in many situations to exploit the potential of distributed codes to such a degree that this exploitation is economically justified.

CHAPTER FOUR

CONSTRUCTION, CALIBRATION AND VALIDATION OF HYDROLOGICAL MODELS

4.1 Sources of Uncertainty in Hydrological Modeling

4.1.1 Deterministic Modeling Concept

The concept of deterministic mathematical modeling can be illustrated as in Figure 4.1, where the physical system, in this case a catchment, is shown to the left. The mathematical model, which is the sign-representation of the physical system is shown to the right. Both the quantification of the physical system through monitoring and the representation through mathematical modeling are subject to errors.

The temporal and spatial variability of inflows, outflows and internal conditions are quantified from measurements at discrete locations. Unfortunately, these measurements alone can neither provide us with any complete picture of the conditions inside the catchment area nor an understanding of the mass, energy and other exchanges between the catchments and its surroundings. Firstly, because it is not feasible to measure all the spatial and temporal variations of flows and state variables, and secondly because, the measurements include errors. Consequently, the model will be using an approximate dataset which to some degree contains sampling errors. On the other hand, by definition, the physical system experiences the real data and responds to this real input. However, the response is measured with some uncertainty.

When the hydrological model is used to simulate the behaviour of the physical system, it produces output data, which is affected by the approximate input data. In order to test the accuracy of the developed model, simulated output is then compared with the recorded data which also is subject to uncertainties. A desired model accuracy is achieved by changing the parameter values used in the model until a satisfactory agreement between simulated and the recorded variables is obtained. This parameter adjustment process is the process of calibration.

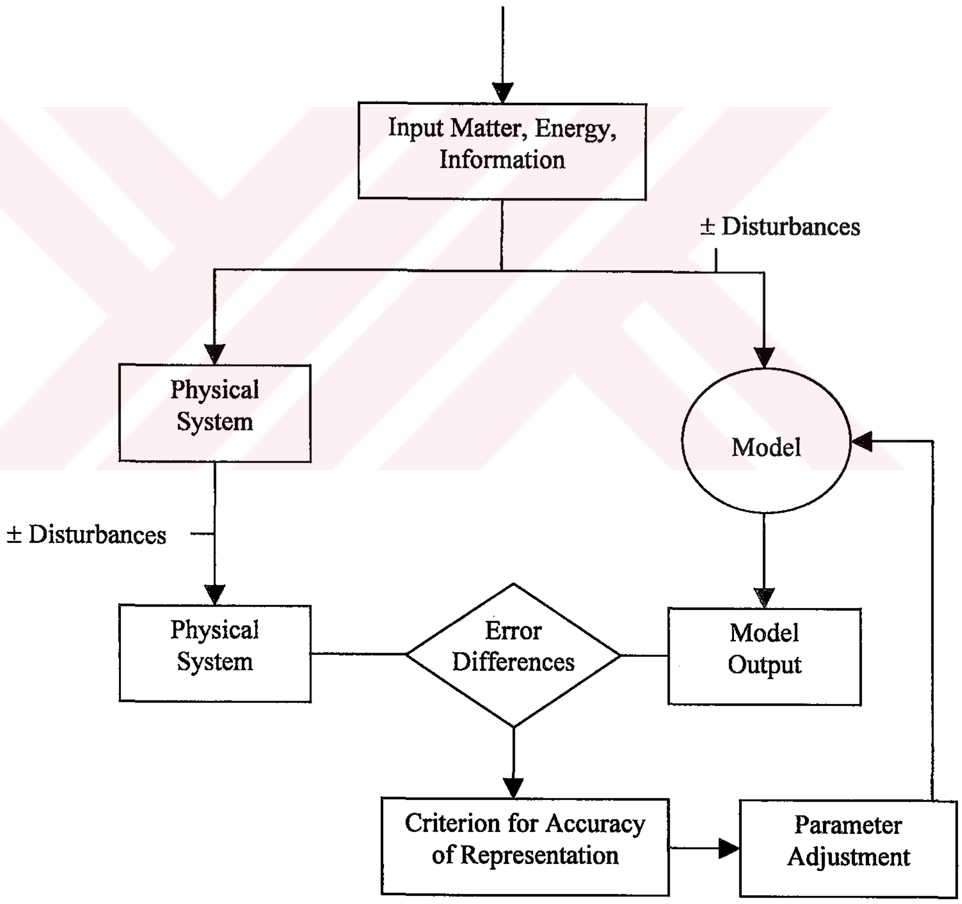


Figure 4.1 The concept of deterministic mathematical modeling (Fleming, 1975).

4.1.2 Sources of Uncertainty

Differences between recorded data and simulated model output arise basically from four sources of uncertainty.

1. Random or systematic errors in the input data, i.e. precipitation, temperature and evapotranspiration etc. used to represent the input conditions in time and space over catchment.
2. Random or systematic errors in the recorded data, i.e. the river water levels, groundwater heads, discharge data or other data used for comparison with the simulated output.
3. Errors due to non-optimal parameter values.
4. Errors due to an incomplete or biased model structure.

Although a disagreement between simulated and recorded data is the combined effect of all four error sources, only error source (3) can be minimized during the calibration process. The measurement errors, error sources (1) and (2), are the "background noise" which determine the maximum achievable agreement, which modeler can hope to obtain. Changes in parameter values or model structure cannot and should not improve the results beyond that. The objective of a calibration process is therefore to reduce the error source (3) until it becomes insignificant compared to the data error sources (1) and (2).

During a calibration process, it is of utmost importance to ensure that a clear distinction is drawn between the different error sources, so no attempt is made to compensate for errors from one source by adjustments within another source, such as compensating for a data error by parameter adjustments. Otherwise, the calibration will approach curve fitting, which may result in a reasonable fit within the calibration period but may incidentally provide unreliable predictions.

It is also important that the modeler recognizes the limitations of a chosen modeling approach and does not try to impose a certain conceptual representation of the physical system because it fits to the mathematical formulation in the model code applied.

4.2 Goodness of Fit and Accuracy Criteria

During the calibration procedure, different accuracy criteria can be used to compare the simulated and measured data. This allows us to define an objective measure of the goodness of fit associated with each set of model parameters and estimate the parameter values which provide the best overall agreement between model output and measured data. However, the selection of an appropriate criterion is complicated by variation in the sources of error discussed in the previous section. It further depends on the objective of the model simulation (e.g. to simulate flood peaks or low flows) and on the type of information available to check model output variables, such as phreatic surface levels, soil moisture contents, stream discharges, or stream water levels.

No single criterion is entirely suitable for all variables, and even for a single variable, it is not always easy to establish a satisfactory criterion. Hence a large number of different criteria has been developed. Green and Stephenson (1986) discussed the problem in detail and listed 21 approaches which can be used for single-event simulations depending on the simulation objectives, range of simulation conditions and other factors. Criteria for the detection of systematic errors relevant to long-term simulations are discussed by Aitken (1973).

It is possible to calibrate a model by optimizing just one criterion. However, a calibration based on a blind optimization of a single numerical criterion can produce physically unrealistic parameter values which, if applied to a different time period, may give poor simulation results. Green and Stephenson (1986) concluded that no single criterion is sufficient to assess adequately the overall measure of fit between a computed and an observed hydrograph, particularly in view of the many objectives behind hydrological modeling. At the same time, it should be remembered that the criteria measure only the correctness of the estimates of the hydrological variables generated by the model and not the hydrological soundness of the model relative to the processes being simulated. It is therefore recommended that, in a calibration, numerical criteria be used for guidance only.

Finally, the benefit of using graphical comparison of e.g. simulated and observed hydrographs should be emphasized. Although the analysis becomes more subjective, graphical comparisons provide a good overall indication of the model capabilities, they are more easily assimilated and may impart more practical information than statistical functions alone. Figure 4.2 illustrates the combined use of numerical and graphical comparisons of runoff data. In the figure, the flow duration curve error index, EI is a numerical measure of the difference between the flow duration curves of the simulated and observed daily flows (perfect agreement for EI=1). Similarly, R2 refers to the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970), computed on the basis of the sequence of observed and simulated monthly flows.

4.3 Model Construction

Model construction is the process of preparing the data in a correct format and entering them into a set of input data files required by the model code so that the first model run can be made as the first step in the subsequent model calibration.

For lumped conceptual model codes or similar type of model codes, which only require few parameter values for a set of empirical equations, the model parameters can generally not directly be estimated from catchment characteristics, but must be estimated through calibration. The data requirements are therefore very small and the data preparation is usually confined to construction of data files containing time series of climatic input data and a corresponding time series of control data e.g. river discharges. These can usually be prepared very quickly.

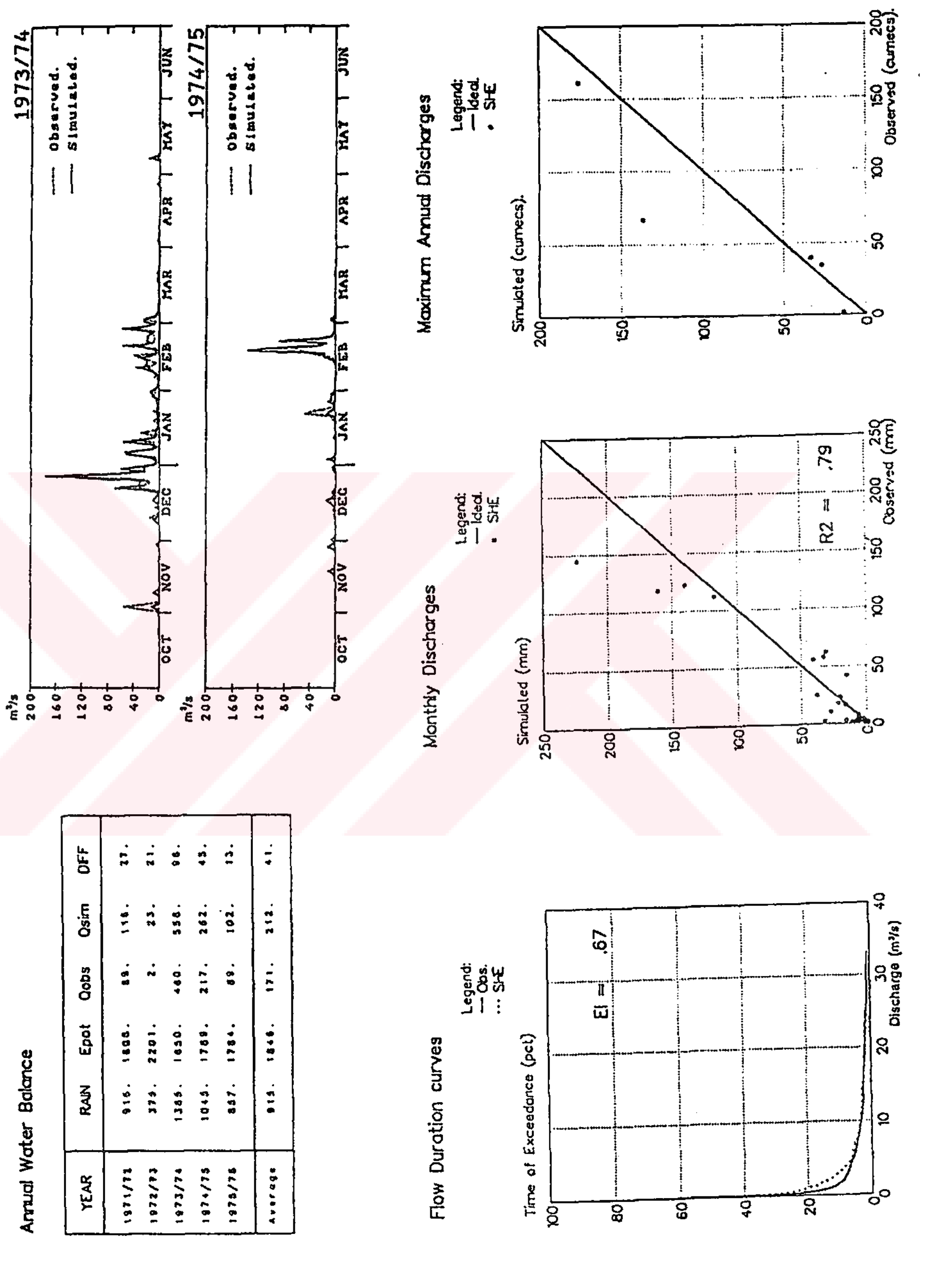


Figure 4.2 Example of the combined use of numerical and graphical criteria. Example from proxy-basin validation test of MIKE SHE to the Lundi catchment in Zimbabwe (DHI, 1993)

For distributed models, the data preparation phase is more complicated and involves often a comprehensive program of work. A fully distributed model contains only parameters which can be assessed from field data, so that, in principle, a calibration would not be necessary if sufficient data were available. In practice, distributed model codes are most often applied at scales on which the parameter values cannot be directly assessed and will therefore require calibration. In the subsequent calibration phase, allowed parameter variations may be restricted to relatively narrow intervals compared to parameter values related to the empirical functions in empirical or lumped conceptual models.

Distributed models describe the spatial variations in catchment characteristics and input data in a network of grids points. In order to provide a sufficient detail, the spatial resolution often requires several thousands of grid points, each of which is characterized by one or more parameters. Although the parameter values in principle (as in nature) vary from grid point to grid point, it is neither feasible nor desirable to allow the parameter values to vary so freely. Instead, a given parameter should only reflect the significant and systematic variation described in the available field data, as exemplified by the practice of using representative parameter values for individual soil types, vegetation types or geological layers. This process of defining the spatial pattern of parameter values, which is denoted as "*parameterization*", effectively reduces the number of free parameter coefficients which need to be adjusted in the subsequent calibration procedure.

An example of a parameterization procedure used for constructing SHE models for catchments in India is presented in Refsgaard et al., (1992) and Jain et al., (1992). As an example the 820 km^2 Kolar catchment is parameterized into three soil classes and 10 land use/soil/depth classes. For the soil type classes calibration was allowed for the hydraulic conductivity in the unsaturated zone (for each soil type class the conductivity could vary among three different land uses =>nine parameter values). For the land use/soil depth classes, the calibration parameters comprised soil depths (10 parameters in total) and the Strickler overland flow coefficients for four land use types (four parameters in total). Further, three parameters were subject to calibration (hydraulic conductivity in the saturated zone, an (empirical) by-pass coefficient and a surface retention parameter; all kept constant through the catchment). Although the 26 calibration parameters could not be assessed from field data alone, but had to be modified through calibration, the physical realism of parameter values resulting from the subsequent calibration procedure could be evaluated from available field data.

An example of parameterization procedure for combined groundwater/surface water model for an 800 km^2 area near Aarhus, Denmark is given by Refsgaard et al., (1994).

A rigorous parameterization procedure is crucial in order to avoid methodological problems at the subsequent phases of model calibration and validation. The following points are important to consider in the parameterization procedure.

- The parameter classes (soil types, vegetation types, climatological zones, geological layers, etc.) should be selected so that it becomes easy, in an objective way, to associate parameter values. Thus, the parameter values in the different classes should, to the highest possible degree, be assessable from available field data.
- It should explicitly be evaluated as to which parameters can be assessed from field data alone and which need some kind of calibration. For the parameters subject to calibration, physically acceptable intervals for the parameter values should be estimated.
- The number of real calibration parameters should be kept low, both for practical and methodological points of view. This can be done, for instance, by fixing a spatial pattern of a parameter and allowing its absolute value to be modified through calibration.

4.4 Calibration Methods

In a calibration procedure, values are estimated for those parameters which can not be assessed directly from field data. In principle, three different calibration methods can be applied:

1. Trial-and-Error, manual parameter adjustment
2. Automatic, numerical parameter optimization
3. A combination of (1) and (2).

In the following section, the three methods as well as their advantages and disadvantages are described. The specific status of calibration techniques within the areas of lumped conceptual and distributed modeling are summarized in the further sections.

4.4.1 Trial-and-Error Manual Calibration

The trial-and error method implies a manual parameter assessment through a number of simulation runs. This method is by far the most widely used and is the most recommended method, especially for more complicated models. A good graphical representation of the simulation results is a prerequisite for the trial-and error method.

4.4.2 Automatic Parameter Optimization

Automatic parameter optimization involves the use of a numerical algorithm which finds the extremum of a given numerical objective function. The purpose of automatic parameter optimization is to search through as many combinations and permutations of parameter levels as possible to achieve the set which is the optimum or "best" in terms of satisfying the criterion of accuracy.

The advantages of automatic parameter optimization over the trial-and error method are;

- Automatic optimization is fast, because almost all work is carried out by the computer.
- Automatic optimization is less subjective than the trial and error method, which to a large degree depends on visual hydrograph inspection and the personal judgment of the hydrologist.

The disadvantages of automatic parameter optimization include;

- The criterion to be optimized has to be a single numerical criterion based on a single variable. As discussed in Section 4.2, though, the selection of an appropriate criterion under these constraints is a complicated and, in turn, often quite subjective task.
- If the model contains more than very few parameters, the optimization will probably result in the location of a local optimum instead of the one.
- Most theories behind the search algorithms assume that the model parameters are mutually independent. This assumption is usually not justified.
- An automatic routine cannot distinguish between the different error sources mentioned in Section 4.1. Accordingly, an automatic optimization algorithm may try to compensate, for example, for data errors by parameter adjustments, with the result that the parameter values often become physically unrealistic and give poor simulation results when applied to a period different from the calibration period.

To these purely technical considerations may be added a more general one (Todini, 1988). To calibrate the parameters of a model by the optimization of an objective function means adopting some statistical technique (least squares, linear or non-linear regression, maximum likelihood, etc.) based on analysis of residuals, while the procedure of automatic calibration, rather than capitalizing on prior knowledge intrinsic to the structure of the model, avoids it, and thus emphasizes the uncertainty inherent in every statistical analysis.

4.4.3 Combination of Trial-and-Error and Automatic Parameter Optimization

A combination could involve, for example, an initial adjustment of parameter values by trial-and-error to delineate rough orders of magnitude, followed by a fine adjustment using automatic optimization within the delineated range of physical realistic values. The reverse procedure is also possible: first carrying out sensitivity tests by automatic optimization to identify the important parameters and then calibrating them by trial-and error. The combined method can be very useful but does not yet appear to have been widely adopted in practice.

4.5 Calibration of Lumped Conceptual Models

The most widely used method for the calibration of conceptual rainfall-runoff models is still the manual trial-and error method. These models are simple and fast to operate. However, their calibration requires an experienced user. An experienced hydrologist can usually achieve a calibration using visual hydrograph inspection within 5-15 trial runs.

Much research work during the past two decades has concentrated on establishing appropriate automatic parameter estimation methods based on traditional numerical search algorithms. One of the oldest methods, which was very popular in the 1970's, is Rosenbrock's method (Rosenbrock, 1960). A comparison of different search optimization algorithms and a discussion of some problems relating to automatic calibration are reported in Gupta and Sorooshian (1985) and Sorooshian et al. (1993).

A different method, which has emerged within the last few years, is based on expert system technology. An expert system can be defined as a computer program in which knowledge is introduced within a first-order predicate logical frame that allows it to operate at an expert level. The idea in this approach is to let an experienced user teach adjustments to carry out before the next run. One example of a rule-based expert system is given by Azevedo et al. (1993).

Automatic parameter optimization was extensively attempted in practice during the 1970's, but is not used very much today owing to the problems outlined in section 4.4.

4.6 Calibration of Distributed Models

Comprehensive research has been carried during the past decade on establishing and testing methods for automatic parameter optimization methods in groundwater modeling (described as inverse modeling), see e.g. Keidser and Rosbjerg (1991). Computer programs comprising inverse methods applicable for two-dimensional flow problems are available but are not much used in practice. For solute transport problems and for three-dimensional models, the inverse methods are still at the experimental stage.

For distributed hydrological catchment modeling systems such as MIKE SHE, which simulate many catchment processes and the dynamic interactions between them, suitable optimization methods are not yet available, and indeed are not even at a research stage. There are many problems related to the application of automatic parameter optimization methods in such complex models. One important problem relates to the necessity of having a multicriteria objective function, containing, for example references to discharge, soil moisture, groundwater levels and possibly also concentration values at several points with in catchment.

However, the massive investments in inverse methods in other fields, such as meteorology and oceanography may be expected to provide tools that will be applicable to hydrology also. Certainly, inverse methods currently appear as the most promising candidates for promoting the practice of distributed hydrological models over the next decade.

4.7 Model Validation

If a model contains a large number of parameters, it is often possible to find a combination of parameter values which provides an acceptable match between measured data and simulated output data for a short simulation period. This may be true even if the structure of the model is inappropriate or the conceptual understanding of the hydrological system is incorrect. A good match does not necessarily guarantee that a correct set of parameter values has been found, because the calibration may have been achieved purely by numerical curve fitting without considering whether the parameter values obtained are physically reasonable. This may also be illustrated by the fact that if identical models were calibrated by different people, apparently equally good calibrations would be achieved based on different combinations of parameter values.

In order to assess whether a calibrated model can be considered valid for subsequent use, it must be tested (validated) against data different from those used for the calibration (e.g. Stephenson & Freeze, 1974). Klemes (1986) stated that a simulation model should be tested to show whether it can perform the kind of task for which it is specifically intended.

4.7.1 Scheme for Constructing Systematic Validation Tests

Klemes (1986) proposed a hierarchical scheme for systematizing validation tests of hydrological simulation models. The scheme is said to be hierarchical because the modeling tasks are ordered according to their increasing complexity, and the demands of the testing increase in the same direction. The scheme was originally developed for rainfall-runoff modeling, but the methodology can be applied more generally.

Klemes (1986) distinguished between simulations conducted for the same station (catchment) as was used for calibration and simulations conducted for the ungauged catchments. He also distinguished between cases where catchment conditions (climate, land use, groundwater abstraction etc.) are stationary and cases where they are not.

This divisions leads to the definition of four basic categories of typical modeling tests:

A. *Split-Sample Test*: Calibration of model based on, say 3-5 years of data, and validation on another period of similar length.

B. *Differential Split-Sample Test*: Calibration of a model based on data before catchment change occurred, the adjustment of model parameters to characterize the change and a validation based on subsequent period.

C. *Proxy-Basin Test*: No direct calibrations are allowed but advantage is taken of the information available from other gauged catchments. Hence, validation will comprise the identification of a gauged catchment deemed to be of a similar nature to the validation catchment, the initial calibration, the transfer of the model, including the adjustment of parameters to reflect actual conditions within the validation catchment, and validation.

D. *Proxy-Basin Differential Split-Sample Test*: Again no direct calibration is allowed but information from another catchments may be used. Hence, validation will comprise an initial calibration on other relevant catchment, the transfer of the model to the validation catchment, the selection of two parameter sets to represent the periods before and after the change, and subsequent validations on both periods.

Split-Sample Test

The split-sample test is the classical test, being applicable to cases where there is sufficient long time series of control data for both calibration and validation, and where the catchment conditions remain unchanged, i.e. are stationary.

The available data record is divided into two parts. A calibration is carried out in turn for each part and then validated against the other part. Both these calibration and validation exercises should give acceptable results.

The main problem associated with the split-sample test is that not all the available data are used for calibration. Therefore, the data record should be of such length that, when split into parts, these parts can support an adequate calibration. On the other hand, if both split-sample test results produce acceptable results, a final calibration of the model can make use of the full record.

Differential Split-Sample Test

This test should be applied whenever a model is to be used to simulate flows, groundwater levels and other variables in a given gauged catchment under conditions different from those corresponding to the available data. The test may have several variants depending on the specific nature of the modeling study.

If, for example, a simulation of the effects of a climate change is intended, the test should have the following form. Two periods with different values of the climate parameters of interest should be identified in the historical record, such as one with a high average precipitation, and the other with a low average precipitation. If the model is intended to simulate streamflow for a wet climate scenario, then it should be calibrated on a dry segment of the historical record and validated on a wet segment.

Similar test variants can be defined for the prediction of changes in land use, effects of groundwater abstraction and other such changes. In general, the model should demonstrate an ability to perform through the required transition regime.

Proxy-Basin Test

This test should be applied when there is not sufficient data for a calibration of the catchment in question. If, for example, streamflow has to be predicted in an ungauged catchment Z, two ungauged catchments X and Y within the region should be selected. The model should be calibrated on catchment X and validated on catchment Y and vice versa. Only if the two validation results are acceptable and similar, can the model command a basic level of credibility with regard to its ability to simulate the streamflow in catchment Z adequately.

Proxy-Basin Differential Split-Sample Test

This is the strongest test to pass for a hydrological model, because it deals with cases, where there is no data available for calibration, and where the model is intended for prediction of non-stationary conditions.

4.8 Different Validation Requirements for Lumped and Distributed Models

The validation procedure is basically the same for lumped and distributed model codes, but because of the differences in model structures, modes of operation and objectives of application, the validation requirements are much more comprehensive for distributed models. Traditional validation based on comparing simulated with observed outflows at the catchment outlet still remains the only option in many practical cases. However, as emphasized by Rosso (1994), this method is poorly consistent with spatial distributed modeling. The differences are summarized in Table 4.1., which clearly illustrates the need for multicriteria, multi-scale validation criteria.

The table shows that, because the project objectives and the output requirements are more demanding for distributed models, the success criteria has to be more rigorous. Validation against one single discharge station (e.g. at the catchment outlet) is sufficient if the purpose is to generate streamflow values at that location, but not sufficient to draw any conclusions about the internal representation of the flow conditions within the catchment. Based on the single discharge station, the total water balance may be correct; but, for example, a systematic underestimation of the actual evapotranspiration could lead to unrealistic trends in the groundwater heads over the entire or parts of the catchment.

Basically, a success criterion needs to be fulfilled for each output variable which we intend to make predictions for. Multi-site calibration/validation is needed if spatial distributed predictions are required, and multi-variable checks are required if predictions of the behavior of individual sub-systems within the catchments are needed.

Styczen and Storm (1995) showed that calibration of both streamflow and the trend in groundwater heads was required to ensure that the simulated groundwater recharge rates for estimation of nitrate leakage was correct.

In Storm and Punthakey (1995), MIKE SHE was used to simulate the groundwater table variations in an irrigation district. Data from a very detailed groundwater observation network was available for the calibration, but no drainage flow data were available. Although the model was used to estimate groundwater accessions from the land surface, they could not guarantee that the actual flow passing through the groundwater system was simulated correctly.

4.9 The Credibility of a Generic Modeling System

According to the terminology defined in Chapter 2, a modeling system can, in principle, never be validated. Instead of a full validation we can think of the degree of validity as the credibility of a given modeling system. The degree of validity of a modeling system is expressed in the first and most immediate place by the sum of all successful validations of all models that have been constructed and operated to date using the modeling system. As the number of such successful model increases, so the credibility of the system itself grows in strength.

Behind this most superficial of views, lies the assumption that the modeling system is in fact being improved on the basis of the operating experience; that it is functioning within its market, tracking the needs of that market and thus learning from this market. From this point of view, the development of a modeling system is not one that leads directly to a finished, rounded and complete product, but it is rather a process of adaption through evolution. Thus, although the modeling system is indirectly a product, it is one that is constantly evolving, so that its evolution corresponds to a process. The general principles of such a development have been expressed by Floyd (1987).

Table 4.1 An illustration of the need for the incorporation of multicriteria and multi-scale aspects in methodologies for validation of distributed models.

	LUMPED CONCEPTUAL	DISTRIBUTED
Output	At one Point: ❑ Runoff =>Single variable	At many Points: ❑ Runoff ❑ Surface water level ❑ Groundwater head ❑ Soil moisture =>Multi variable
Success Criteria	Measured <=> Simulated ❑ Runoff, one site => Single criteria	Measured <=> Simulated ❑ Runoff, multi-site ❑ Water levels ❑ Groundwater heads ❑ Soil moisture => Multicriteria
Typical Model Appication	Rainfall-Runoff ❑ Stationary conditions ❑ Calibration data exist	Rainfall-Runoff, unsaturated zone, groundwater, basis for subsequent water quality modelingi impacts of man's activity ❑ Non-stationary conditions some times ❑ Calibration data do not always exist
Validation Test	Usually "Split-sample test" is sufficient	Split-sample test, differential split sample test, proxy basin test
Modeling Scale	Model: catchment scale Field Data: catchment scale	Model: depends on discretization Field Data: many different scales

CHAPTER FIVE

PROBLEM STATEMENT AND OBJECTIVE OF THE THESIS

5.1 Problems in Hydrologic Modeling

Hydrologic models are computationally intensive. This makes it undesirable to develop the model in a computer environment with a significant system overhead. In spatially distributed process models computing time increases exponentially as increasingly detailed spatially distributed data are introduced (e.g. in a raster GIS, as the cell size decreases, the computing time increases exponentially). Computing time also increases arithmetically as the real extent of simulation is increased since calculations must be performed on each unit area. In addition, the horizontal component of flow must be calculated. The result is that computational requirements have typically made the complete integration of the hydrologic model with a GIS infeasible for anything except surface runoff for single storm events.

With the ever improving performance of computers comes the possibility of taking advantage of their greater power. However, even with the currently available work stations, a multi-event spatially distributed calibrated hydrologic model would still be computationally intensive to the point of being prohibitive. New approaches are required to reduce computation time to the point of making the simulation feasible. Faster machines in conjunction with new algorithms that speed up the processing of spatially distributed computations can make a complete synthesis of the hydrologic model and GIS a reality.

Moving the hydrologic model into the GIS requires a standardized unit of area. Incorporation of irregular polygonal data structures (Triangulated Irregular Networks-TINs) is problematic as their irregular shape makes iterative horizontal flow simulations difficult, given no systematic method of addressing neighboring polygons and routing flow from one to the other. Raster map algebra functions and operators are naturally suited to the complex series of equations necessary for a hydrologic model. However, using the standard eight neighbors available in a raster based system creates unrealistic drainage networks (Xu and Lathrop, 1994). Thus, while working within the raster GIS, the limitations of spatial representation must be overcome to make use of the algebraic expressions

5.2 Model Parameters and Complexity of the Model Structure

Hydrologic models must be reliable and robust as these qualities influence all applications based on model output. Previous studies on conceptual rainfall-runoff models have shown that one of the basic causes of their output uncertainty is model over parameterization. During the past 30 years, many modelers of the rainfall-runoff relationship have considered that increasing model complexity is the paramount solution for improving model performances. In 2001, Perrin et al. (2001) quantified model complexity by the number of parameters optimized during the calibration phase for 19 conceptual daily rainfall-runoff models. They showed that, in calibration mode, models with a larger number of parameters generally benefit from this increase in degrees of freedom and yield a better fit of observed data. But, they also pointed out that, this trend disappears at the verification stage where models with a limited number of parameters achieve results as good as those of more complex models.

Ye et al., (1997) and Gan et al., (1997) already noticed this lack of overall superiority of complex models over simpler ones. This can be partly explained by the decreasing stability of performances from calibration to simulation and means that the complex models tend to be less robust, i.e. they tend to have less stable performances than the simpler ones (Perrin et al., 2001).

Perrin et al. (2001) also noticed that, in calibration or simulation, models with the same number of parameters may produce quite different results. This strengthens the argument by Gan et al. (1997) that the structure of the model (i.e. the type of storages, the nature of mathematical functions (linearity and non-linearity), the way elements are inter-related in the structure, the parameterization of loss or routing modules) is of crucial importance for the success in modeling. Complexity alone cannot guarantee reliable performances. To date, model structures do not seem to be accurate enough to support a high complexity.

5.3 Modeling Problems in Developing Countries such as Turkey

Advanced lumped and distributed modeling systems such as HEC (Hydrologic Engineering Center), SLURP (Simple LUmped Reservoir Parametric), PRMS (Precipitation Ronoff Modeling System), HSPF (Hydrologic Simulation Program, Fortran), SHE (Systéme Hydrologique Européen), etc. were developed in scientific research institutes in developed countries. These models were designed first by considering the countries' needs such as coping with floods, water quality, river basin management, and so on. Thus, these models were designed to use data which were collected in the native countries and which used specific formats. Due to these facts, the use of advanced modeling systems in developing counties which suffer from lack of hydrometeorological data seems difficult. Since Turkey has no sufficient hydrometeorological databases, data collection networks, and even land information, the application of such systems to real problems may result in failure. The main problem in Turkey is the lack of proper data sets required by popular modeling systems.

Another problem in developing countries like Turkey is data quality. Apart from the problems of data quantity, data quality and reliability is the second crucial issue. Since there are no sufficient data collection networks which are well designed to increase the information content of data, the data collected by current sampling procedures are mostly inaccurate. Old fashioned gauging equipments such as mechanic water level meters in the stream gauging stations and rainfall recorders are also the other sources of errors in collected data.

In addition to the lack of data and the current data quality and reliability problems, the acceptance of model applications by the official institutions, which are responsible for the water resources of developing countries, is a major constraint to encourage the national researcher for modeling efforts. The authorities still have doubts in the results of deterministic modeling studies in comparison with those of stochastic modeling. This lack of confidence does not support the research and applications of the deterministic hydrologic modeling studies.

5.4 Objective of the Thesis

Based on the problems stated in the above sections, the objective of the thesis are foreseen as the following:

- To review the modeling concepts such as terminology, classifications, model construction, calibration and verification of hydrologic modeling since these topics are quite new in water resources research in Turkey. These topics are already mentioned in Chapters 2, 3 and 4,
- To develop a method to integrate GIS and a hydrologic model, which is the recent issue in hydrologic research,
- To develop a simple, parsimonious hydrologic simulation model which needs less hydrometeorological data than the complex ones, and which considers

spatial distribution of land use and soil data and input variables by using GIS integration,

- To realize an application of the developed hydrologic simulation model for daily streamflow in a real case study which includes calibration and verification processes.

CHAPTER SIX

DAILY RAINFALL RUNOFF SIMULATION MODEL (DRRSM)

6.1 Introduction

DRRSM (Daily Rainfall-Runoff Simulation Model) is a distributed, conceptual, continuous watershed model that is developed to estimate daily mean runoff from medium-sized rural watersheds where precipitation, land cover and soil properties are spatially distributed. DRRSM can simulate evapotranspiration, surface detention, surface runoff, sub-surface storage, sub-surface runoff, groundwater storage and groundwater runoff by evaluating cell-based precipitation, land cover and soil properties of the watershed. It uses raster data and parameter layers in order to consider the spatial variability of both data and watershed properties such as precipitation distribution, land cover distribution and soil properties distribution.

DRRSM consists of three components which govern the simulations. One of them is the **H**ydrologic **R**esponse **U**nits (HRU) component which evaluates watershed properties such as precipitation distribution, land cover and soil properties, considering their spatial variations, and which generates hydrologicaly homogeneous areas to be used in the simulations. The second component is the **V**ertical **W**ater **B**udget (VWB) component, which runs water fluxes from surface, sub-surface and groundwater zones within each hydrological response unit (HRU). The last one is the **D**ata and **P**arameter (D&P) component that organizes which hydrological response unit uses which precipitation and evaporation records as inputs, and which parameter sets belong to which hydrological response unit. The following sections describe these components of the DRRSM.

6.2 Assumptions of the DRRSM

During the development of the DRRSM, the following assumptions and definitions are considered.

- Hydrologic models are classified based on their spatial scale as small-size, medium-size and large-size watersheds (Singh, 1995). Although, that classification is arbitrary, usually, a watershed with an area of 100 km^2 or less can be called small, those with an area of 100 to 1000 km^2 medium, and those with an area of larger than 1000 km^2 large, in modeling studies. For consideration of runoff generation on these watersheds, two phases can be considered; land phase and channel phase. Each phase has its own storage characteristics. Large watersheds have well-developed channel networks and channel phase, and thus, channel storage is dominant. Such watersheds are less sensitive to short duration, high intensity rainfalls. On the other hand, small watersheds have dominant land phase and overland flow, have relatively less conspicuous channel phase, and are highly sensitive to high-intensity, short-duration rainfalls. Considering the above definitions, the DRRSM is a medium-size watershed model since the dominant phase is the land phase in DRRSM, but the duration and intensities of the rainfall in a day are not considered.

- The resolution of the land properties of the watersheds is high, such as 1-100 m, in small scale watershed models since runoff highly depends on the definitions in detail of land surface properties. On large scale watersheds, spatial variations can be represented by the resolution of the land properties up to 10 or 20 km satisfactorily. Consequently, 1 or 2 km resolution is sufficient for medium size watersheds. Another important issue in the resolution of watershed models is computing considerations. The computing time and labor of the model increase while the resolution of the model increases. There is no point in increasing the resolution of the model if meaningful improvements in the results do not occur. As a medium size watershed model, 1-5 km resolution of the land properties is satisfactory in the DRRSM.

- The main input of the model DRRSM is daily rainfall of which the duration and intensities are not considered in the simulations. The model runs with only one-day time step, thus, it uses the summed inputs (daily rainfall) and generates averaged outputs (daily mean runoff). There are no computations where the time step is smaller than a day in the simulation framework.

- Hydrological computations in the DRRSM are carried out based on a linear system approach just like many other analyses in hydrology (Bayazıt, 1998) in order to develop a parsimonious model and to make computations simple. All runoff components such as surface, sub-surface and groundwater runoff are linear functions of relevant storages. Thus, well-known linear runoff-storage relationships are the basic equations of the runoff generation process. However, for generating surface and sub-surface runoff, there is one assumption that runoff occurs only when the maximum storage capacities of surface and sub-surface storages are exceeded and that all the excess water reaches the lower storage system or stream network, and then the outlet of the watershed in one time step. Thus, in large watersheds, DRRSM must be employed by dividing the watershed into medium size watersheds. The groundwater system continuously releases water depending on underground storage which is considered as a linear system.

- The runoff routing in the channel is not considered in the DRRSM. The model computes only the surface, sub-surface and groundwater runoff components of the watersheds at the watershed outlet.

- The runoff generated by the snow melt process is not considered in the DRRSM. Thus, the model can be used at watersheds where no effective snow cover exists.

6.3 DRRSM Components

6.3.1 Hydrologic Response Units (HRU) Component

As mentioned before, DRRSM is a cell-based or in another words, a raster-based simulation model. Hydrologic computations are carried out on a cell-based pattern. It is obviously clear that the number of cells affects the computation time and the use of computer memory. If the watershed area is large or cell dimensions are too small, the number of cells increases so that the computational time increases and the free memory (unused memory) of computers decreases. In order to cope with this problem, in another words, instead of doing the same computations for similar cells, one computation for a group of homogeneous cells is preferred. The main problem is now to define homogeneous cells or areas which receive the same precipitation, and have the same soil properties and the same land cover attributes. In order to define homogeneous areas, a GIS (Geographical Information System) analysis technique is applied to raster data layers. This approach is explained in the next section.

6.3.1.1 Cell-Based Data (Raster Data) Structure

A spatial object is in raster form if it is based on the aggregation of grid cells (or pixels, in the case of digital image). Most implementations are built around square or rectangular grid cells, but other shapes, such as triangular and hexagonal shapes are also possible. In the simplest case, grid cells are uniform and can, therefore, be referenced by their row and column numbers. Each grid cell may be assigned only one value, which represents the value of the attribute being mapped (Figure 6.1). Different types of attributes are handled by creating data layers or overlays.

→ Column

↓ Row

1	1	1	1	1	1	1
3	1	1	1	1	1	1
3	3	1	1	1	1	2
3	3	3	1	1	2	2
3	2	2	2	2	2	2
3	3	3	3	2	2	2
3	3	2	2	2	2	2

1. Clay
2. Sand
3. Silt

Figure 6.1 Raster representation of data layers such as that of the spatial distribution of soil.

Raster spatial data structures are simple to conceptualize and to use for overlay analysis. Further, they can be used efficiently for modeling high spatial variability, which makes them appealing for the manipulation of remotely sensed data and digital images. On the negative side, data files tend to be huge, even though data compression techniques can reduce this burden.

6.3.1.2 Overlay Analysis and Identification of Homogeneous Areas

Figure 6.2 describes the overlay analysis and the identification of homogeneous areas. Each cell in each raster data layer has a numerical code such as 1, 2, 3, etc. Each code defines an attribute. For example, in Figure 6.2 the first layer defines soil distribution of an area with 5 columns x 5 rows. The second layer defines land use distribution of the same area. In overlay analysis, each layer is overlaid onto others by merging numerical codes. While merging codes, the codes are not added mathematically; they are only merged alphanumerically. For example, in Figure 6.2 merged codes in the third layer (overlay result of the first and second layers) are obtained by merging codes in the specific column and row of both the first and the second layers. The code in the first column and the first row of the resulting layer is 13, which is obtained by merging 1 and 3, which are at the same column and the same row of the first and the second layers, respectively.

In Figure 6.2 the soil type layer consists of 2 classes that are 1 and 2; land cover layer has 4 different classes (1, 2, 3, and 4). The resulting layer which is the merged layer of soil type and land cover, has 6 different classes (11, 12, 13, 14, 22, and 23) where each class represents a homogeneous area regarding only soil type and land cover properties.

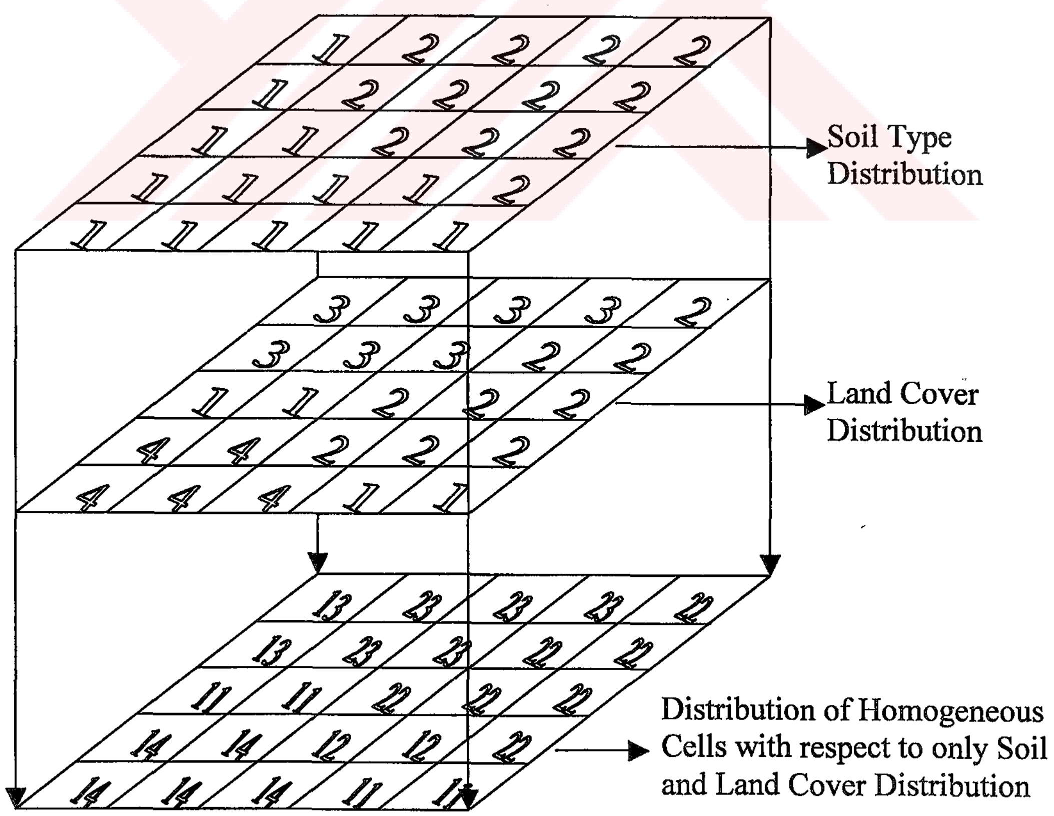


Figure 6.2 Example of overlay analysis concept in the DRRSM for defining homogeneous areas.

DRRSM considers 3 spatially distributed watershed properties such as rainfall distribution, soil type distribution, and land cover distribution as digital raster data layers. Then, the HRU component reads these 3 raster data layers of a watershed to be simulated and creates homogeneous hydrological land segments (HRU). Figure 6.3 represents the definition of homogeneous hydrological land segments by the HRU component.

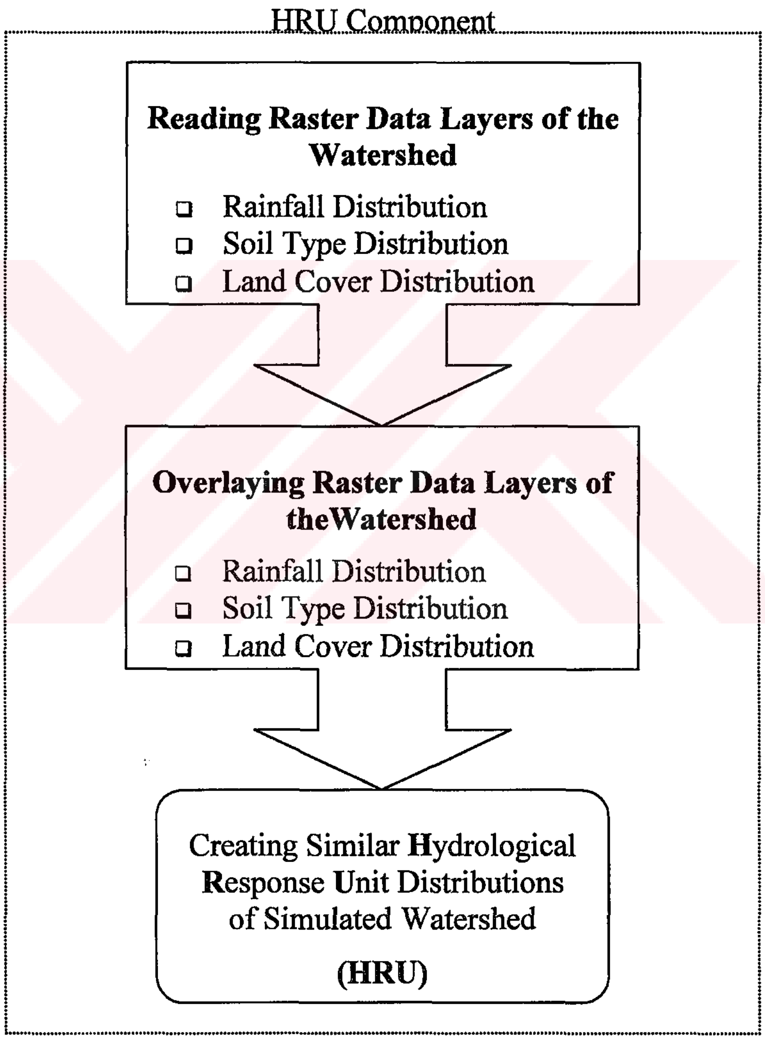


Figure 6.3 Defining the distribution of Similar Hydrological Response Unit over the watershed by the HRU Component.

6.3.2 The Vertical Water Budget (VWB) Component

Figure 6.4 shows DRRSM's vertical water budget component, which is the main component of the model. This component computes storages and runoff of each **H**ydrologic **R**esponse **U**nit (HRU), accounting for the spatially and temporally distributed parameters and inputs. HRUs are homogeneous land segments in which precipitation, land cover and soil properties do not vary in themselves. Entire watershed consists of several HRUs. The identification of HRUs is been discussed in the above sections.

After the number of HRUs and their precipitation, soil and land cover properties are determined by the DRRSM, vertical water budget component gets this information and reads the related inputs and parameters, such as precipitation and evaporation data. Then, DRRSM runs the hydrologic simulation described in Figure 6.4, using the input data.

As seen in Figure 6.4, precipitation is the major input of the vertical water budget component. Specific rainfall and evapotranspiration data with respect to HRU's properties are taken from data files.

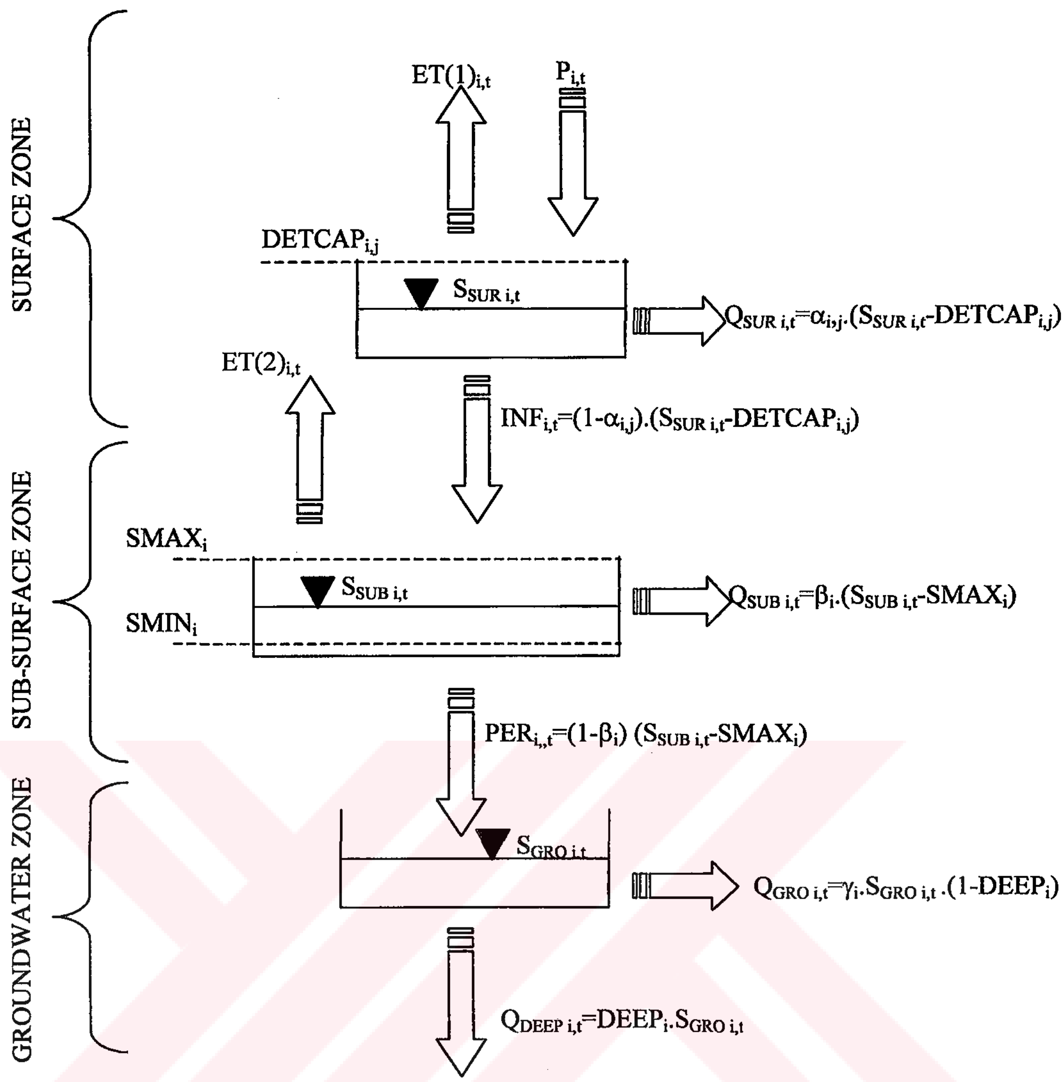


Figure 6.4 Vertical Water Budget Component of the DRRSM (ET: Evapotranspiration, P: Rainfall, DETCAP: Surface Detention Capacity, INF: Infiltration, PER: Percolation)

6.3.2.1 Potential Evapotranspiration

In literature, daily potential evapotranspiration (PET) can be estimated by using several methods such as Penman (1948), Penman-Monteith (1965), and Prestley-Taylor (1972). These methods require a lot of meteorological data such as canopy properties, solar radiation, air temperature, wind speed, and relative humidity as input. Since these methods need comprehensive data, it is difficult to use them in the catchment where such data are not collected.

In the DRRSM, daily potential evapotranspiration is calculated by using only daily pan evaporation (EPAN) and a coefficient (EC) which depends on the land cover characteristics. Eqn. 6.1 defines the estimation of daily potential evapotranspiration with respect to daily pan evaporation and land cover types.

$$PET_{i,t} = EC_{i,mon}\, EPAN_{i,t} \tag{6.1}$$

where;

$PET_{i,t}$: daily potential evapotranspiration (mm/day) of the i^{th} HRU at time t^{th} day.

$EC_{i,mon}$: evapotranspiration coefficient of the i^{th} HRU, that depends on land cover properties and varies between 0 and 1. This coefficient changes on a monthly scale, thus it stays constant during a specific monthly interval.

$EPAN_{i,t}$: pan evaporation (mm/day) of the i^{th} HRU at time t^{th} day.

$EC_{i,mon}$ is a parameter to be calibrated by the user if potential evapotranspiration is calculated by Equation 6.1. If sufficient meteorological data are available, potential evapotranspiration may be calculated by another method and then can be used as an input time series for the DRRSM.

As can be seen from the Equation 6.1, in order to calculate potential evapotranspiration, pan evaporation data $EPAN_{i,t}$ have to be obtained as an input time series.

6.3.2.2 Actual Evapotranspiration

Actual evapotranspiration depends on the amount of water intercepted by soil surface and vegetation, and the water content of the soil layer. If potential evapotranspiration exceeds the total water storage of both the surface and soil layers, actual evapotranspiration has to be less than the potential.

Figure 6.4 describes the evapotranspiration process as conceptualized in DRRSM. In DRRSM, evapotranspiration is extracted first from the surface zone (ET1), which stores water on the vegetation and the soil surface, and then from the sub-surface zone (ET2), which has a minimum and maximum water content boundaries (SMIN, SMAX).

6.3.2.3 Surface Detention

In DRRSM, when a HRU receives precipitation, the precipitation is diverted into the detention storage. Detention storage is a surface zone storage volume, which depends on land cover and has a maximum capacity (DETCAP). If the amount of water in the surface zone storage (S_{SUR}) exceeds its capacity (DETCAP), a specific percent of that water (α) is diverted as surface flow and the remaining percent of water ($1-\alpha$) is diverted to subsurface zone storage (S_{SUB}) as infiltration.

Maximum capacity of surface detention (DETCAP) depends on land cover properties. Surface runoff and infiltration occur only when surface zone storage

(S_{SUR}) exceeds that capacity value, which changes monthly in the model. DETCAP is defined by the user, and it is another model parameter which has to be calibrated.

6.3.2.4 Surface Runoff and Infiltration

Surface runoff occurs only when surface zone storage (S_{SUR}) exceeds the surface detention capacity (DETCAP). Surface runoff is assumed as a linear function of the amount of excess water as defined in Equation 6.2:

$$Q_{SURi,t} = \alpha_{i,j} \left(S_{SURi,t} - DETCAP_{i,j} \right) \quad (6.2)$$

where;

$Q_{SURi,t}$: Surface runoff (mm/day) of the i^{th} HRU on the t^{th} day.

$\alpha_{i,j}$: Surface runoff coefficient (1/day) of the i^{th} HRU on the j^{th} month which includes the t^{th} day. This coefficient depends on land cover properties and changes monthly during the simulations.

$S_{SURi,t}$: Surface layer storage (mm) of the i^{th} HRU on the t^{th} day.

$DETCAP_{i,j}$: Detention capacity of the surface layer (mm) of the i^{th} HRU on the j^{th} month which includes the t^{th} day.

Infiltration depends on the surface zone water storage as in the case of surface runoff. If the surface zone storage exceeds the detention capacity, infiltration process occurs. Infiltration rate is again assumed as a linear function of the water exceeding detention capacity. Since α represents the surface runoff portion of the excess water, $(1-\alpha)$ must be used as an infiltration coefficient in respect of continuity. Equation 6.3 defines the daily infiltration of a HRU in the DRRSM:

$$INF_{i,t}=(1-\alpha_{i,j}).(S_{SUR\ i,t}-DETCAP_{i,j}) \quad (6.3)$$

where;

$INF_{i,t}$: daily amount of infiltration (mm/day) of the i^{th} HRU on the t^{th} day.

$\alpha_{i,j}$: Surface runoff coefficient (1/day) of the i^{th} HRU on the j^{th} month which includes the t^{th} day. This coefficient depends on land cover properties and changes monthly during the simulations.

$S_{SURi,t}$: Surface layer storage (mm) of the i^{th} HRU on the t^{th} day.

$DETCAP_{i,j}$: Detention capacity of the surface layer (mm) of the i^{th} HRU on the j^{th} month which includes the t^{th} day.

6.3.2.5 Sub-Surface Runoff and Percolation

Sub-surface runoff depends on the sub-surface zone water storage (S_{SUB}) as sketched in Figure 6.4. As in the case of surface flow, sub-surface flow is assumed to be a linear function of the sub-surface zone water storage (S_{SUB}).

Sub-surface zone has a minimum and maximum storage capacity (SMIN, SMAX). Storage in the sub-surface zone changes during the simulations between these boundary values. Minimum and maximum values of the storage depend on the soil properties of the HRU. As can be seen from Figure 6.4, if the amount of water stored in the surface zone is not enough for the daily evapotranspiration, the deficit is covered by the sub-surface storage if there is available water there (ET2). Then, the water content of the sub-surface zone is reduced by evapotranspiration. If the water deficit due to evapotranspiration is more than the amount of water content of sub-surface zone, the water content of sub-surface zone is reduced to SMIN, and evapotranspiration has to be less than potential.

After infiltration occurs, water content of the sub-surface zone (S_{SUB}) is increased by adding infiltration. Then, if the sub-surface water content exceeds the maximum capacity of the sub-surface zone storage (SMAX), sub-surface runoff and percolation occur. Equation 6.4 and 6.5.define the daily sub-surface runoff and percolation of an HRU in the DRRSM, respectively.

$$Q_{SUB\ i,t}=\beta_i.(S_{SUB\ i,t}-SMAX) \qquad (6.4)$$

where;

$Q_{SUBi,t}$: Sub-surface runoff (mm/day) of the i^{th} HRU on the t^{th} day.

$\beta_{i,}$: Sub-surface runoff coefficient (1/day) of the i^{th} HRU. This coefficient depends on soil properties.

$S_{SUB\ i,t}$: Sub-surface zone storage (mm) of the i^{th} HRU on the t^{th} day.

$SMAX_i$: Maximum capacity of the sub-surface zone storage (mm) of the i^{th} HRU. This parameter depends on soil properties.

$$PER_{i,,t}=(1-\beta_i)\ (S_{SUB\ i,t}-SMAX_i) \qquad (6.5)$$

where;

$PER_{i,t}$: Percolation (mm/day) of the i^{th} HRU on the t^{th} day.

$\beta_{i,}$: Sub-surface runoff coefficient (1/day) of the i^{th} HRU. This coefficient depends on soil properties.

$S_{SUB\ i,t}$: Sub-surface zone storage (mm) of the i^{th} HRU on the t^{th} day.

$SMAX_i$: Maximum capacity of the sub-surface zone storage (mm) of i^{th} HRU. This parameter depends on soil properties.

6.3.2.6. Groundwater Runoff and Deep Percolation

Groundwater runoff depends on groundwater zone water storage (S_{GRO}) as illustrated in Figure 6.4. Groundwater runoff is simulated as a linear function of the groundwater zone storage.

Water infiltrating through the surface and percolating from the sub-surface zone storage to the groundwater zone storage may flow to active groundwater storage or may be lost by deep percolation. Active groundwater eventually reappears as baseflow, but deep percolation is considered lost from the simulated system.

Groundwater runoff is simulated as in the Equation 6.6.

$$Q_{GRO\,i,t} = \gamma_i . S_{GRO\,i,t} . (1 - DEEP_i) \tag{6.6}$$

where;

$Q_{GROi,t}$: Groundwater runoff (mm/day) of the i[th] HRU on the t[th] day.

$\gamma_{i,}$: Groundwater runoff coefficient (1/day) of the i[th] HRU. This coefficient depends on soil properties.

$S_{GRO\,i,t}$: Groundwater zone storage (mm) of the i[th] HRU on the t[th] day.

$DEEP_i$: Coefficient for deep percolation of i[th] HRU which depends on soil properties.

6.3.2.7 Runoff Routing

In DRRSM, runoff routing is considered as the process of finding the total runoff at the watershed outlet. Since the simulation time step of the DRRSM is longer than hours, and since the time distribution of the precipitation in a day is not considered, runoff routing in the DRRSM has to be lumped. As the runoff parameters α, β, γ yield the amount of water leaving the watershed as portions of the previous storages, the sum of the runoff amounts already represents the routing itself. Consequently, the total runoff leaving the watershed is defined by adding all runoff volumes that come from surface, sub-surface, and groundwater storages of each HRU. However, sub-surface and groundwater runoff of each HRU may be considered to be slower than surface runoff. In order to account for the time lag between surface and sub-surface and groundwater runoff, DRRSM can use time lag parameters which must be expressed in integers such as 1 day or 2 days, etc. according to watershed area. Equation 6.7. defines the runoff routing of the DRRSM.

$$\left.\begin{aligned}
Q^{t}_{\text{watershed, surface}} &= \sum_{i=1}^{M} Q^{t}_{\text{i, surface}} \\
Q^{t}_{\text{watershed, sub-surface}} &= \sum_{i=1}^{M} Q^{t}_{\text{i, sub-surface}} \\
Q^{t}_{\text{watershed, groundwater}} &= \sum_{i=1}^{M} Q^{t}_{\text{groundwater}} \\
Q^{t}_{\text{watershed, total}} &= \sum_{i=1}^{M} Q^{t}_{\text{i, surface}} + \sum_{i=1}^{M} Q^{t-k}_{\text{i, sub-surface}} + \sum_{i=1}^{M} Q^{t-p}_{\text{i, groundwater}}
\end{aligned}\right\} \quad (6.7)$$

where;

M : the number of HRU

k : time lag for sub-surface runoff (1, 2 days, etc.)

p : time lag for groundwater runoff (1, 2 days, etc.)

t : day

6.3.3 Data and Parameter Components

Data and parameter components of the DRRSM organize input data and model parameters in order to obtain proper usage by the hydrological response units.

Since DRRSM is a daily based rainfall-runoff simulation model, model inputs which are daily total rainfall and evaporation must be introduced as a daily time series. As described in section about the vertical water budget component, model parameters of DRRSM which depend on land cover properties changes monthly and which depend on soil properties are constant during the simulations. Data and parameter component recognizes the days of the simulation and calls input data which are daily rainfall (P) and evaporation (EPAN) for each hydrological response unit (HRU) from the input data file, considering the type of the HRU. Then, the evapotranspiration parameters (EC) and surface runoff parameters (α) are called from the parameter file, considering the month of the simulated day. Finally, data and parameter component reads the soil properties of each hydrological response unit (HRU) and calls the sub-surface runoff parameter (β), maximum and minimum sub-surface zone storage capacities (SMIN, SMAX), and groundwater runoff parameters (γ and DEEP).

After all data and parameters are defined the data and parameter component forwards them to the vertical water budget component.

6.3.4 Calibration Processes

Calibration is the process of adjusting the model parameters in order to reach the best results of the simulation regarding the observed flows. As mentioned in Chapter 4, there are several calibration methods given in literature. Although the automatic calibration techniques may seem to be more effective, they are much more difficult to utilize than the manual calibration techniques. In DRRSM, three manual calibration techniques are preferred due to their easiness, and they are widely used in similar models.

The first approach is to find the minimum value of the sum of the squared differences between observed and simulated runoffs as described in Equation 6.8.

$$D = \sum_{t=1}^{N} \left(Q_{t,\,observed} - Q_{t,\,model}\right)^2 \qquad (6.8)$$

where;

D :sum of the square of the differences between observed and simulated runoff

$Q_{t,observed}$:observed runoff at the t^{th} day

$Q_{t,model}$:simulated runoff at the t^{th} day

N :the number of days used in the calibration process.

The second approach is to find the maximum value of the correlation coefficient between the observed and the simulated runoff as described in Equation 6.9.

$$R = \frac{S_{(Qo,\,Qm)}}{S_{(Qo)}\,S_{(Qm)}} \qquad (6.9)$$

where;

R : Correlation coefficient between observed and simulated runoff

$S_{(Qo,Qm)}$: Covariance between observed and simulated runoff

$S_{(Qo)}$: Standard deviation of observed runoff

$S_{(Qm)}$: Standard deviation of simulated runoff

The third approach is proposed by WMO (World Meteorological Organization) (WMO, 1986). In this approach, the best model parameters give the closest value to "1" for the F parameter defined in Equation 6.10.

$$F = 1 - \frac{\sum_{t=1}^{N}\left(Q_{m,t} - Q_{o,t}\right)^2}{\sum_{t=1}^{N}\left(Q_{m,t} - \overline{Q_m}\right)^2} \tag{6.10}$$

where,

F : the calibration parameter to be close to 1

$Q_{m,t}$: simulated runoff at t^{th} day

$Q_{o,t}$: observed runoff at t^{th} day

$\overline{Qm}$: mean value of the simulated runoff

N : the number of days used in calibration

6.4 DRRSM Simulation Framework

The DRRSM simulation framework is presented in Figure 6.5. According to Figure 6.5 simulation framework of the DRRSM covers the following:

1. Hydrological Response Units component reads all three raster data layers, namely the precipitation distribution, land cover distribution and the soil types distributions.
2. HRU component determines homogeneous hydrological areas and lists the number of homogeneous hydrological response units.
3. Data and parameter component reads time series data which are daily precipitation and pan evaporation rates.

4. Parameters are read by data and parameters component, and they are matched with the HRUs according to HRU's precipitation, land cover and soil type properties.

5. For each HRU, the vertical water budget component computes runoff and water storage of the different zones.

6. Runoff series comprising surface runoff, sub-surface runoff and groundwater are accumulated for all HRUs and watershed discharges are obtained for each day.

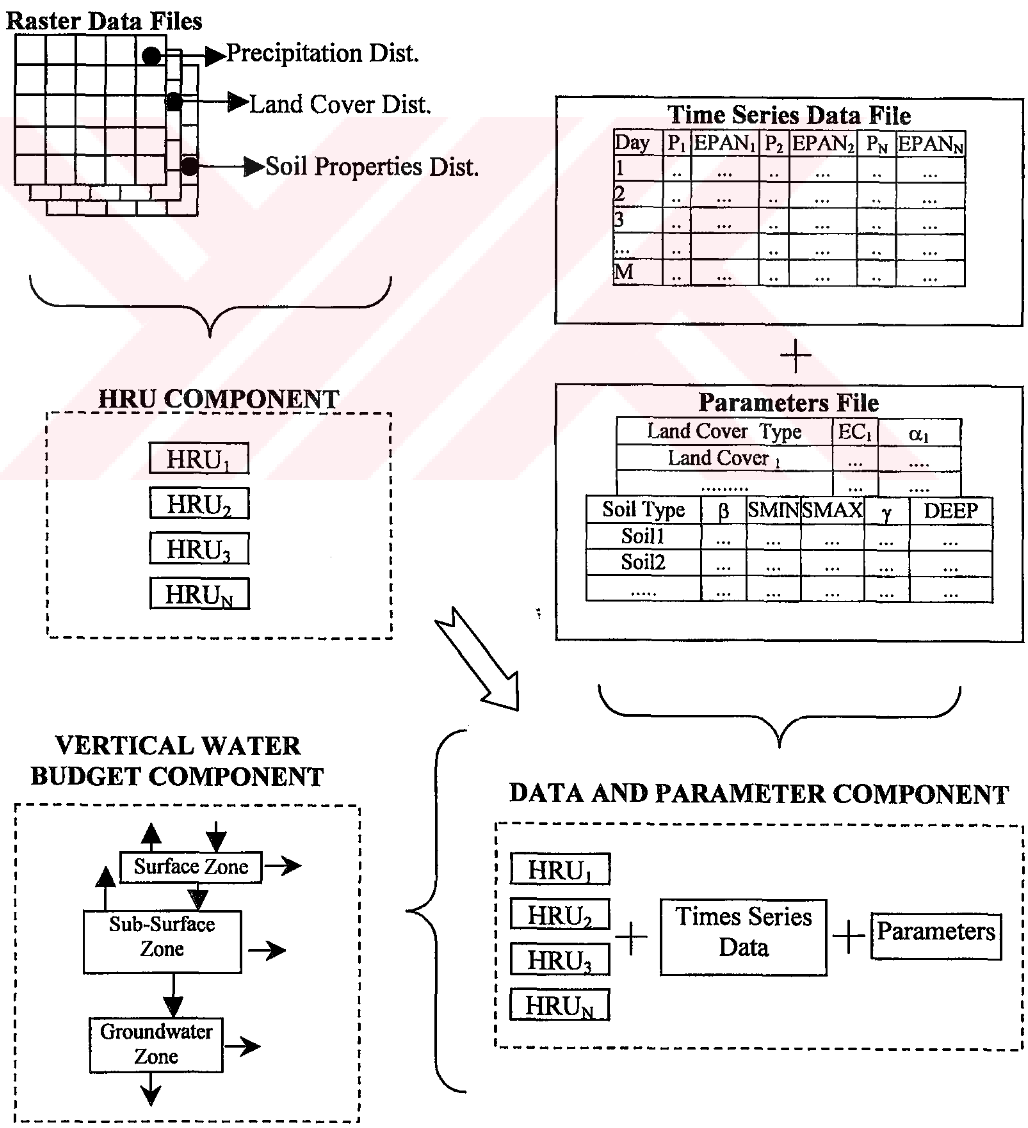


Figure 6.5 Simulation framework of the DRRSM.

6.5 Computer Programming of DRRSM

Computer program of the DRRSM is designed by using MS-VisualBASIC© programming language. VisualBASIC is a programming language that uses MS-BASIC© codes and commands as program algorithms for developing MS-Windows© based softwares. Visual-BASIC is preferred in order to develop DRRSM since;

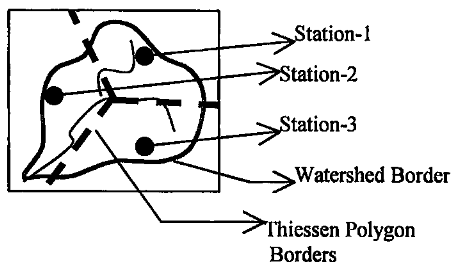
- It has a powerful component library,
- It is convenient for OOP (Object Oriented Programming),
- It has wide and comprehensive help documentations,
- It is quite similar to the old fashioned BASIC codes,
- It is widely used all over the world.

DRRSM is designed by considering user requirements and future developments. The program has a very flexible structure where the user can change all hydrologic computations and equations without any doubt. The user may redesign runoff equations and interrelations between surface, sub-surface and groundwater zones, by defining, for example, non-linear equations.

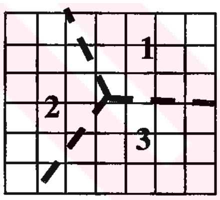
6.5.1 Raster Data File Structure

Raster data files in DRRSM consist of precipitation distribution, land cover distribution and soil type distribution. All these files are in raster format where all features are represented by cells. Each cell has a code that defines the properties of raster layers.

Precipitation distribution is defined by using the locations of the existing meteorological stations. After each meteorological station is located on the watershed map, Thiessen polygons are created by GIS methods. Each cell in each polygon represents the precipitation properties of the meteorological station located at the center of the Thiessen polygon. Figure 6.6 represents the precipitation distribution of the DRRSM. The file structure has a matrix form where the numbers of columns and rows are equal to those of the raster precipitation distribution layer. These files can be created by GIS file management systems easily by saving the raster file as ASCII text file.



a) Meteorological stations and Thiessen Plygons



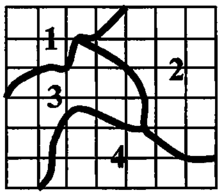
b) Raster rainfall distribution image

2	2	1	1	1	1	1
2	2	2	1	1	1	1
2	2	2	1	1	1	1
2	2	2	3	3	3	3
2	2	3	3	3	3	3
2	3	3	3	3	3	3

c) ASCII rainfall distribution file

Figure 6.6 Representation of precipitation distribution file of DRRSM.

Land cover distribution data can be obtained from several data sources such as remote sensing applications, aerial photogrometry, or scanned paper land cover maps. The raster format of land cover distribution and its file structure are given in Figure 6.7.



1: Forest

2: Irrigated Area

3: Barren

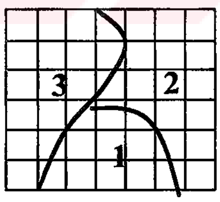
4: Maki

1	1	1	1	2	2	2
1	1	3	3	2	2	2
1	3	3	3	2	2	2
3	3	4	3	3	2	2
3	4	4	4	4	2	2
3	4	4	4	4	4	4

a) Raster land cover distribution image *b) ASCII land cover distribution file*

Figure 6.7 Representation of land cover distribution file of DRRSM.

Soil type distribution of the DRRSM can be obtained by digitizing paper soil maps. The digitized soil maps are in vector formats that represent the soil features by its boundary coordinates. Vector formats must be converted to raster formats by GIS data conversion tools. As in the case of land cover distribution, soil type distribution is represented in Figure 6.8.



1: Soil Type A

2: Soil Type B

3: Soil Type C

3	3	3	3	2	2	2
3	3	3	3	2	2	2
3	3	3	2	2	2	2
3	3	1	1	1	2	2
3	3	1	1	1	1	2
3	1	1	1	1	1	2

a) Raster soil type distribution image *b) ASCII soil type distribution file*

Figure 6.8 Representation of soil type distribution file of DRRSM.

Land cover and soil type raster data files are created as ASCII text format in matrix form as in the case of precipitation distribution file.

6.5.2 Time Series Data File of DRRSM

There is only one time series data file for the DRRSM. This data file includes all precipitation and evaporation records as inputs for the watershed to be simulated. The file type of the time series data file is ASCII type, and this file can be created by any ASCII text creator such as EDIT, EXCEL, and NOTEPAD. The structure of the time series data file depends on the number of meteorological stations of the watershed simulated. For each meteorological station, daily rainfall and daily pan evaporation values must be defined in time order. In Table 6.1, there is a sample file structure of the time series input file.

Table 6.1 Structure of the time series data file of the DRRSM.

				Station-1		Station-2		Station-N	
Step	**Day**	**Month**	**Year**	**$Prec_1$**	**$Evap_1$**	**$Prec_2$**	**$Evap_2$**	**$Prec_N$**	**$Evap_N$**
1	15	10	1999	9.8	2.1	10.4	3.2	--	--
2	16	10	1999	0.0	2.2	0.0	3.0	--	--
3	17	10	1999	0.0	2.1	0.0	3.1	--	--
4	18	10	1999	1.6	2.3	0.0	3.3	--	--
--	--	--	--	--	--	--	--	--	--
894	21	03	2002	2.3	1.4	3.3	1.1	--	--

6.5.3 Parameter File of the DRRSM

There is only one parameter file, which covers all surface, sub-surface, and groundwater runoff parameters in the DRRSM. The file structure of the parameter file is again ASCII text file, which is quite easy to create by any text editor such as EDIT or NOTEPAD. In the parameter file there are five blocks of parameters; the first three depend on land cover, the other one on soil types, and the last one is for initial values of the surface, sub-surface and groundwater zone storages.

The first block consist of evapotranspiration parameters (EC). As mentioned in section 6.3.2.1, EC depends on land cover types, since evapotranspiration depends on vegetation cover. Thus, there are 12 EC values for each land cover type to represent the monthly changes of the land cover situations. The number of EC classes must be equal to the number of land cover types in the raster data file.

The second block comprises detention capacity parameters (DETCAP). This parameter has been defined in section 6.3.2.3. As in the case of EC, DETCAP parameters depend on land cover properties which change on a monthly time basis; thus, there are 12 DETCAP values for each land cover class, and the number of DETCAP classes must be equal to the number of land cover types defined in the raster data file.

The third block includes surface runoff parameters (α). This coefficient has been defined in section 6.3.2.4. As in the case of EC, α depends on land cover properties which change on a monthly basis. Thus, there are 12 α values for each land cover class, and the number of α classes must be equal to the number of land cover types in the raster data file.

The fourth block consists of the sub-surface and groundwater runoff parameters (β, SMIN, SMAX, γ, DEEP), which depend on soil properties of the watershed. Thus, the number of β, SMIN, SMAX, γ, DEEP classes must be equal to the number of soil types of the watershed.

The fifth block is designed for to define the initial values of the surface (S_{SUR}) and sub-surface (S_{SUB}) and groundwater (S_{GRO}) zone storages. Thus, the number of initial surface storages must be equal to the number of land cover classes; and, the number of initial sub-surface and groundwater storages must be equal the number of soil type classes. Table 6.2 represents the parameter file structure of the DRRSM.

Table 6.2. Parameters file structure of the DRRSM

EC	1	2	3	4	5	6	7	8	9	10	11	12	BLOCK 1
LC_1	0.1	0.2	0.4	0.5	0.6	0.8	0.8	0.8	0.7	0.6	0.4	0.2	
LC_2	0.0	0.0	0.0	0.3	0.5	0.6	0.6	0.6	0.4	0.3	0.0	0.0	
..	..	..	..	..	..	..	..	..	..	..	..	..	
LC_N	0.0	0.0	0.0	0.2	0.3	0.4	0.5	0.5	0.4	0.3	0.2	0.0	

DETCAP	1	2	3	4	5	6	7	8	9	10	11	12	BLOCK 2
LC_1	1	1	2	3	3	4	2	2	2	1	1	1	
LC_2	3	3	4	5	6	5	4	3	2	2	2	3	
..	..	..	..	..	..	..	..	..	..	..	..	..	
LC_N	0	0	0	3	3	4	4	5	5	0	0	0	

α	1	2	3	4	5	6	7	8	9	10	11	12	BLOCK 3
LC_1	0.01	0.01	0.01	0.02	0.03	0.04	0.04	0.04	0.03	0.02	0.02	0.02	
LC_2	0.02	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.04	0.03	0.02	0.02	
..	..	..	..	..	..	..	..	..	..	..	..	..	
LC_N	0.03	0.03	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	

	β	SMIN	SMAX	γ	DEEP	BLOCK 4
SL_1	0.025	10	280	0.013	0.20	
SL_2	0.033	40	345	0.016	0.40	
..	..					
SL_N	0.018	25	295	0.011	0.10	

DETCAP	INI		SSUB	SGRO	BLOCK 5
LC_1	1	SL_1	110	10	
LC_2	3	SL_2	180	5	
..	..	..	..		
LC_N	5	SL_N	175	4	

LC: Land Cover Type SL: Soil Type

6.6 User Interfaces

As mentioned earlier, the program algorithms and user interfaces are written in the VisualBASIC programming language. The source codes of the DRRSM and its components are given in Appendix.

The first user interface is the " File System Environment" window, which changes the current working directory of the operating system to the selected one. The selected directory must contain raster data files, input data file and parameter file. The simulated runoff values are written in that directory automatically as an ASCII text file. Figure 6.9 represents the "File System Environment" window of the DRRSM.

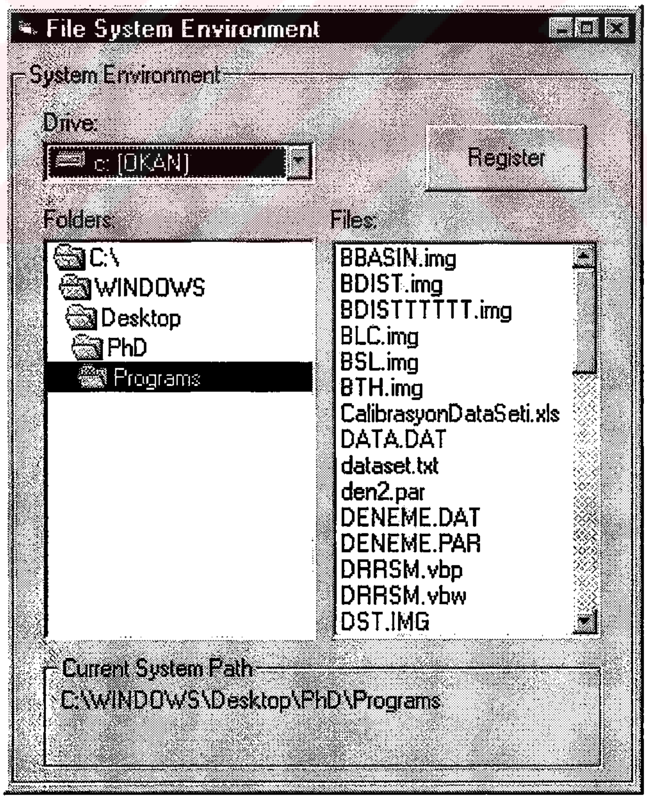


Figure 6.9 "File System Environment" window of the DRRSM.

After the user sets up the working directory to the location of the existing model files, the DRRSM brings in the second interface called "File Manager" in which the raster data files, input data file, and parameter file are described. The user must select the proper files in the drop-down menus of that window, and then click the "Raster GIS Files Control" button in order to check the file structure of the raster files. If there is an error in the raster files, such as the existence of different number of columns and rows among the raster files, "File Manager" alerts the user for errors; otherwise it warns the user to go to the next step. The next step is to check the input data and the parameter file. The "Time Series Data and Parameters File Control" button controls the input data file structure and parameters file structure to see whether there is an error. If no errors are achieved, the last step in this window is to create the similar Hydrologic Response Units for which the technical information is given in the above section. Figure 6.10 shows the "File Manager" window of the DRRSM.

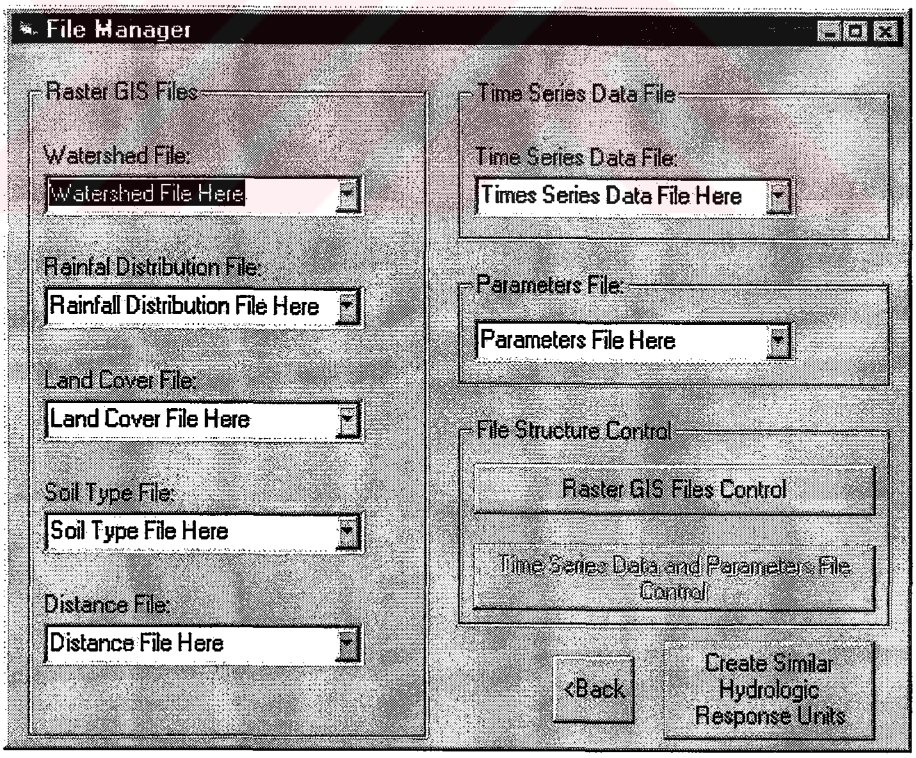


Figure 6.10 "File Manager" window of the DRRSM.

After creating HRU, the next user interface, which is the "Parameters" window, comes up. As described in 6.5.3, parameters are read from the parameters file, and the user can change any parameter and save every parameter combination with different file names. When the user wants to see outputs of the DRRSM according to these parameters, the "Run" button is clicked, and the results are presented as charts. Figure 6.11 shows the "Parameters" window of the DRRSM.

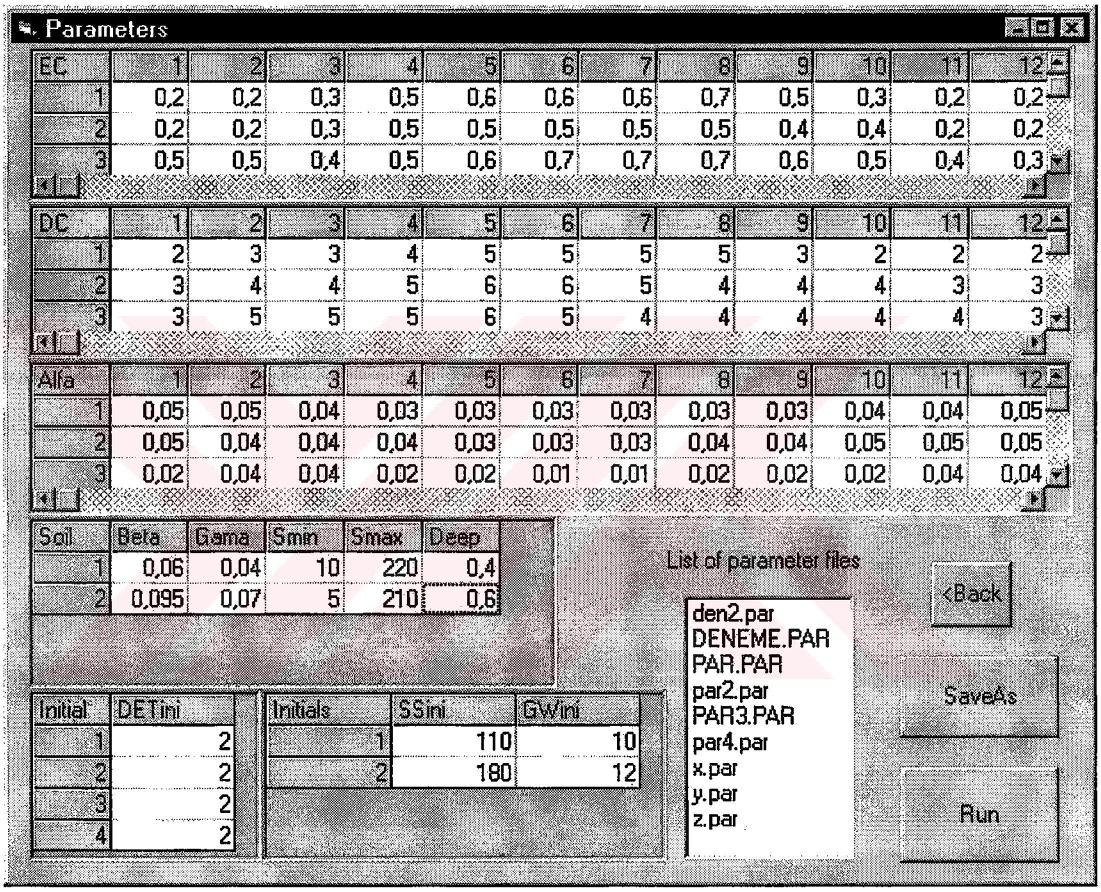


Figure 6.11 "Parameters" window of the DRRSM.

The final interface is the "Graphics" window in which user can select the runoff outputs to be plotted. The surface, sub-surface, groundwater and total runoff values can be displayed as a time series on the screen and compared to the observed runoff series. In addition, the user can obtain the means and standard deviations of the simulated runoff and observed runoff as well. Calibration statistics are also given in this window. Figure 6.12 shows the "Graphics" window of the DRRSM.

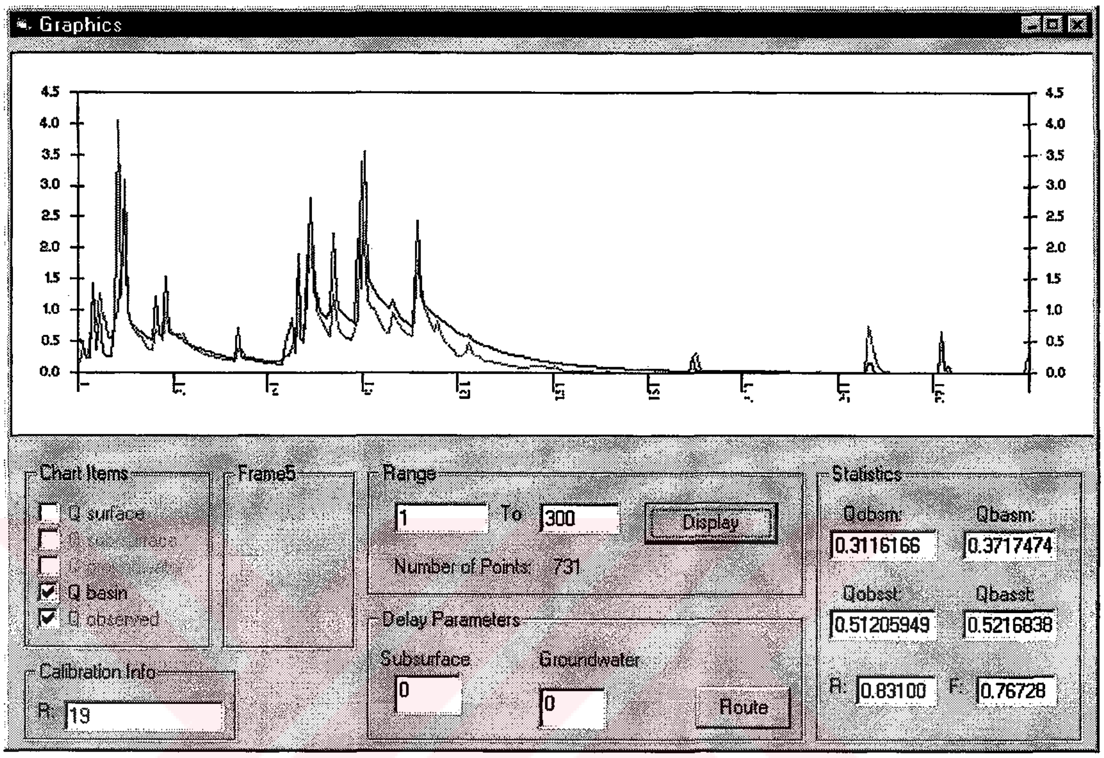


Figure 6.12 The "Graphics" window of the DRRSM.

CHAPTER SEVEN
APPLICATION OF DRRSM TO THE GEDIZ RIVER BASIN

7.1 Introduction of Application Watershed

In order to test the performance of the proposed hydrologic simulation model DRRSM, an application is realized in the Gediz River basin.

The Gediz River in western Turkey has a length of about 275 km, drains an area of 17.200 km^2 and flows from east to west into the Aegean Sea, just north of Izmir. The river basin is located between 38^0 04' and 39^0 13' north latitudes and 26^0 42' and 29^0 45' east longitudes. Figure 7.1 describes the location of the Gediz River basin.

The river is heavily controlled by reservoirs and regulators that divert water for irrigation. The reservoirs of which the biggest one is Demirköprü Dam Reservoir, store river flow from the predominantly winter precipitation for release during the summer. Precipitation in the basin ranges from over 1000 mm/year in the 2300 m high mountains at the eastern end of the basin to a low of around 500 mm/year near the Aegean coast. The climate is hot and dry in the summer season while its warm and wet in the winter season. The water potential of the whole basin is about 1.910^9 m^3/year. The river carries the average amount of 80 ton/km^2/year sediment to the Aegean sea. The natural river bed was discharging to the Izmir bay until the end of 1886 when the downstream of the river was diverted artificially to the outer bay in order to prevent the Izmir bay from sediment load carried by the river.

As mentioned above, there are several reservoirs the sizes of which vary from small to large, providing water for irrigation fields and industrial areas. The biggest reservoir in the basin is Demirköprü Dam reservoir, which is located in the upper Gediz River basin. The reservoir collects water flowing from 4 sub-watersheds called Demirci, Deliiniş, Selendi and Murat. The Demirköprü Dam reservoir affects the downstream flows since it collects the winter flows to release them in the summer season for irrigation. Thus, only the upstream flows of the Demirköprü Dam have the natural rainfall-runoff characteristics.

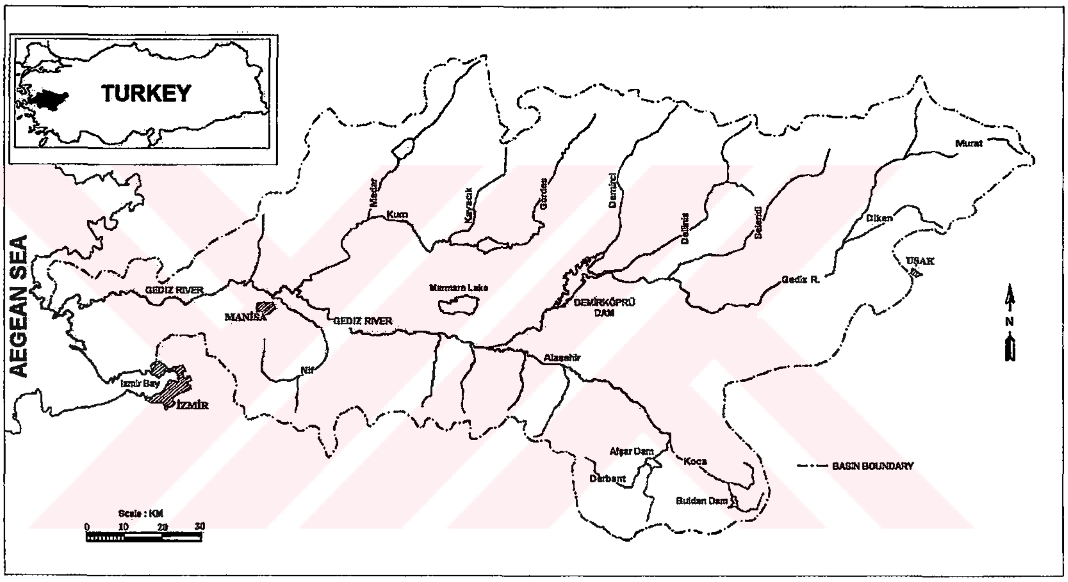


Figure 7.1 The location of the Gediz River basin in Turkey.

The application of the DRRSM is carried out by using the available hydrometeorological data, which constitute the major constraint of the application in the upper Gediz River basin. The problems in both obtaining hydrometeorological data and finding an observation period which must be of same length for both precipitation and discharge observations have forced the application to be only in the Demirci sub-watershed.

Demirci watershed is located on just north of the Demirköprü Dam reservoir, and its flows are observed by Borlu Station which is operated by EIE. The number of station is EIE-522, and this station has been operated since 1970. The daily discharges of the Demirci watershed are observed at this station by using a level meter which takes two measurements per day. The runoff volumes of the station are published in the "Discharge Annual" of the EIE.

Precipitation on the watershed is observed by one meteorological station which is located in the Demirci Town. The meteorological station is operated by DMI and it records total daily rainfall and evaporation. In order to consider the spatial variability of the rainfall, additional meteorological stations are needed for DRRSM. There is just one additional meteorological station, which is located just out of the watershed, called Icikler, and it is operated by DSI. The rainfall records of the Icikler station could be found only for 1995 and 1996. Figure 7.2 shows the Demirci watershed and the hydrometeorological stations used in the study.

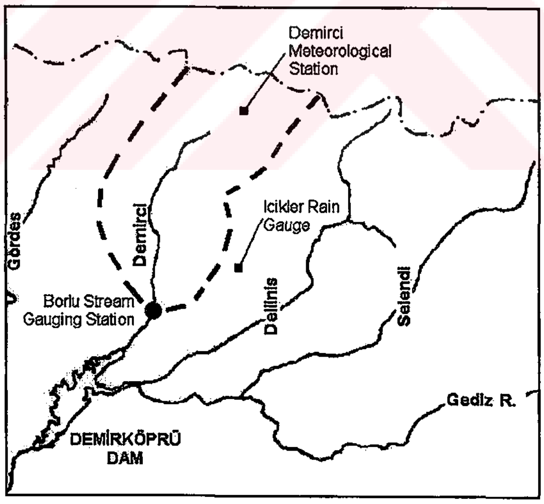


Figure 7.2 Demirci watershed and hydrometeorological stations.

7.2 Preparation of Hydrometeorological Data

7.2.1 Precipitation Data

Spatial variability of the areal precipitation on the Demirci watershed is modeled by using both the Demirci and the Icikler meteorological stations. In order to construct the spatial variability of the precipitation, Demirci watershed is divided into two sections, which are obtained from the Thiessen polygon between Demirci and Icikler stations. The upper part of the Demirci watershed receives the Demirci precipitation, and the lower part of the watershed receives the Icikler precipitation in DRRMS as illustrated in Figure 7.2.

Figure 7.3 describes both the Demirci and the Icikler precipitation data between 01.01.1995 and 31.12.1996, which are used for calibration and verification processes.

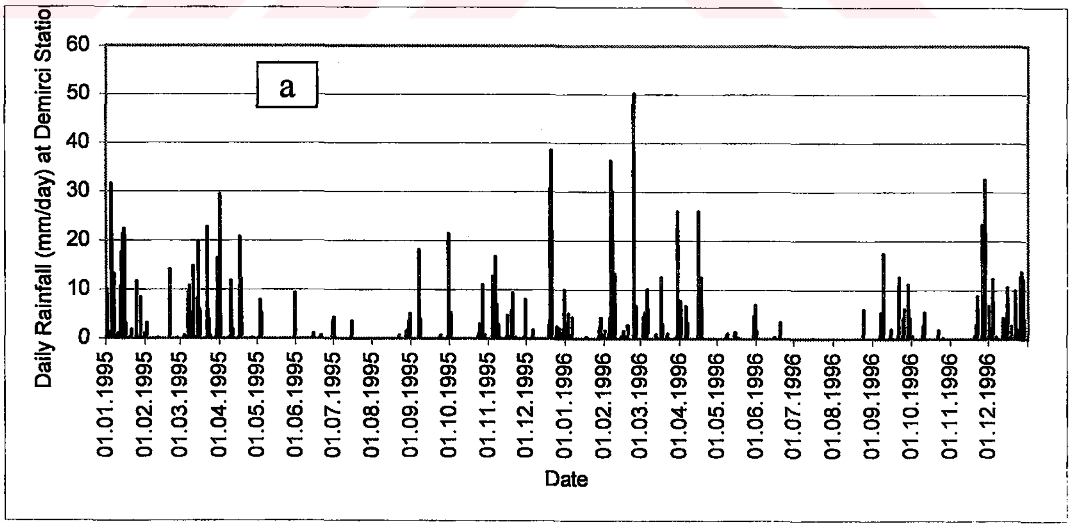


Figure 7.3 Daily rainfall values at Demirci (a) and Icikler (b) Rainfall Stations during 1995 and 1996.

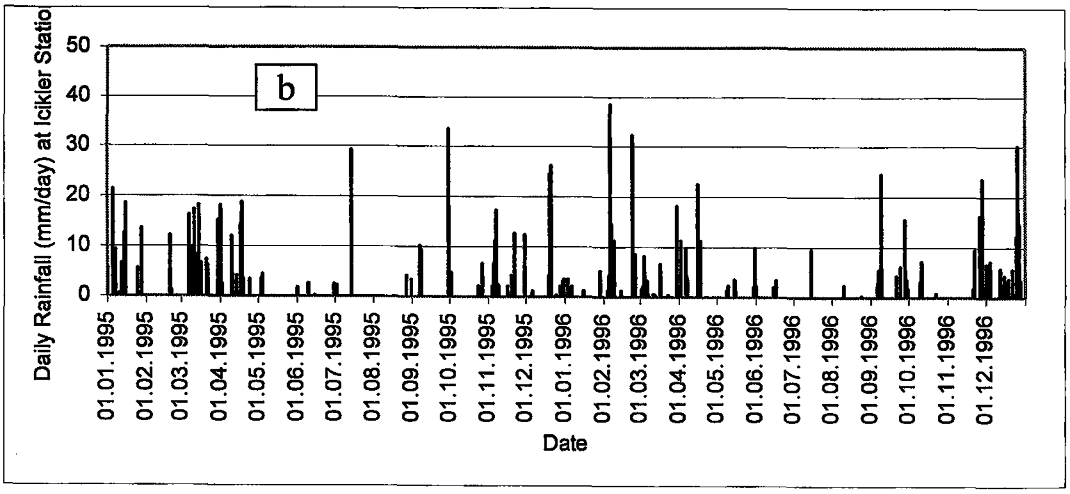


Figure 7.3 (Continued)

Table 7.1 gives some statistics for rainfall records of the Demirci and Icikler stations.

Table 7.1 Statistics of the Demirci and Icikler Station during 1995 and 1996.

Station	Year	Total (mm)	Mean (mm/day)	St. Dev. (mm/day)	Skewness
Demirci	1995	673.4	1.84	5.22	3.82
	1996	584.1	1.60	5.17	5.36
Icikler	1995	571.3	1.57	4.59	3.87
	1996	507.2	1.39	4.49	4.89

7.2.2 Evaporation Data

Evaporation observations are mostly available at big climate stations operated by DMI in Turkey. Thus, every meteorological station does not have evaporation observations and it is very difficult to find evaporation data for every location in Turkey. The same difficulty occurred during the study presented, and the spatial distribution of evaporation could not be evaluated.

Since only the Demirci Meteorological Station observe the evaporation for the Demirci watershed, these observations are assumed to represent the areal watershed evaporation.

On the other hand, the observations of the Demirci Meteorological Station are not continuous. There is no record from the beginning of December to the end of April each year. In order to fill in the gaps in the evaporation observations, continuous temperature observations are used by correlating them with evaporation data. Figure 7.4 and Figure 7.5 represents the daily evaporation and temperature observations of the Demirci station during 1995 and 1996.

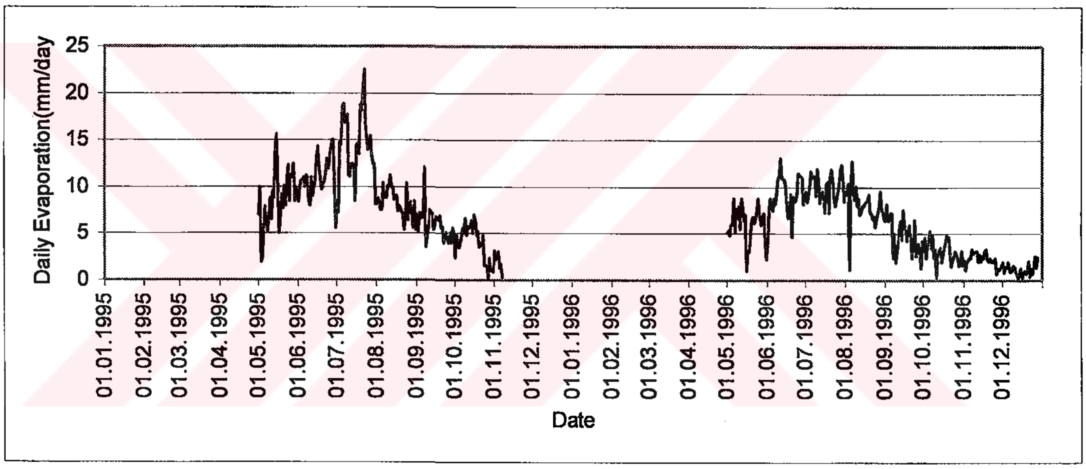


Figure 7.4 Daily evaporation observed at Demirci station during 1995 and 1996.

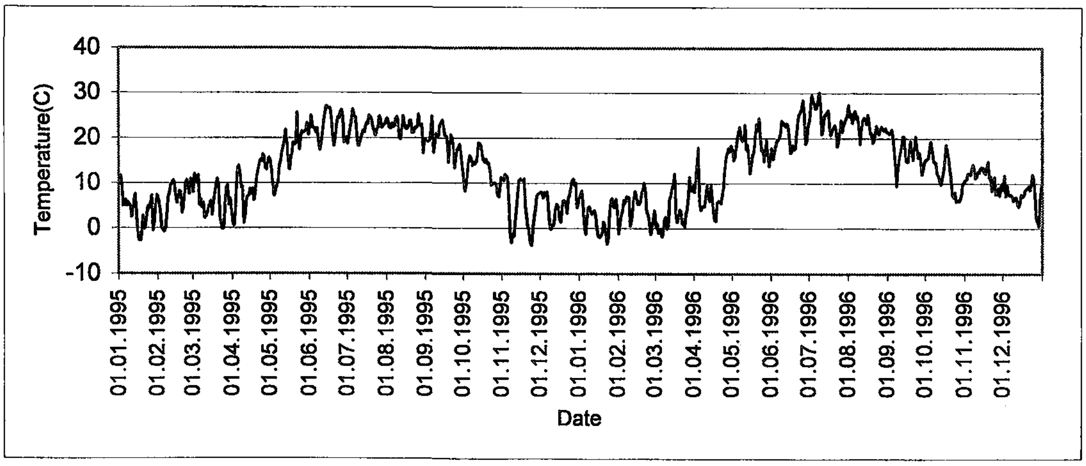


Figure 7.5 Daily temperatures observed at Demirci station during 1995 and 1996.

The correlation analysis, described in Figure 7.6, between daily evaporation and daily temperature showed a significant exponential relationship which can be described as follows;

$$E_{Demirci} = 0.73e^{0.112T_{Demirci}} \quad R=0.80 \tag{7.1}$$

where;

E: Daily evaporation (mm/day)

T: Daily mean temperature (C^0)

R: Correlation coefficient

The missing values in the evaporation records of the Demirci station are filled in by using Equation 7.1, and then, the full time series of evaporation for 1995 and 1996 period are obtained as described in Figure 7.7.

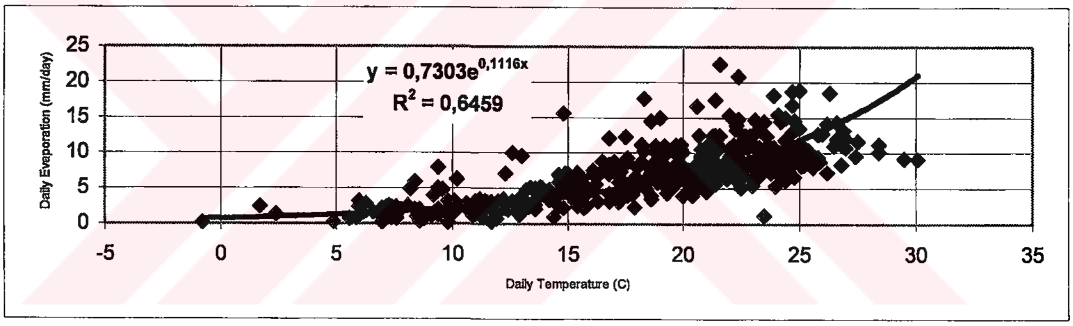


Figure 7.6 The correlation analysis between daily temperature and evaporation values of the Demirci station during 1995 and 1996.

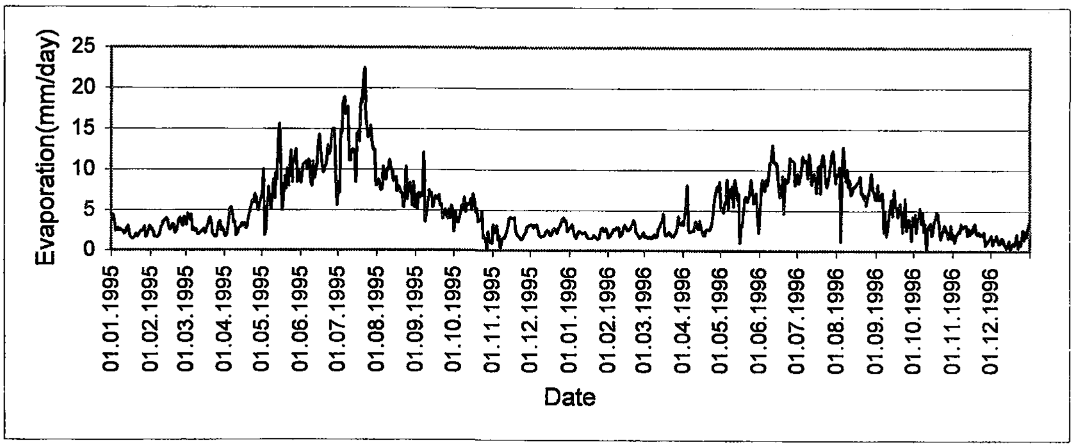


Figure 7.7 Completed daily evaporation at Demirci station during 1995 and 1996.

7.2.3 Runoff Data

Runoff observations in the Demirci watershed are collected at the Borlu Stream Gauging Station which is operated by EIE since 1970. The automatic water level meter is used to determine the flow depth at the station and then, the discharges of the station are calculated by using rating curves prepared before the installation of the station. The rating curves are updated due to the changes of the stream cross section at the location of the station.

Since the runoff records obtained from the discharge annals published by EIE are daily mean discharges in m^3/sec, they are converted to mm/day by dividing them by the watershed area which is 818 km^2. Consequently, all inputs (rainfall and evaporation) and outputs (discharges) are transformed in to the same units.

In Figure 7.8 daily mean discharges (mm/day) of the Borlu station are given for the period between 1995 and 1996, which are the calibration and verification years, respectively. Table 7.2 also gives some statistics of the Borlu stream gauging station during 1995 and 1996.

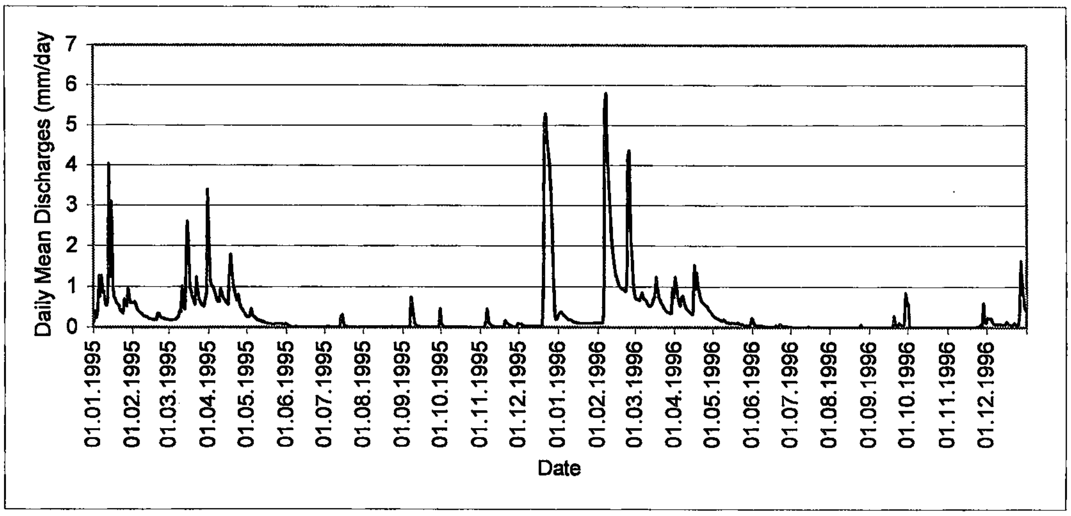


Figure 7.8 The daily mean discharges in mm/day of the Borlu Stream Gauging Station during 1995 and 1996.

Table 7.2 Some statistics of the observed runoff during 1995 and 1996 at Borlu stream gauging station.

Station	Year	Total (mm)	Mean (mm/day)	St. Dev. (mm/day)	Skewness
Borlu	1995	127.9	0.351	0.728	4.16
	1996	115.1	0.314	0.689	4.73

7.3 Preparation of Raster Data

Preparation of the raster data layers require a GIS (Geographical Information System) software. In this thesis, IDRISI software which is the popular GIS developed by Clark Labs. is used for raster data manipulations. IDRISI is a raster based GIS which includes all kinds of raster GIS operations needed for analyzing and manipulation of raster data. It can display, store and analyze the raster data and can convert vector GIS files to raster format so that they can be used.

In the following sections, GIS operations performed by IDRISI are described in the relevant applications.

7.3.1 Topography, Watershed Boundary and River Network

Topography of the Demirci watershed is obtained from the USGS (United States Geological Survey) EROS (Earth Observation Sytem) Data Center which can be reached via internet. This center distributes several data of the world such as topography, land use and cover, climate properties in different formats. GTOPO30 data sets include world topography as DEM (Digital Elevation Model) images with 30-arc seconds (0.008333333333333 degrees), which indicates 1kmx1km resolution. This image is in WGS84 projection system which defines the coordinate system. The image of the world consists of 33 sub images and each sub image covers a specific region of the world. The E020N40 sub image includes the region where the Gediz

Basin is located. This sub image is downloaded and re-projected by using GIS operations in the IDRISI as UTM (Universal Transverse Mercator), which is also used as a map projection system in Turkey. The transferred topographic image is presented in Figure 7.9.

After obtaining the topography of the Gediz River Basin region, watershed operation of the IDRISI is performed and watershed of the Gediz River basin is obtained. The boundary of the basin is produced by using topography with a 1km x 1km cell resolution. Figure 7.10 gives the DEM and the basin boundaries of the Gediz River basin.

The flow accumulation operation of the IDRISI generates the river network of a basin. This operation is performed to obtain the Gediz River network with the same resolution of the topography.

In order to determine the watershed area and the boundaries, at the Borlu (EIE525) station, again the watershed operation of IDRISI is performed on the location of the Borlu station and watershed boundaries of the station are obtained. Watershed of the Borlu station obtained from topography with 1km x 1km resolution is calculated 800 km^2 by the area operation of the IDRISI. The watershed area of the station is given as 818 km^2 in the EIE annals. This small difference is caused by the resolution of the raster topography map. Figure 7.11 shows the watershed boundaries of the Borlu station, river network of the whole Gediz River basin, and the hydrometeorological stations used in the application.

After determining the watershed area of the Borlu station, IDRISI creates the DEM of the Demirci watershed by using the overlay operation between DEM of the Gediz River basin and Demirci watershed boundary. Finally, Figure 7.12 gives the DEM of the Demirci watershed behind the Borlu stream gauging station.

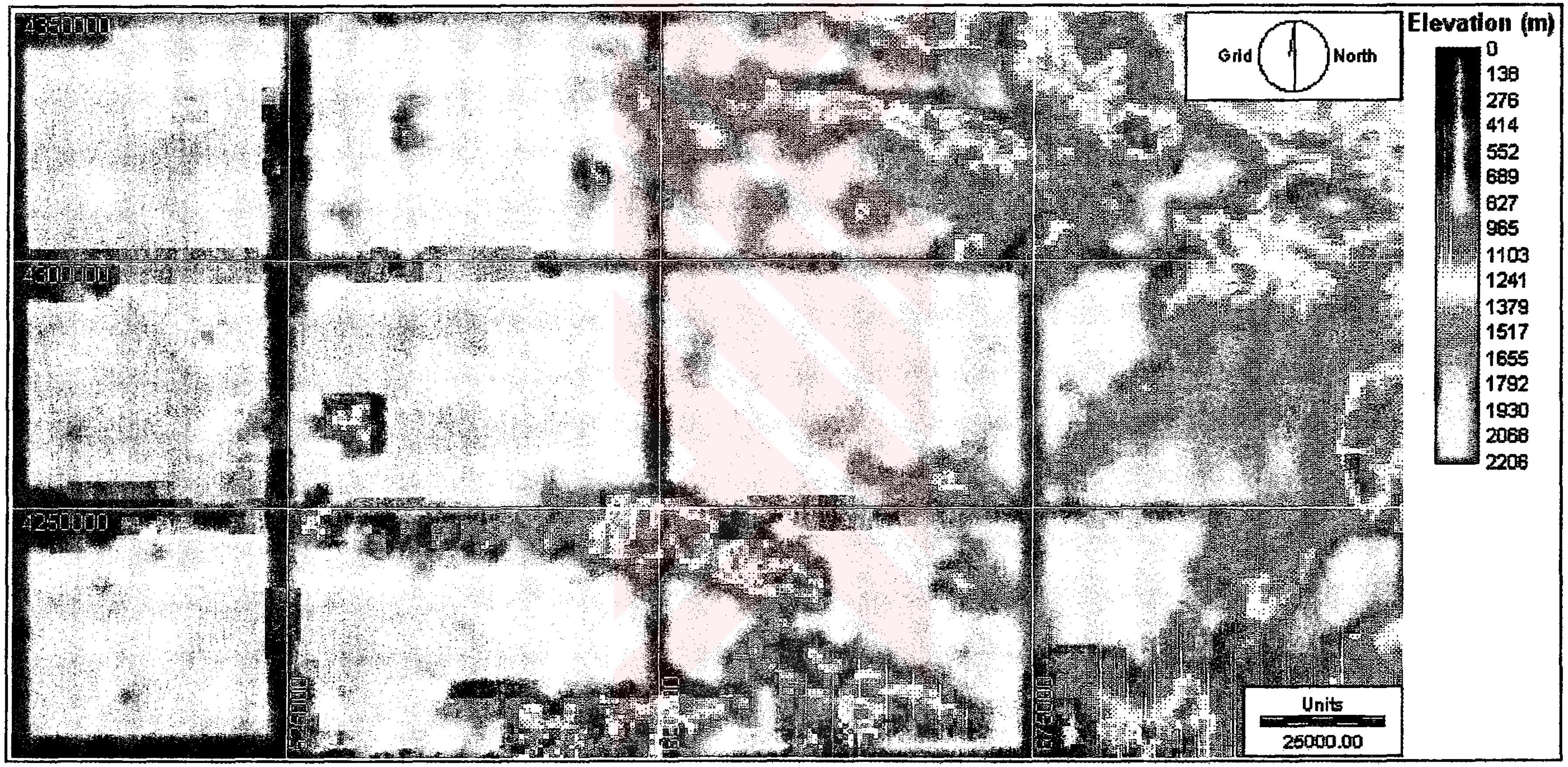


Figure 7.9 Topography of the Gediz River basin region obtained from USGS EROS Data Center.

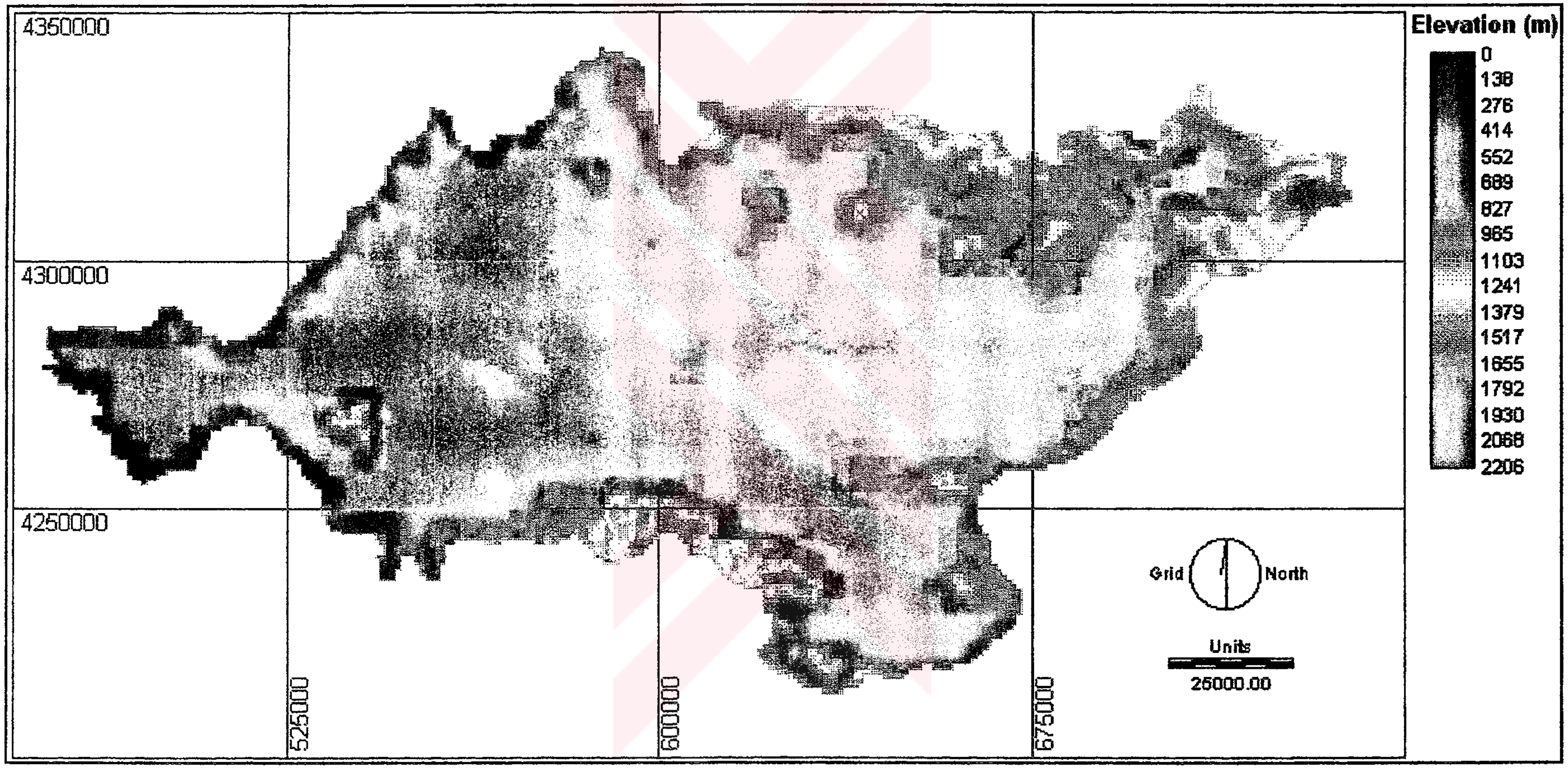


Figure 7.10 Gediz River basin topography and basin boundaries.

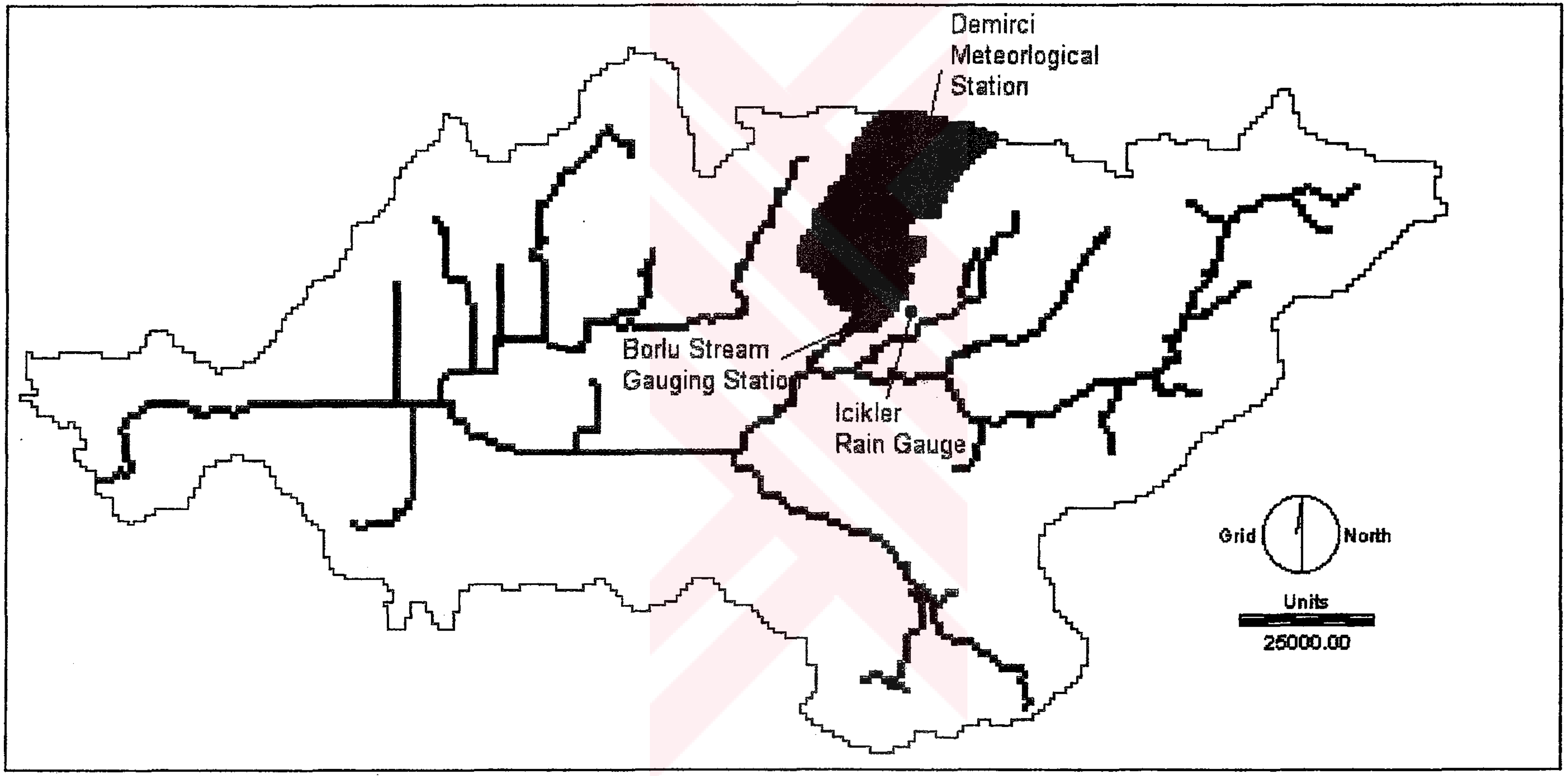


Figure 7.11 Watershed boundaries of the Borlu Station, river network and hydrometeorological stations.

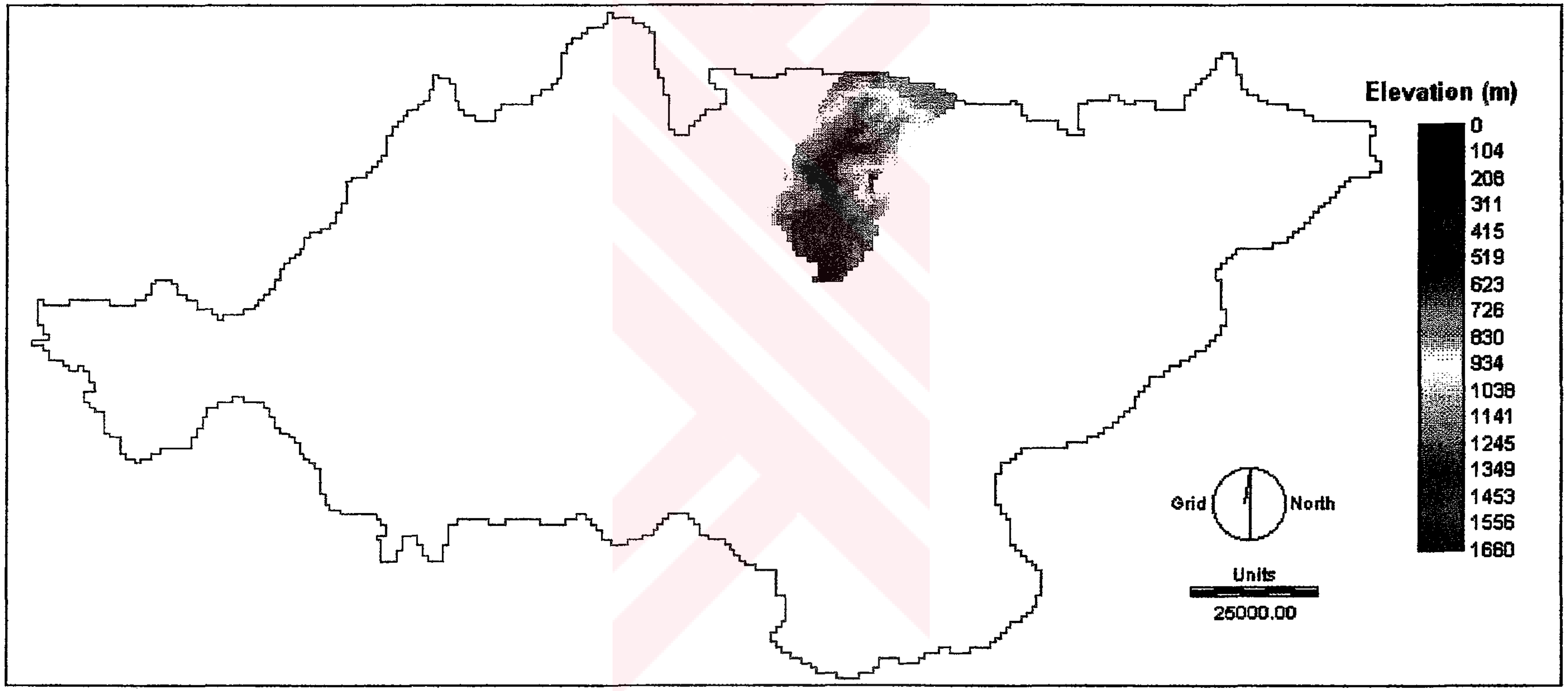


Figure 7.12 DEM of the Demirci watershed behind the Borlu stream gauging station.

7.3.2 Land Cover

As explained in the above section, EROS Data Center distributes several data sources where land cover information also exists in 1km x 1km resolution. These data are stored in the LCC (Land Cover Characteristics) V2.0 data set which is divided into 6 regions. Euroasia region, where Gediz Basin region is located, has 3 different map projection systems which are Interrupted Goode Homolosine, The Lambert Azimuthal Equal Area optimized for Europe, and Lambert Azimuthal Equal Area optimized for Asia. In this application, The Lambert Azimuthal Equal Area optimized for Europe is selected and converted to the UTM projection system by using re-project operation of the IDRISI. The converted image is again in 1km x 1km resolution and is convenient for use with topographic maps.

The land cover characteristics map has 253 different land cover classes which define the land cover properties such as forest, water body, cropland, etc. The re-projected image is reclassified by using the IDRISI reclass operation. According to these classes, the land cover distribution of the Gediz River basin is obtained. The resulting image is given in Figure 7.13.

Finally, the land cover distribution of the Demirci watershed is extracted by IDRISI using the whole Gediz River basin land cover data. Figure 7.14 shows the land cover distribution of the Demirci watershed used in the DRRSM model.

By using the area operation of the IDRISI, it's found that 2.1% of the watershed area is used for non-irrigated agriculture which includes wheat, barley, rhye and corn, 47.8% of the watershed area is covered by sparse maki, 37.7% of the watershed area is covered by coniferous with low density, and 12.4% of the watershed area is barren.

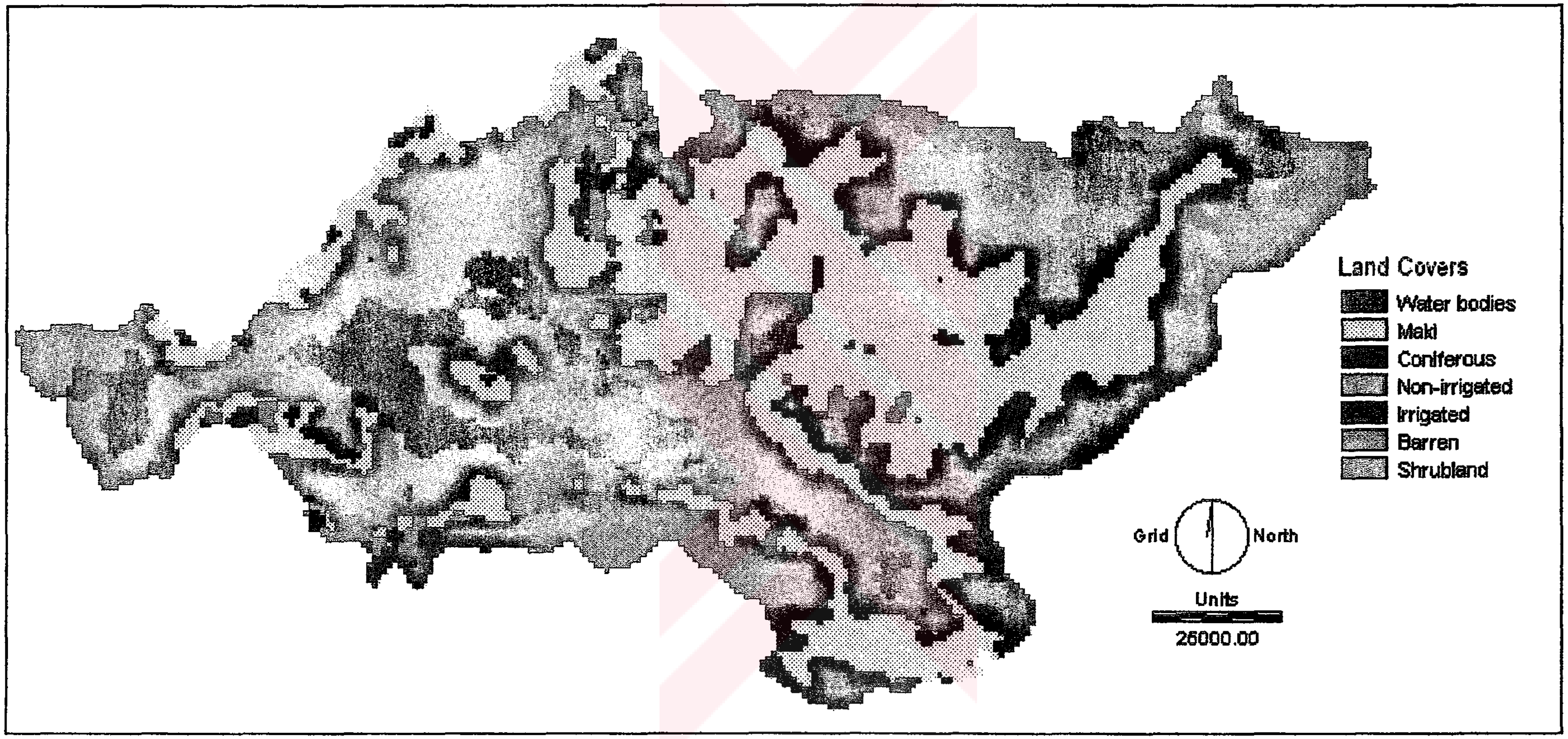


Figure 7.13 Land cover distribution of the Gediz River basin.

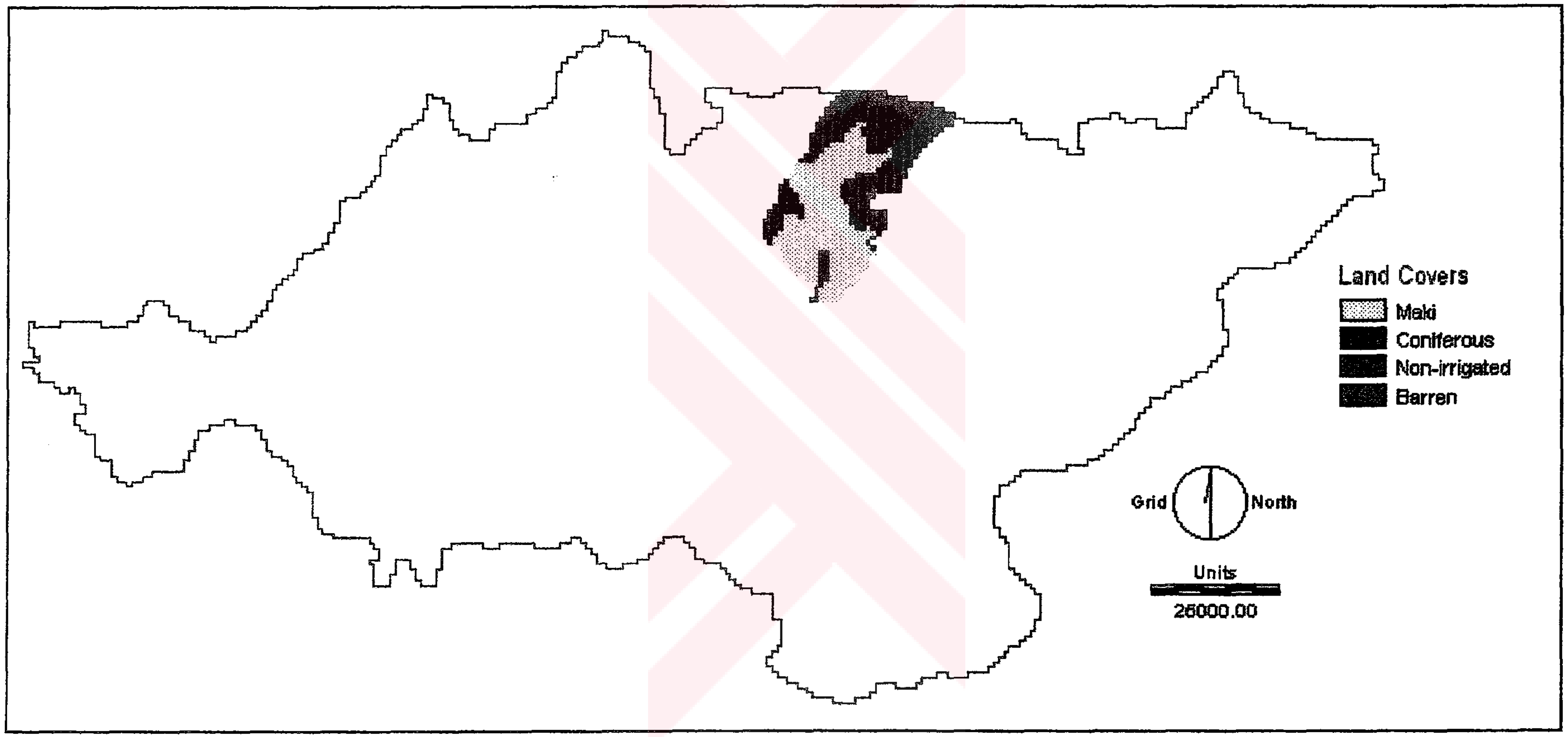


Figure 7.14 The land cover distribution of the Demirci watershed, used in the DRRSM.

7.3.3 Soil Properties

The EROS Data Center also has the major soil classes information of the whole world, but this information is not as comprehensive as the topography and land cover information. The data set includes major soil classification of the world with a 0.5 degree resolution which is equal to about 60 km x 60 km resolution. This resolution is not as satisfactory as resolution of the topography and land cover information in the same data center. In addition, the simulated watershed is quite small in comparison with the soil data resolution. Consequently, the use of the soil information available on the EROS Data Center is omitted due to the resolution inadequacy.

In order to represent the distribution of the soil properties over the Gediz River basin, traditional soil maps of the basin is digitized and used in the application. The soil maps of the Gediz River basin are designed by the TOPRAKSU in 1974. By several in-situ measurements and field studies, TOPRAKSU prepared soil maps of the Gediz River basin, considering soil texture, soil depth and surface conditions. The published maps are in 1/200 000 scale and has no reference projection.

First of all, the soil maps are digitized by considering soil type polygons on the maps, which define soil properties. These digitized maps are in vector formats. Then, using the convert operations in the IDRISI, these vector maps are converted to raster maps. Since these maps have no projection reference yet, the locations of the big cities and towns are designed as reference locations. Then, the locations of the towns are transferred to the original locations on the topography map which is projected in the UTM projection reference. The distortions of the town locations are used to re-project the whole soil map converted to the raster layer. Finally, the raster soil map with UTM projection is obtained.

The classified texture map of the Gediz River basin is presented in Figure 7.15. There are 3 main texture classes, which are fine, medium and coarse in the Gediz River basin.

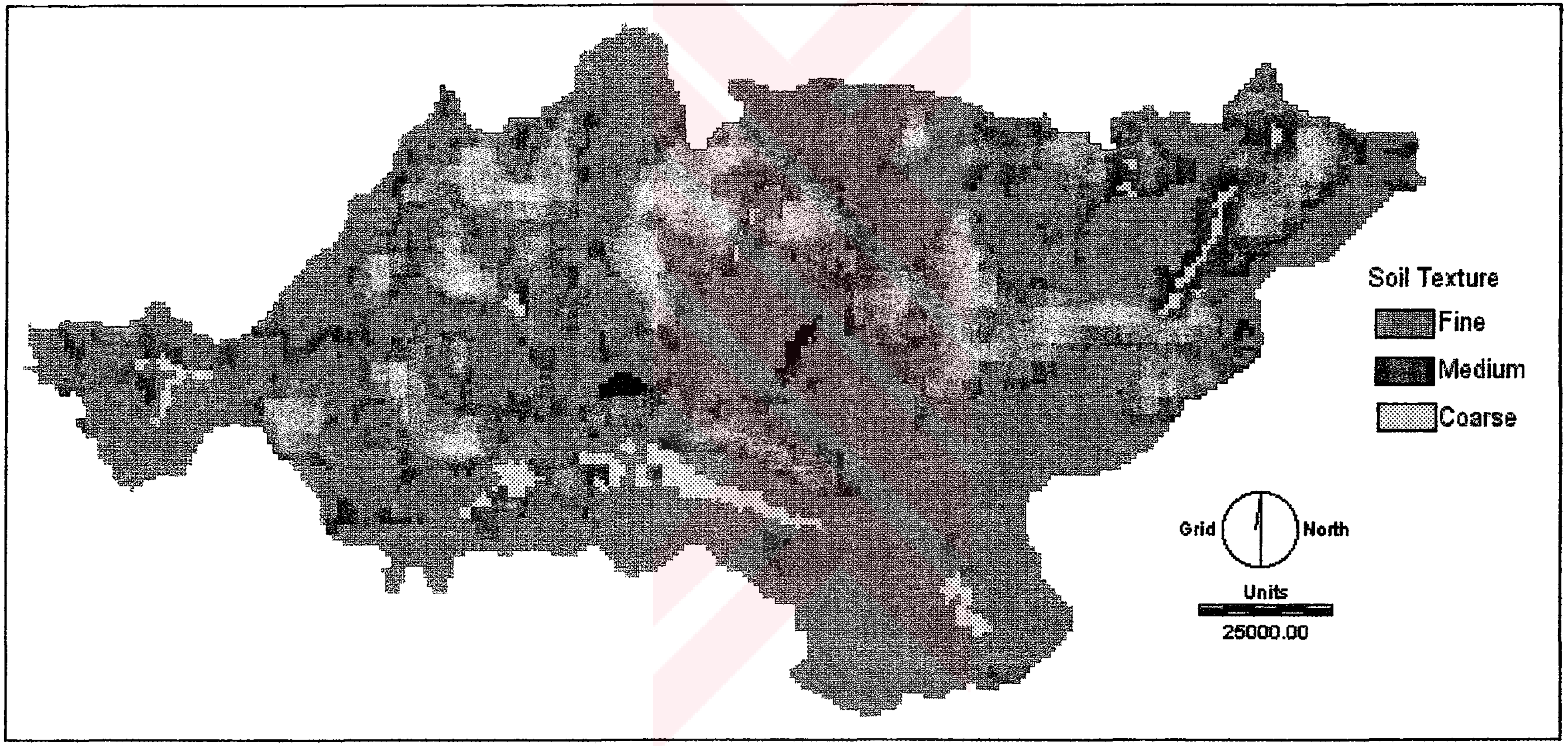


Figure 7.15 Distribution of the soil texture properties of the Gediz River basin.

Considering the soil texture of the Gediz River basin, the distribution of the soil texture properties of the Demirci watershed is obtained by using IDRISI overlay operations. Figure 7.16 defines the soil texture classes used in the DRRSM model.

7.3.4 Spatial Variability of the Rainfall

As mentioned in Section 7.2.1, spatial variability of the rainfall is presented by means of the Thiessen polygon constructed between Demirci meteorological station and Icikler rain gauge. Figure 7.17 shows the Thiessen polygon over Demirci watershed and the locations of the rainfall observation stations. The upper part of the Demrici watershed receives the precipitation of the Demirci Meteorological Station, the lower part of the watershed receives the precipitation of the Icikler Rain Gauge.

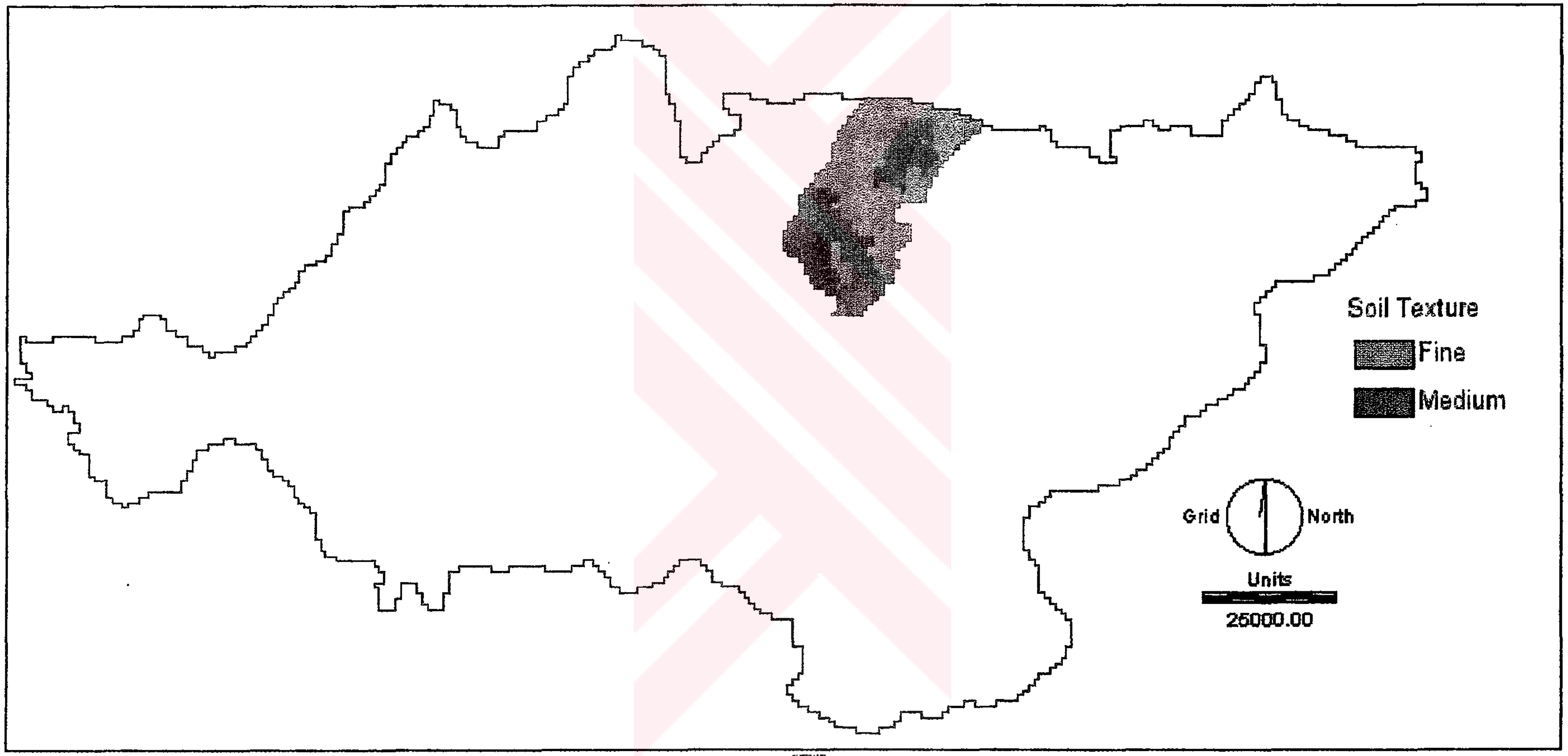


Figure 7.16. Soil texture classes of the Demirci watershed used in the DRRSM.

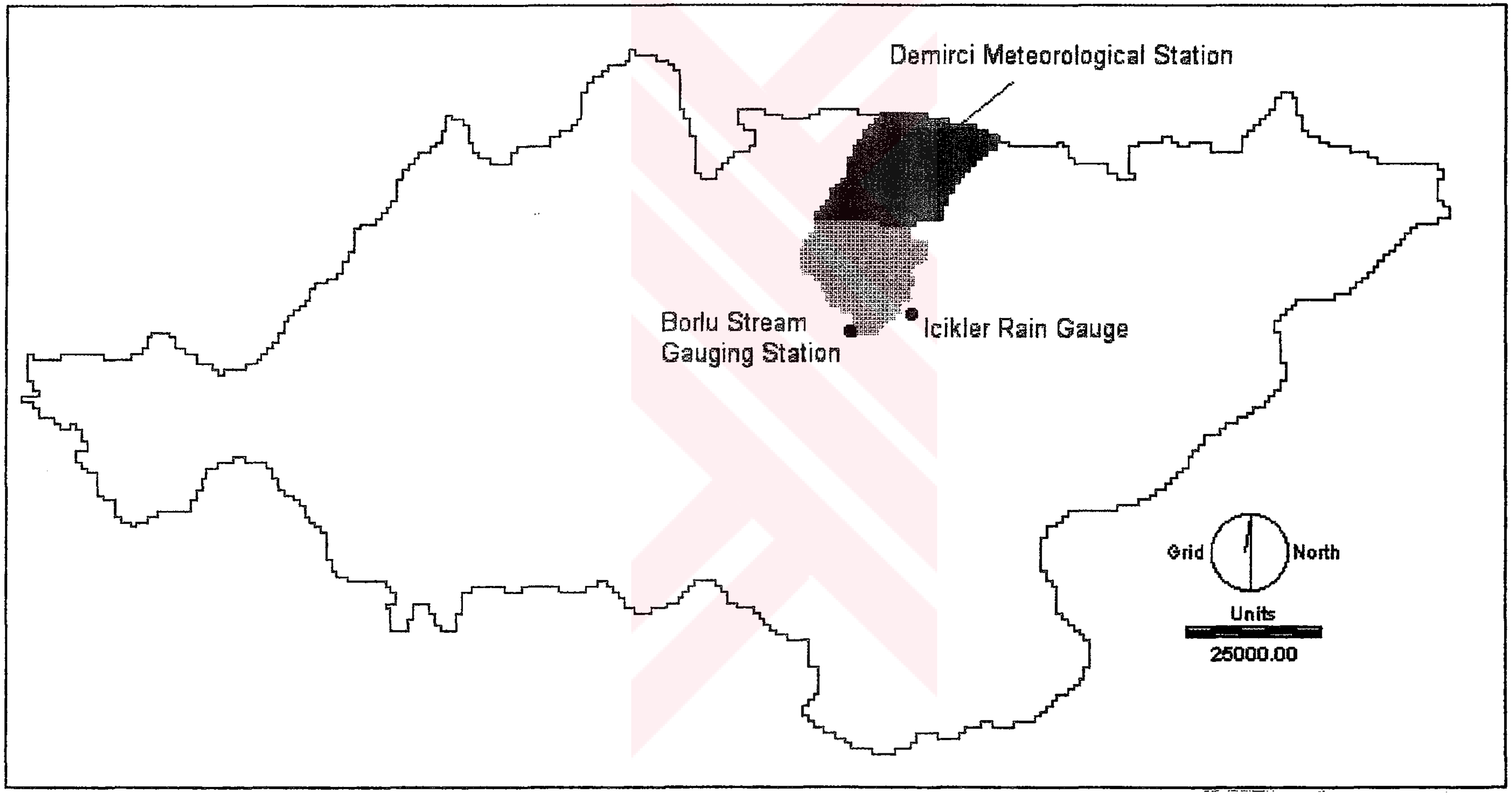


Figure 7.17 The spatial distribution of the rainfall over the Demirci watershed and the locations of the rainfall stations.

7.4 Preparation of HRUs

As mentioned in Chapter 6, HRUs (Hydrological Response Units) are homogeneous land segments in a watershed with respect to land cover, soil properties and rainfall distribution. According to the above explanation, spatial land cover, soil texture and rainfall distribution of the Demirci watershed are overlaid on each other, and each homogeneous land segment is obtained by the method explained in Chapter 6. Figure 7.18 shows the HRU of the Demirci watershed.

7.5 Data and Parameter Files of DRRSM

Data file of the DRRSM includes simulation times, rainfall records, evaporation data and observed runoff values in ASCII text format. The structure of the data file is explained in Chapter 6. Table 7.3 gives input values of only the first 10 days in data file for DRRSM, which has 731 days for the whole simulation. The first 365 values which belong to the year of 1995 are used for calibration and the remaining 366 values which belong to the year of 1996 are used for verification.

Table 7.3 Data file structure of the DRRSM for simulation in Demirci watershed.

Step	Year	Month	Day	$P_{Icikler}$	$P_{Demirci}$	$E_{Demirci}$	$E_{Demirci}$	Q_{Borlu}
1	1995	1	1	5.8	10.3	3.7	3.7	0.150
2	1995	1	2	0	9.1	4.4	4.4	0.408
3	1995	1	3	0	0	3.8	3.8	0.233
4	1995	1	4	0	1.2	2.5	2.5	0.448
5	1995	1	5	21.3	31.6	2.5	2.5	1.267
6	1995	1	6	2.2	2.4	2.8	2.8	0.768
7	1995	1	7	9.3	13.3	2.5	2.5	1.267
8	1995	1	8	0	0.5	2.6	2.6	0.859
9	1995	1	9	0	0	2.5	2.5	0.888
10	1995	1	10	0.6	1.1	2.4	2.4	0.564

(All values are in mm/day unit.)

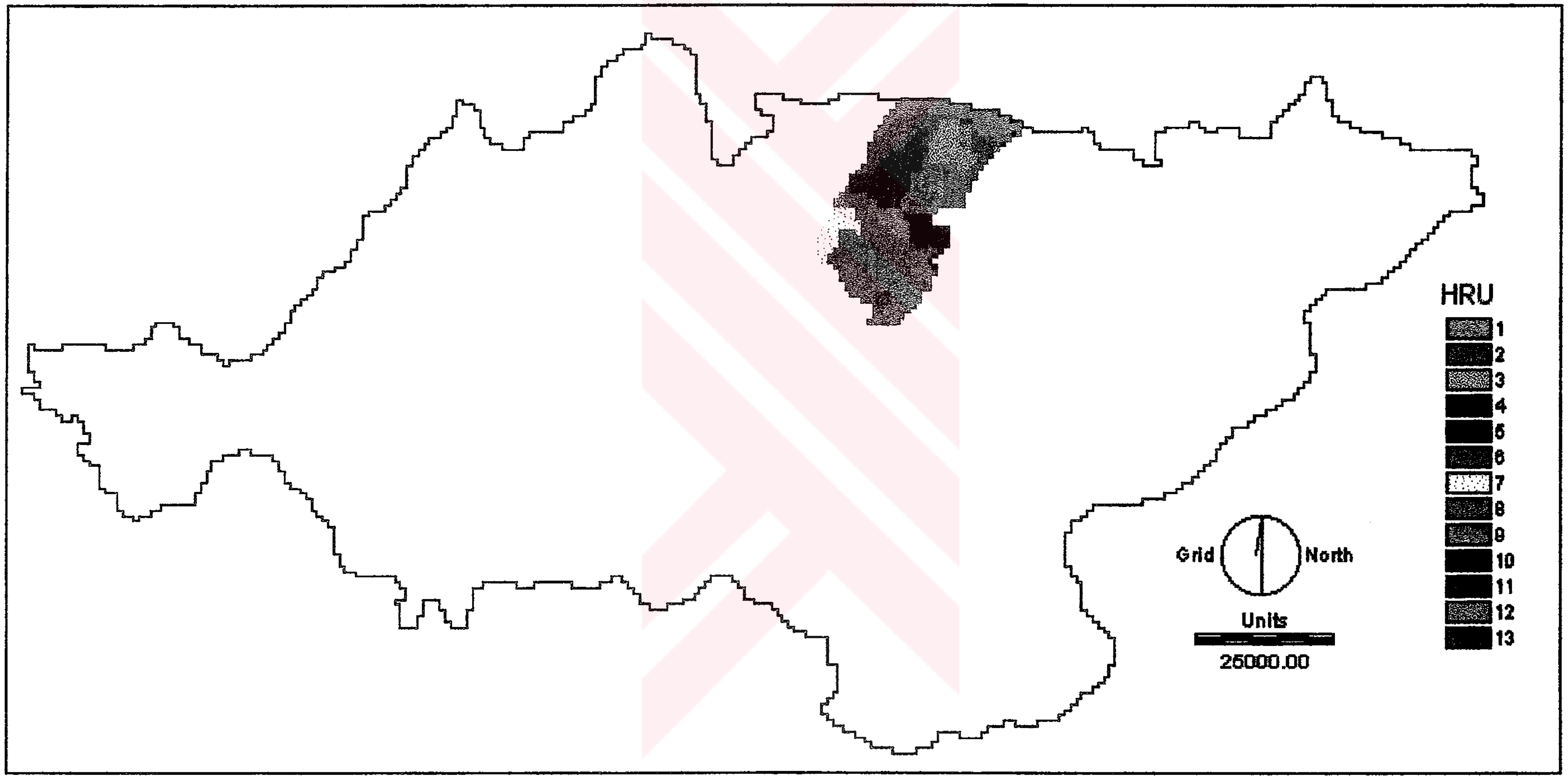


Figure 7.18 Spatial distribution of the HRUs over Demirci watershed.

The parameter file describes the parameter values for the land cover and soil types. The details of the parameters in the DRRSM are explained in Chapter 6. The initial values of the parameters are determined as all values are the same without considering the spatial variation of land covers and soil textures. This assumption makes the model run as a lumped type. After that, all parameters are adjusted by considering land cover type, soil texture and seasonal variations.

In Demirci watershed, there are 4 different land cover types and 2 soil texture types. Table 7.4 gives the explanation of the land cover type and soil texture type and their corresponding numerical codes used in the DRRSM for Demirci watershed. Table 7.5 also gives the initial values of the model parameters for Demirci watershed.

Table 7.4 Land cover and soil texture types and corresponding codes in the DRRSM for Demirci watershed.

Land CoverType	**Code in DRRSM**
Non-irrigated	1
Maki	2
Coniferous	3
Barren	4

Soil Texture Type	**Code in DRRSM**
Fine	1
Medium	2

Table 7.5 Initial values of the parameters for Demirci Watershed.

		Months											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
		Evapotranspiration Coefficients (EC)											
Land Cover Type	**1**	0.1	0.2	0.4	0.4	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1
	2	0.1	0.2	0.4	0.4	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1
	3	0.1	0.2	0.4	0.4	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1
	4	0.1	0.2	0.4	0.4	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1
		Detention Capacities (DETCAP)											
Land Cover Type	**1**	1	1	2	2	2	1	1	1	1	1	1	1
	2	1	1	2	2	2	1	1	1	1	1	1	1
	3	1	1	2	2	2	1	1	1	1	1	1	1
	4	1	1	2	2	2	1	1	1	1	1	1	1
		Surface Runoff Coefficients (α)											
Land Cover Type	**1**	0.015	0.01	0.015	0.015	0.005	0.005	0.005	0.005	0.01	0.01	0.01	0.01
	2	0.015	0.01	0.015	0.015	0.005	0.005	0.005	0.005	0.01	0.01	0.01	0.01
	3	0.015	0.01	0.015	0.015	0.005	0.005	0.005	0.005	0.01	0.01	0.01	0.01
	4	0.015	0.01	0.015	0.015	0.005	0.005	0.005	0.005	0.01	0.01	0.01	0.01

		Sub-Surface Runoff Coefficient (β)	Groundwater Runoff Coefficient (γ)	Minimum Soil Water Storage (SMIN)	Maximum Soil Water Storage (SMAX)	Deep Percolation Coef. (DEEP)
Soil Texture Type	1	0.08	0.06	0	75	0.6
	2	0.08	0.06	0	75	0.6

		Initial Values for Surface Detention
Land Cover Type	1	1
	2	1
	3	1
	4	1

		Initial Values for Soil Water Storage	Initial Values for Groundwater Storage
Soil Texture Type	1	35	3
	2	35	3

7.6 Calibration of DRRSM for Demirci Watershed

In the above section, the initial values of the DRRSM parameters are given as they are not considered spatially distributed. Each parameter group which depends on land cover types (EC, DETCAP, α) is adjusted by considering land cover type properties and seasonal variations in itself. A similar approach is applied to the parameters which depend on soil texture types (β, γ, DEEP, SMIN and SMAX) by considering soil texture properties.

The following sections, explain the adjustment criteria for parameters of both the land cover and soil texture types.

Land Cover Coefficients (EC, DETCAP, α)

Evapotranspiration coefficient converts the daily pan evaporation into daily evapotranspiration considering land cover properties. In the Demirci watershed, there are 4 different land cover types which are non-irrigated, maki, coniferous and barren areas as described earlier in Table 7.4.

Non-irrigated areas include crops such as wheat, barley, corn, etc. which are planted around the 10^{th} month and cut until the end of the 9^{th} month (Topraksu, 1974). Crop development reaches the highest stage after the 4^{th} month; thus, canopy has the maximum level for evapotranspiration and surface detention. However, at this period surface runoff capability of the canopy decreases.

The canopy of the Maki areas increases in the spring season; then, evapotranspiration coefficients of these areas reach the maximum values at that time period. Similarly, detention capacity of the canopy is bigger than that of the fall and summer seasons. Consequently, surface runoff capability of the canopy in Maki areas in fall and summer seasons is lower than that of the spring season.

Coniferous areas include low density forest patterns which are oak, pine, ash tree, etc. The canopy of these trees increases by means of leaf area in the spring season, and the highest evapotranspiration coefficients and detention capacity of the coniferous occur while surface runoff capability of those areas decrease in that season.

Barren areas include low density shrub and weed; thus, the evapotranspiration coefficients and surface detention capacities of the canopy of the plants in the barren area increase in the spring season. On the contrary, the surface runoff capability of the canopy decreases in the same season.

Soil Texture Coefficients (β, γ, SMIN, SMAX, DEEP)

There are two soil texture types which are fine and medium, in the Demirci watershed (Topraksu, 1974). The soils with Fine texture store less amount of water than soils with Medium texture, and the minimum storage capacities of fine-texture-soils are bigger than those of medium-texture-soils. In Demirci watershed, fine-texture-soils generally consist of Rendzina soils, which occur on the Marn geological formation layers where substantial deep percolation can occur. Similarly, medium-texture-soils generally consist of brown forest soils which occur on Andezit and Bazalt layers where deep percolation can not occur as much as that on Marn layers.

The adjustment criteria of the model parameters explained in the above section are employed by the manual calibration method until the best result of simulation in comparison with the observed runoff in 1995 is achieved. The performance of the calibration is measured by means of three statistics mentioned in Chapter 6.

Manual Calibration of DRRSM

The first statistic is **D,** which is the sum of the square of differences between observed and simulated runoff explained in Equation 6.8. The statistic **D** is used to compare the results of consecutive simulations in which the parameter values are adjusted. A decrease in the values of **D** during the adjustment process of the parameters, shows the convergence to the best parameter set. The second statistic is **R,** which is the correlation coefficient between observed and simulated runoff as described in Equation 6.9. The last statistics is **F** which is proposed by WMO (World Meteorological Organization) (WMO, 1986). In this approach, the best model parameters give the closest value to "1" for the **F** parameter defined in Equation 6.10. Both the **R** and **F** statistics are considered as the dominant indicators of the goodness of fit associated with each set of model parameters.

Finally, after more than a hundred simulations and adjustments in the model parameters (***EC, DETCAP, α, β, γ, SMIN, SMAX, DEEP)***, the best result of the simulation is achieved. The optimum parameters of the DRRSM for Demirci watershed is given in Table 7.6.

Table 7.6 The optimum parameter values in DRRSM for Demirci watershed during year of 1995.

		Months											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
		Evapotranspiration Coefficients (EC)											
Land Cover Type	**1**	0.2	0.2	0.2	0.3	0.3	0.4	0.3	0.3	0.3	0.2	0.2	0.2
	2	0.3	0.3	0.4	0.6	0.6	0.4	0.3	0.3	0.3	0.3	0.3	0.3
	3	0.4	0.4	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.4
	4	0.3	0.3	0.3	0.3	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.3
		Detention Capacities (DETCAP)											
Land Cover Type	**1**	1	1	1	2	2	2	2	2	2	1	1	1
	2	2	2	3	4	4	3	3	3	3	3	2	2
	3	4	4	4	6	6	4	4	4	4	4	4	4
	4	3	3	3	4	4	3	3	3	3	3	3	3
		Surface Runoff Coefficients (α)											
Land Cover Type	**1**	0.025	0.025	0.010	0.005	0.005	0.005	0.005	0.005	0.010	0.025	0.025	0.025
	2	0.020	0.020	0.015	0.010	0.005	0.010	0.015	0.020	0.020	0.020	0.020	0.020
	3	0.030	0.020	0.015	0.010	0.005	0.010	0.010	0.020	0.020	0.030	0.030	0.030
	4	0.020	0.020	0.010	0.005	0.005	0.010	0.015	0.020	0.020	0.020	0.020	0.020

		Sub-Surface Runoff Coefficient (β)	**Groundwater Runoff Coefficient (γ)**	**Minimum Soil Water Storage (SMIN)**	**Maximum Soil Water Storage (SMAX)**	**Deep Percolation Coef. (DEEP)**
Soil Texture Type	**1**	0.09	0.08	40	100	0.65
	2	0.08	0.06	20	130	0.55

		Initial Values for Surface Detention
Land Cover Type	**1**	1
	2	1
	3	1
	4	1

		Initial Values for Soil Water Storage	**Initial Values for Groundwater Storage**
Soil Texture Type	**1**	70	3
	2	60	2

The calibration statistics D, R and F are given in Table 7.7. The simulated and observed runoff values considering the above parameters for 1995 are given in Figure 7.19.

Table 7.7 The calibration statistics for Demirci watershed during 1995.

Calibration Year	D	R	F
1995 (N=365)	89	0.72	0.06

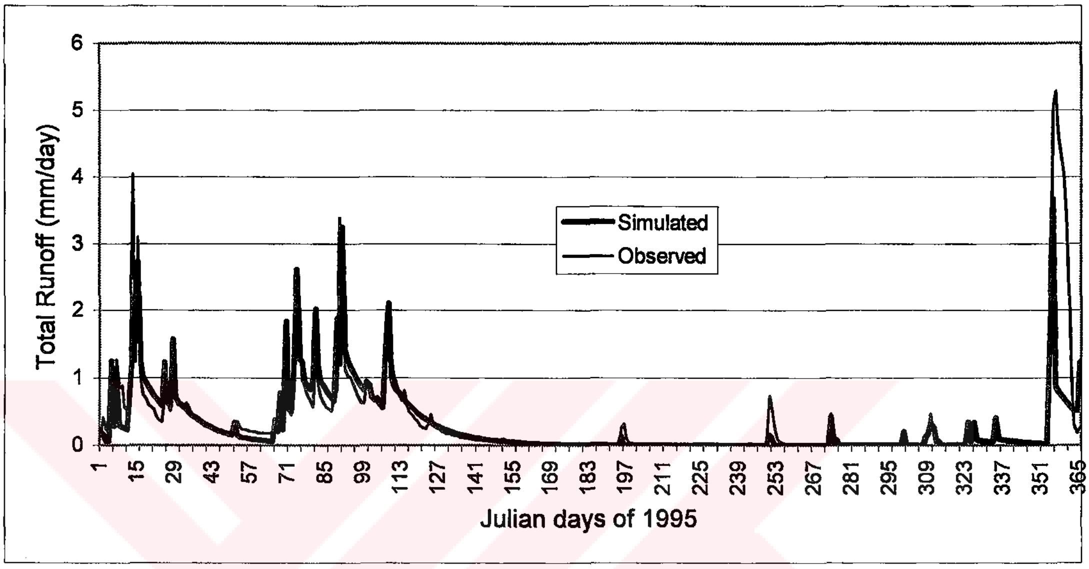


Figure 7.19 Simulated and observed runoff during calibration period 1995

As can be seen from Figure 7.19, at the end of the year 1995, there are big differences between the observed and the simulated runoff. These differences which continue for 10 days affect the calibration statistics given in Table 7.7. Although, the rainfall records during the last 10 days of the year 1995 do not show very high values, the observed runoff values recorded at Borlu station are too high. That means there are sampling errors in the observed runoff values at the end of year 1995, possibly caused by a fault in the water level meter.

When the last 10 days of the year 1995 are eliminated from the calibration process, considerable changes occur in the calibration statistics (D, R, F) and in the mean value and standard deviations of both the observed and the simulated runoff. Table 7.8 gives the calibration statistics of the DRRSM after eliminating the last 10 days from the simulation in Demirci watershed. In addition to that, Table 7.9 gives the mean and the standard deviation of the observed and simulated runoff values for both the full record (N=365 days) of 1995 and the 10 days eliminated record (N=355 days).

Table 7.8 The calibration statistics calculated from last 10 days eliminated record of 1995 for Demirci watershed.

Calibration Year	**D**	**R**	**F**
1995 (N=355)	19	0.88	0.80

Table 7.9 Mean and standard deviations of the observed and simulated runoff values for both the full record of 1995 and the last 10 days eliminated record of 1995.

Year		**Number of days used for calibration**	**Means**	**Standard Deviations**
Full record of 1995	Observed Runoff	365	0.35	0.73
	Simulated Runoff	365	0.30	0.51
Last 10 days eliminated record of 1995	Observed Runoff	355	0.29	0.55
	Simulated Runoff	355	0.29	0.51

7.7 Verification of DRRSM for Demirci Watershed

In order to test the model performance, verification of the DRRSM for Demirci watershed is realized by using the parameters given in Table 7.6 and the rainfall record of the year 1996. The simulation is carried out by using full record of the year 1996 and the results of the simulation are given in Figure 7.20.

Tables 7.10 and 7.11 give the calibration statistics for the verification period 1996 and the mean and standard deviations of the observed and the simulated runoff values of the Demirci watershed, respectively.

Figure 7.21 also shows all the runoff components which are surface, sub-surface and groundwater runoff during 1996.

Table 7.10 Calibration statistics (D, R, F) calculated for verification period 1996 of Demirci watershed

Verification Year	D	R	F
1996 (N=366)	39	0.87	0.66

Table 7.11 Mean and standard deviations of the observed and simulated runoff values for the verification period 1996.

Year		Number of days used for calibration	Means	Standard Deviations
Full record of 1996	Observed Runoff	366	0.31	0.69
	Simulated Runoff	366	0.31	0.56

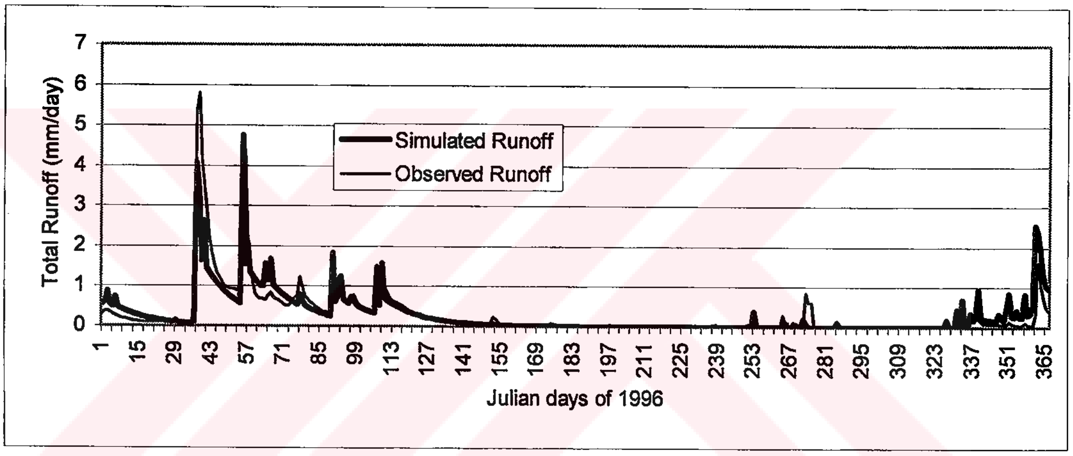


Figure 7.20 Simulated and observed runoff during the verification period 1996

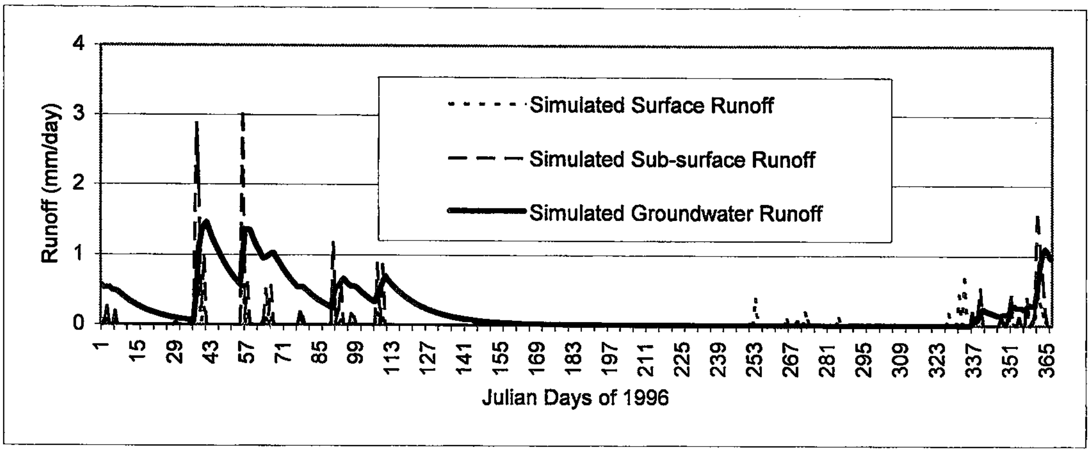


Figure 7.21 Simulated surface, sub-surface and groundwater runoff of Demirci watershed during the 1996.

CHAPTER EIGHT
CONCLUSIONS

8.1 Review

In this thesis, Chapters 2 through 4 include the reviews of the basic concepts in hydrologic modeling and discuss distributed conceptual hydrologic modeling in detail. As these topics are quite new for Turkey, it is aimed to introduce the basics in conceptual modeling.

Chapter 5 states technically the current problems in conceptual modeling and discusses the state-of-the-art in modeling studies in Turkey, starting from data collection to institutional aspects. The lack of data and technical infrastructure, which are the major problems in hydrologic modeling studies, are presented. The inadequacy in data for hydrologic modeling has initiated efforts to develop a new model to be used in Turkey, which has quite reasonable and acceptable results.

Chapter 6 introduces this new model which is developed to use only the rainfall and pan evaporation data collected in Turkey and which needs less data in comparison with the other complex and data-intensive models such as HSPF, MIKE-SHE, and PRMS. The developed model (DRRSM) is an integration of the GIS (Geographical Information Systems) and the hydrologic model and can consider the spatial distribution of watershed properties such as land cover and soil types.

Chapter 7 presents the application of the DRRSM to the Demirci watershed, which is a sub-watershed of the Gediz River basin located in western Turkey. The

GIS data such as topography and land cover information of the Demirci watershed are obtained via internet sources which are easily accessed. Soil types are digitized from proper soil maps scaled 1/200 000. The hydrometeorological data such as daily rainfall and pan evaporation are obtained from the EIE, DSI and DMI. Calibration and verification of the DRRSM for Demirci watershed is presented in this chapter. The results of the DRRSM are quite satisfactory in comparison with the observed runoff.

8.2 Result of DRRSM

DRRSM (Daily Rainfall Runoff Simulation Model) is developed in the scope of this thesis, and applied to the Demirci watershed. The developed model is a distributed, continuous and conceptual hydrologic model with less data requirements compared to other complex models in the market. The model can simulate surface, sub-surface and groundwater runoff from land segments of which all properties such as land cover and soil types are defined in a watershed.

DRRSM has a flexible structure in hydrologic computations. In the current state of the model, it uses simple linear equations for estimating runoff values from the storages on the land segments. However, the user can change the forms of equations to non-linear if desired, since the program is designed by means of independent components and object oriented programming (OOP) techniques. However, changing the equations causes an increase in the number of parameters and makes the model structure divert from a parsimonious model type.

The application of the DRRSM shows that the limited number of parameters and simple forms of equations are quite satisfactory since the spatial distribution of the parameters is considered. In addition, the results of the DRRSM in the Demirci watershed show that the GIS data obtained from the internet sources such as topography and land cover with 1km x 1km resolution can be used for hydrologic analysis and water resources research.

The simulation results of the DRRSM in Demirci watershed indicate that this model can be used for water resources management and research as a tool for identifying the hydrologic processes in the watershed. In addition to that, DRRSM is used to estimate daily runoff volumes in watersheds where there are no flow observations.

As can be seen from Figures 8.1 and 8.2, which present the comparison of the simulated and the observed runoff values of the verification period 1996 in Demirci watershed, the results of the DRRSM can also be used as a data generation tool for stochastic analyses in the water resources management and planning studies to support the decision making process for management and planning.

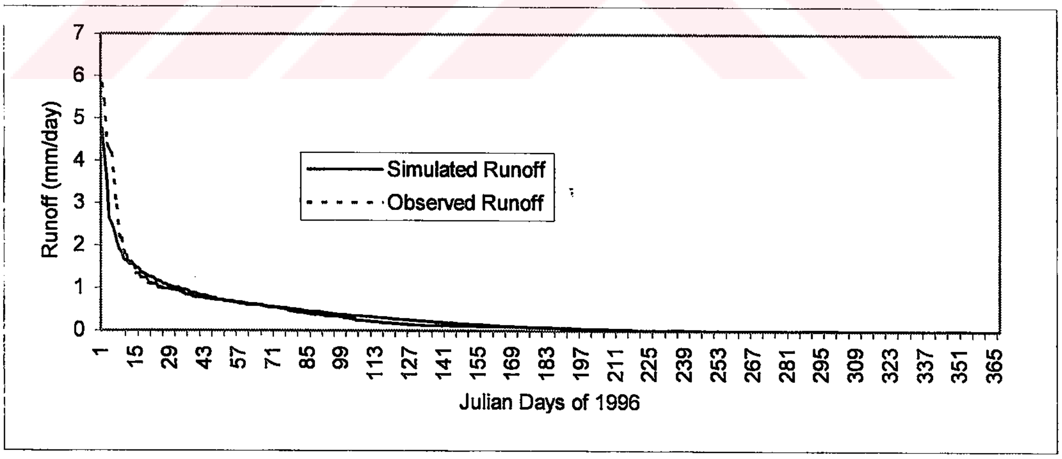


Figure 8.1 Comparison of the observed and simulated runoff values during the verification period 1996 in Demirci watershed.

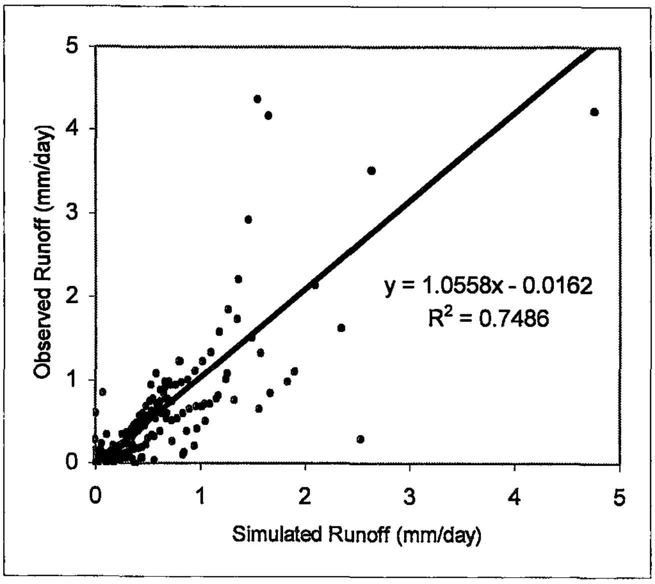


Figure 8.2 Correlation analysis between observed and simulated runoff values values during the verification period 1996 in Demirci watershed.

8.3 Future Studies

There are three future studies which are planned to follow up this thesis. The first one is to develop the snow melt component of the DRRSM which is again planned to be used on data from internet sources such as NOAA (National Oceanic and Atmospheric Administration) satellite images for snow cover. After developing the snow melt component, DRRSM can be applied to every watershed where snow cover exists in Turkey.

The second study planned on the DRRSM is to develop a daily flow routing component for large basins consisting of several medium size watersheds. The flow routing component will be developed in such a way as to read all runoff values simulated from the sub-watersheds and to route them considering main river basin morphology.

The final study planned on the DRRSM is to validate the fully developed model by realizing several simulations in different basins over Turkey. It is clear that this study will require data of several hydrometeorological stations, which implies huge amount of costs and administrative difficulty under the current conditions of Turkey.

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APPENDIX

COMPUTER PROGRAM OF DRRSM

```
Files - 1
Private Sub Command1_Click()
Dim cyberncol(5) As Long
Dim cybernrow(5) As Long
'Raster GIS Files are reading and controlling
On Error GoTo 300
Open Combo1.Text For Input As #1
On Error GoTo 300
Open Combo2.Text For Input As #2
On Error GoTo 300
Open Combo3.Text For Input As #3
On Error GoTo 300
Open Combo4.Text For Input As #4
On Error GoTo 300
Open Combo5.Text For Input As #5
Input #1, cybernrow(1)
Input #1, cyberncol(1)
coun = 0
Do
coun = coun + 1
Input #1, wt(coun)
Loop While Not EOF(1)
If coun <> cyberncol(1) * cybernrow(1) Then
MsgBox ("Error on Watershed File Length")
End If
Input #2, cybernrow(2)
Input #2, cyberncol(2)
coun = 0
Do
coun = coun + 1
Input #2, rn(coun)
Loop While Not EOF(2)
If coun <> cyberncol(2) * cybernrow(2) Then
MsgBox ("Error on Rainfall File Length")
End If
Input #3, cybernrow(3)
Input #3, cyberncol(3)
coun = 0
Do
coun = coun + 1
Input #3, lnd(coun)
Loop While Not EOF(3)
If coun <> cyberncol(3) * cybernrow(3) Then
MsgBox ("Error on Land Cover File Length")
End If
Input #4, cybernrow(4)
Input #4, cyberncol(4)
```

```
coun = 0
Do
coun = coun + 1
Input #4, sl(coun)
Loop While Not EOF(4)
If coun <> cyberncol(4) * cybernrow(4) Then
MsgBox ("Error on Soil Type File Length")
End If
Input #5, cybernrow(5)
Input #5, cyberncol(5)
coun = 0.Files - 2
Do
coun = coun + 1
Input #5, dst(coun)
Loop While Not EOF(5)
If coun <> cyberncol(5) * cybernrow(5) Then
MsgBox ("Error on Distance File Length")
End If
If cyberncol(1) <> cyberncol(2) Or cyberncol(2) <> cyberncol(3) Or
       cyberncol(3) <> cyberncol(
4) Or cyberncol(4) <> cyberncol(5) Then
MsgBox ("Raster GIS File Column Length Conflict")
End If
ncol = cyberncol(5)
If cybernrow(1) <> cybernrow(2) Or cybernrow(2) <> cybernrow(3) Or
       cybernrow(3) <> cybernrow(
4) Or cybernrow(4) <> cybernrow(5) Then
MsgBox ("Raster GIS File Row Length Conflict")
End If
nrow = cybernrow(5)
Command2.Enabled = True
GoTo 200
200
MsgBox ("No Error Captured")
GoTo 400
'MsgBox (ncol)
'MsgBox (nrow)
300 MsgBox ("File Name Error (Missing File Name #1)")
400
Close
End Sub
Private Sub Command2_Click()
Dim cybernodays As Integer
Dim cybernorain As Integer
'Data File are reading and controlling
'On Error GoTo 100
Open Combo6.Text For Input As #6
```

```
Input #6, cybernodays
Input #6, cybernorain
simdays = cybernodays
coun = 0
Do
coun = coun + 1
Input #6, stp(coun), yr(coun), mon(coun), dy(coun)
For i = 1 To cybernorain
Input #6, p(i, coun)
Next i
For i = 1 To cybernorain
Input #6, evap(i, coun)
Next i
Input #6, qobs(coun)
Loop While Not EOF(6)
If coun <> cybernodays Then
MsgBox ("Error on Data File Length")
GoTo 500
End If
GoTo 150
100 MsgBox ("Data File Name Error (Missing File)").Files - 3
GoTo 500
150 'Data files are readed
MsgBox ("No Error on Data File")
'Parameters File are reading and controlling
On Error GoTo 250
Open Combo7.Text For Input As #7
Input #7, nolc
Input #7, nosl
'MsgBox (nolc)
'MsgBox (nosl)
For i = 1 To nolc
Input #7, lcnum
If lcnum <> i Then
MsgBox ("Error in parameter file #1")
GoTo 500
End If
For j = 1 To 12
Input #7, evapcoe(i, j)
Next j: Next i
For i = 1 To nolc
Input #7, lcnum
If lcnum <> i Then
MsgBox ("Error in parameter file #2")
GoTo 500
End If
For j = 1 To 12
```

```
Input #7, detcap(i, j)
Next j: Next i
For i = 1 To nolc
Input #7, lcnum
If lcnum <> i Then
MsgBox ("Error in parameter file #3")
GoTo 500
End If
For j = 1 To 12
Input #7, alfa(i, j)
Next j: Next i
For i = 1 To nosl
Input #7, slnum
If slnum <> i Then
MsgBox ("Error in parameter file #4")
GoTo 500
End If
Input #7, beta(i), gamma(i), smin(i), smax(i), deep(i)
Next i
For i = 1 To nolc
Input #7, lcnum
If lcnum <> i Then
MsgBox ("Error in parameter file #5")
GoTo 500
End If
Input #7, detini(i)
Next i
For i = 1 To nosl
Input #7, slnum
If slnum <> i Then
MsgBox ("Error in parameter file #6")
GoTo 500
End If.Files - 4
Input #7, sini(i), gwini(i)
Next i
Input #7, cont$
'Stop
If cont$ <> "END" Then
MsgBox ("Error in Parameters File #7")
GoTo 500
End If
GoTo 300
250 MsgBox ("Parameters File Name Error (Missing File)")
GoTo 500
300 'Parameters file are readed
MsgBox ("No Error on Parameters File")
500
```

```
Close
End Sub
Private Sub Command3_Click()
'Merged image is creating
k = 1
For i = 1 To nrow
For j = 1 To ncol
mrg(i, j) = Val(Str(wt(k)) + Str(rn(k)) + Str(lnd(k)) + Str(sl(k)) +
       Str(dst(k)))
k = k + 1
Next j: Next i
k = 1: nk = 1
cntr = 1
For i = 1 To nrow
For j = 1 To ncol
If mrg(i, j) = 0 Then
m(i, j) = 0
GoTo 1000
End If
If cntr = 1 Then
typ(k) = mrg(i, j)
m(i, j) = k
cntr = cntr + 1
GoTo 1000
End If
For t = 1 To nk
'if mrg(i,j) is an existing type
If mrg(i, j) = typ(t) Then
m(i, j) = t
GoTo 1000
End If
Next t
'if mrg(i,j) is a new type
m(i, j) = nk + 1
typ(nk + 1) = mrg(i, j)
nk = nk + 1
1000 Next j
Next i.Files - 5
'm(i,j) is classified image that refer to SHRU
'mrg(i,j) is original merged image
'typ(nk) is SHRU type obtained from mrg(i,j) image
'For k = 1 To nk
'MsgBox (typ(k))
'Next k
Dim npor(100) As Long
For k = 0 To nk
'nzero = 0
```

```
npor(k) = 0
For i = 1 To nrow
For j = 1 To ncol
'If m(i, j) = 0 Then
'nzero = nzero + 1
'End If
If m(i, j) = k Then
npor(k) = npor(k) + 1
End If
Next j: Next i: Next k
ntop = 0
For k = 0 To nk
ntop = ntop + npor(k)
Next k
If ntop <> nrow * ncol Then
MsgBox "Error in sum of cell"
MsgBox (ntop)
MsgBox (ncol * nrow)
End If
For k = 1 To nk
por(k) = npor(k) / (ntop - npor(0))
Next k
Unload Files
Parameters.Show
End Sub
Private Sub Command4_Click()
Unload Files
System.Show
End Sub
Private Sub Form_Load()
Command2.Enabled = False
'Command3.Enabled = False
File1.Path = systempath
'For Combo1 list
File1.Pattern = "*.img"
For i = 0 To File1.ListCount
Combo1.AddItem File1.List(i), i
Next i
'For Combo2 list
File1.Pattern = "*.img"
For i = 0 To File1.ListCount
Combo2.AddItem File1.List(i), i
Next i.Files - 6
'For Combo3 list
File1.Pattern = "*.img"
For i = 0 To File1.ListCount
Combo3.AddItem File1.List(i), i
```

```
Next i
'For Combo4 list
File1.Pattern = "*.img"
For i = 0 To File1.ListCount
Combo4.AddItem File1.List(i), i
Next i
'For Combo5 list
File1.Pattern = "*.img"
For i = 0 To File1.ListCount
Combo5.AddItem File1.List(i), i
Next i
'For Combo6 list
File1.Pattern = "*.dat"
For i = 0 To File1.ListCount
Combo6.AddItem File1.List(i), i
Next i
'For Combo7 list
File1.Pattern = "*.par"
For i = 0 To File1.ListCount
Combo7.AddItem File1.List(i), i
Next i
End Sub.Graphics - 1
Private Sub Command1_Click()
'Dim p(1000) As Single
'Dim s(1000) As Single
'Dim ss(1000) As Single
'Dim gw(1000) As Single
'Dim q(1000) As Single
'For i = 1 To 1000
'p(i) = Int(Rnd * 10)
's(i) = p(i) / 3
'ss(i) = p(i) / 6
'gw(i) = p(i) / 10
'q(i) = s(i) + ss(i) + gw(i)
'Next i
'Grafik çizdirilmesi ile ilgili bölüm
MSChart1.ColumnCount = 5
MSChart1.RowCount = Val(Text2.Text) - Val(Text1.Text) + 1
If Check1.Value = 1 Then
MSChart1.Column = 1
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = qsur(j)
Next j
Else
MSChart1.Column = 1
```

```
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = 0
Next j
End If
If Check2.Value = 1 Then
MSChart1.Column = 2
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = qsub(j)
Next j
Else
MSChart1.Column = 2
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = 0
Next j
End If
If Check3.Value = 1 Then
MSChart1.Column = 3
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = qgro(j)
Next j
Else
MSChart1.Column = 3
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1.Graphics - 2
MSChart1.RowLabel = j
MSChart1.Data = 0
Next j
End If
If Check4.Value = 1 Then
MSChart1.Column = 4
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = qbasin(j)
Next j
Else
MSChart1.Column = 4
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
```

```
MSChart1.RowLabel = j
MSChart1.Data = 0
Next j
End If
If Check5.Value = 1 Then
MSChart1.Column = 5
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = qobs(j)
Next j
Else
MSChart1.Column = 5
For j = Val(Text1.Text) To Val(Text2.Text)
MSChart1.Row = j - Val(Text1.Text) + 1
MSChart1.RowLabel = j
MSChart1.Data = 0
Next j
End If
'Grafik çizdirilmesi ile ilgili bölümün sonu
'MSChart1.ColumnCount = 1
'MSChart1.RowCount = Val(Text2.Text) - Val(Text1.Text) + 1
'MSChart1.Column = 1
'k = 0
'For j = Val(Text1.Text) To Val(Text2.Text)
'MSChart1.Row = k + 1
'MSChart1.RowLabel = j
'MSChart1.Data = q(j)
'Next j
Err = 0: toprr = 0
topobs = 0: topbasin = 0: ntop = 0
For i = Val(Text1.Text) To Val(Text2.Text)
Err = Err + (qobs(i) - qbasin(i)) ^ 2
topbasin = topbasin + qbasin(i)
topobs = topobs + qobs(i)
ntop = ntop + 1
toprr = toprr + (qobs(i) * qbasin(i))
Next i
Text3.Text = Err
'Mean Values
ortbasin = topbasin / ntop.Graphics - 3
ortobs = topobs / ntop
'Standart Deviations
Err2 = 0
For i = Val(Text1.Text) To Val(Text2.Text)
topstbasin = topstbasin + (qbasin(i) - ortbasin) ^ 2
topstobs = topstobs + (qobs(i) - ortobs) ^ 2
```

```
Err2 = Err2 + (qbasin(i) - ortbasin) ^ 2
Next i
stbasin = Sqr((1 / ntop) * topstbasin)
stobs = Sqr((1 / ntop) * topstobs)
'Correlation
'For i = Val(Text1.Text) To Val(Text2.Text)
'topr = topr + ((qbasin(i) - ortbasin) / stbasin) * ((qobs(i) -
       ortobs) / stobs)
'Next i
rr = (toprr - ntop * ortbasin * ortobs) / (ntop * stbasin * stobs)
'Calibration Parameter
ff = 1 - Err / Err2
Text6.Text = ortobs
Text7.Text = ortbasin
Text8.Text = stobs
Text9.Text = stbasin
Text10.Text = rr
Text11.Text = ff
End Sub
Private Sub Command2_Click()
Parameters.Show
End Sub
Private Sub Command3_Click()
For i = Val(Text1.Text) To Val(Text2.Text)
ii = i - Val(Text4.Text)
If ii < 0 Then ii = 0
iii = i - Val(Text5.Text)
If iii < 0 Then iii = 0
qbasin(i) = qsur(i) + qsub(ii) + qgro(iii)
Next i
MsgBox ("Click Display Button")
End Sub
Private Sub Form_Load()
Text1.Text = 1
Text2.Text = simdays
Label4.Caption = simdays
Text3.Text = ""
Text4.Text = 0
Text5.Text = 0
End Sub.Parameters - 1
Private Sub Command1_Click()
File1.Refresh
fpar$ = InputBox("Please enter a file name (give extention *.par)")
On Error GoTo 1000
Open fpar$ For Output As #1
'nolc = 3: nosl = 4
'Printing file evapcoe
```

```
Print #1, nolc, nosl
For i = 1 To nolc
Print #1, i;
MSFlexGrid1.Row = i
For j = 1 To 12
MSFlexGrid1.Col = j
If j = 12 Then
Print #1, MSFlexGrid1.Text
GoTo 100
End If
Print #1, MSFlexGrid1.Text; " ";
100 Next j
Next i
'Printing file detcap
For i = 1 To nolc
Print #1, i;
MSFlexGrid2.Row = i
For j = 1 To 12
MSFlexGrid2.Col = j
If j = 12 Then
Print #1, MSFlexGrid2.Text
GoTo 200
End If
Print #1, MSFlexGrid2.Text; " ";
200 Next j
Next i
'Printing file alfa
For i = 1 To nolc
Print #1, i;
MSFlexGrid3.Row = i
For j = 1 To 12
MSFlexGrid3.Col = j
If j = 12 Then
Print #1, MSFlexGrid3.Text
GoTo 300
End If
Print #1, MSFlexGrid3.Text; " ";
300 Next j
Next i
'Printing file beta, gama, smin,smax,deep
For i = 1 To nosl
Print #1, i;
MSFlexGrid4.Row = i
For j = 1 To 5
MSFlexGrid4.Col = j
If j = 5 Then
Print #1, MSFlexGrid4.Text
```

```
GoTo 400
End If
Print #1, MSFlexGrid4.Text; " ";
400 Next j
Next i
'Printing initial conditions
'detini
For i = 1 To nolc.Parameters - 2
Print #1, i;
MSFlexGrid5.Row = i
MSFlexGrid5.Col = 1
Print #1, MSFlexGrid5.Text
Next i
'ssini gwini
For i = 1 To nosl
Print #1, i;
MSFlexGrid6.Row = i
MSFlexGrid6.Col = 1
Print #1, MSFlexGrid6.Text; " ";
MSFlexGrid6.Col = 2
Print #1, MSFlexGrid6.Text
Next i
Print #1, "END"
Close #1
1000
End Sub
Private Sub Command2_Click()
'Reading parameters
'nolc = 3
'nosl = 4
'reading evapcoe
For i = 1 To nolc
MSFlexGrid1.Row = i
For j = 1 To 12
MSFlexGrid1.Col = j
evapcoe(i, j) = Val(MSFlexGrid1.Text)
Next j
Next i
'reading detcap
For i = 1 To nolc
MSFlexGrid2.Row = i
For j = 1 To 12
MSFlexGrid2.Col = j
detcap(i, j) = Val(MSFlexGrid2.Text)
Next j
Next i
'reading alfa
```

```
For i = 1 To nolc
MSFlexGrid3.Row = i
For j = 1 To 12
MSFlexGrid3.Col = j
alfa(i, j) = Val(MSFlexGrid3.Text)
Next j
Next i
'Reading beta, gama,smin,smax,deep
For i = 1 To nosl
MSFlexGrid4.Row = i
MSFlexGrid4.Col = 1
beta(i) = Val(MSFlexGrid4.Text)
MSFlexGrid4.Col = 2
gamma(i) = Val(MSFlexGrid4.Text)
MSFlexGrid4.Col = 3
smin(i) = Val(MSFlexGrid4.Text)
MSFlexGrid4.Col = 4
smax(i) = Val(MSFlexGrid4.Text)
MSFlexGrid4.Col = 5
deep(i) = Val(MSFlexGrid4.Text).Parameters - 3
Next i
'Reading initial conditions
'detini
For i = 1 To nolc
MSFlexGrid5.Row = i
MSFlexGrid5.Col = 1
detini(i) = Val(MSFlexGrid5.Text)
Next i
'ssini and gwini
For i = 1 To nosl
MSFlexGrid6.Row = i
MSFlexGrid6.Col = 1
sini(i) = Val(MSFlexGrid6.Text)
MSFlexGrid6.Col = 2
gwini(i) = Val(MSFlexGrid6.Text)
Next i
'Buraya sýnýflanmýþ Similar Hydrologic Response Unitesler Geliyo
For i = 1 To nk
frst = Left(typ(i), 1)
'MsgBox (frst)
If frst <> 1 Then
MsgBox ("Error in watershed number Error#1")
GoTo 1000
End If
scnd = Right(Left(typ(i), 2), 1)
'MsgBox (scnd)
thrd = Right(Left(typ(i), 3), 1)
```

```
'MsgBox (thrd)
frth = Right(Left(typ(i), 4), 1)
'MsgBox (frth)
ffth = Right(Left(typ(i), 5), 1)
'MsgBox (ffth)
For j = 1 To simdays
'stp(j), yr(j), mon(j), dy(j)
'p(scnd, j)
'evap(scnd, j)
'qobs (j)
'evapcoe(scnd,mon(j))
eto(thrd, j) = evap(scnd, j) * evapcoe(scnd, mon(j))
'detcap(thrd,mon(j))
'alfa(thrd,mon(j))
'beta(frth)
'gamma(frth)
'smin(frth)
'smax(frth)
'deep(frth)
Dim ddetini(100, 3650), ddetend(100, 3650) As Single
Dim ssini(100, 3650), ssend(100, 3650) As Single
Dim ggwini(100, 3650), ggwend(100, 3650) As Single
ddetend(thrd, 0) = detini(thrd)
ssend(frth, 0) = sini(frth)
ggwend(frth, 0) = gwini(frth)
ddetini(thrd, j) = ddetend(thrd, j - 1)
ssini(frth, j) = ssend(frth, j - 1).Parameters - 4
ggwini(frth, j) = ggwend(frth, j - 1)
Call hydromod(p(scnd, j), eto(thrd, j), detcap(thrd, mon(j)),
       smin(frth), smax(frth), ddetini
(thrd, j), ssini(frth, j), ggwini(frth, j), alfa(thrd, mon(j)),
       beta(frth), gamma(frth), deep
(frth), ddetend(thrd, j), ssend(frth, j), ggwend(frth, j), inf(i,
       j), per(i, j), qs(i, j), qs
s(i, j), qgw(i, j))
qtot(i, j) = (qs(i, j) + qss(i, j) + qgw(i, j)) * por(i) 'grafik
       formunda hesaplanabilir
Next j
Next i
'qsur(1) = 0: qsub(1) = 0: qgro(1) = 0: qbasin(1) = 0
For j = 1 To simdays
qsur(j) = 0: qsub(j) = 0: qgro(j) = 0: qbasin(j) = 0
For i = 1 To nk
qsur(j) = qsur(j) + qs(i, j) * por(i)
qsub(j) = qsub(j) + qss(i, j) * por(i)
qgro(j) = qgro(j) + qgw(i, j) * por(i)
qbasin(j) = qbasin(j) + qtot(i, j)
```

```
Next i: Next j
MsgBox ("Computations were completed!!!!")
Graphics.Show
'Unload Parameters
1000
End Sub
Private Sub Command3_Click()
Files.Show
End Sub
Private Sub Form_Load()
'Dim evapcoe(10, 12) As Single
'Dim detcap(10, 12) As Single
'Dim alfa(10, 12) As Single
'Dim beta(10) As Single
'Dim gama(10) As Single
'Dim smin(10) As Single
'Dim smax(10) As Single
'Dim deep(10) As Single
'Dim nolc As Integer
'nolc = 3 burasý ana programda deðiþken olacak tüm nesnelere bak
'Dim nosl As Integer
'nosl = 4
'EvapCoe Parameters
MSFlexGrid1.Cols = 13
MSFlexGrid1.Rows = nolc + 1
For i = 0 To 12
MSFlexGrid1.ColWidth(i - 1) = 600
Next i
MSFlexGrid1.Col = 0
MSFlexGrid1.Row = 0
MSFlexGrid1.Text = "EC"
For i = 1 To nolc
MSFlexGrid1.Col = 0
MSFlexGrid1.Row = i
MSFlexGrid1.Text = i
Next i.Parameters - 5
For i = 1 To 12
MSFlexGrid1.Row = 0
MSFlexGrid1.Col = i
MSFlexGrid1.Text = i
Next i
For i = 1 To nolc
For j = 1 To 12
MSFlexGrid1.Row = i
MSFlexGrid1.Col = j
MSFlexGrid1.Text = evapcoe(i, j)
Next j: Next i
```

```
'DetCap Parameters
MSFlexGrid2.Cols = 13
MSFlexGrid2.Rows = nolc + 1
For i = 0 To 12
MSFlexGrid2.ColWidth(i - 1) = 600
Next i
MSFlexGrid2.Col = 0
MSFlexGrid2.Row = 0
MSFlexGrid2.Text = "DC"
For i = 1 To nolc
MSFlexGrid2.Col = 0
MSFlexGrid2.Row = i
MSFlexGrid2.Text = i
Next i
For i = 1 To 12
MSFlexGrid2.Row = 0
MSFlexGrid2.Col = i
MSFlexGrid2.Text = i
Next i
For i = 1 To nolc
For j = 1 To 12
MSFlexGrid2.Row = i
MSFlexGrid2.Col = j
MSFlexGrid2.Text = detcap(i, j)
Next j: Next i
'Alfa Parameters
MSFlexGrid3.Cols = 13
MSFlexGrid3.Rows = nolc + 1
For i = 0 To 12
MSFlexGrid3.ColWidth(i - 1) = 600
Next i
MSFlexGrid3.Col = 0
MSFlexGrid3.Row = 0
MSFlexGrid3.Text = "Alfa"
For i = 1 To nolc
MSFlexGrid3.Col = 0
MSFlexGrid3.Row = i
MSFlexGrid3.Text = i
Next i
For i = 1 To 12.Parameters - 6
MSFlexGrid3.Row = 0
MSFlexGrid3.Col = i
MSFlexGrid3.Text = i
Next i
For i = 1 To nolc
For j = 1 To 12
MSFlexGrid3.Row = i
```

```
MSFlexGrid3.Col = j
MSFlexGrid3.Text = alfa(i, j)
Next j: Next i
'Beta, Gama, Smin, Smax, Deep parameters
MSFlexGrid4.Cols = 6
MSFlexGrid4.Rows = nosl + 1
For i = 0 To 6
MSFlexGrid4.ColWidth(i - 1) = 600
Next i
MSFlexGrid4.Col = 0
MSFlexGrid4.Row = 0
MSFlexGrid4.Text = "Soil"
For i = 1 To nosl
MSFlexGrid4.Col = 0
MSFlexGrid4.Row = i
MSFlexGrid4.Text = i
Next i
MSFlexGrid4.Row = 0
MSFlexGrid4.Col = 1
MSFlexGrid4.Text = "Beta"
MSFlexGrid4.Col = 2
MSFlexGrid4.Text = "Gama"
MSFlexGrid4.Col = 3
MSFlexGrid4.Text = "Smin"
MSFlexGrid4.Col = 4
MSFlexGrid4.Text = "Smax"
MSFlexGrid4.Col = 5
MSFlexGrid4.Text = "Deep"
For i = 1 To nosl
MSFlexGrid4.Col = 1
MSFlexGrid4.Row = i
MSFlexGrid4.Text = beta(i)
Next i
For i = 1 To nosl
MSFlexGrid4.Col = 2
MSFlexGrid4.Row = i
MSFlexGrid4.Text = gamma(i)
Next i
For i = 1 To nosl
MSFlexGrid4.Col = 3
MSFlexGrid4.Row = i
MSFlexGrid4.Text = smin(i)
Next i
For i = 1 To nosl
MSFlexGrid4.Col = 4
MSFlexGrid4.Row = i
MSFlexGrid4.Text = smax(i).Parameters - 7
```

```
Next i
For i = 1 To nosl
MSFlexGrid4.Col = 5
MSFlexGrid4.Row = i
MSFlexGrid4.Text = deep(i)
Next i
'initial conditions
'detini
MSFlexGrid5.Cols = 2
MSFlexGrid5.Rows = nolc + 1
MSFlexGrid5.ColWidth(0) = 600
MSFlexGrid5.Col = 1
MSFlexGrid5.Row = 0
MSFlexGrid5.Text = "DETini"
MSFlexGrid5.Col = 0
MSFlexGrid5.Row = 0
MSFlexGrid5.Text = "Initial"
For i = 1 To nolc
MSFlexGrid5.Col = 0
MSFlexGrid5.Row = i
MSFlexGrid5.Text = i
Next i
For i = 1 To nolc
MSFlexGrid5.Col = 1
MSFlexGrid5.Row = i
MSFlexGrid5.Text = detini(i)
Next i
'ssini and gwini
MSFlexGrid6.Cols = 3
MSFlexGrid6.Rows = nosl + 1
MSFlexGrid4.ColWidth(0) = 600
MSFlexGrid6.Col = 0
MSFlexGrid6.Row = 0
MSFlexGrid6.Text = "Initials"
MSFlexGrid6.Col = 1
MSFlexGrid6.Row = 0
MSFlexGrid6.Text = "SSini"
MSFlexGrid6.Col = 2
MSFlexGrid6.Row = 0
MSFlexGrid6.Text = "GWini"
For i = 1 To nosl
MSFlexGrid6.Col = 0
MSFlexGrid6.Row = i
MSFlexGrid6.Text = i
Next i
For i = 1 To nosl
MSFlexGrid6.Col = 1
```

```
MSFlexGrid6.Row = i
MSFlexGrid6.Text = sini(i)
MSFlexGrid6.Col = 2
MSFlexGrid6.Row = i
MSFlexGrid6.Text = gwini(i).Parameters - 8
Next i
End Sub
Private Sub MSFlexGrid1_KeyDown(KeyCode As Integer, Shift As
       Integer)
If KeyCode = 46 Then
MSFlexGrid1.Text = ""
End If
End Sub
Private Sub MSFlexGrid1_KeyPress(KeyAscii As Integer)
MSFlexGrid1.Text = MSFlexGrid1.Text + Chr(KeyAscii)
End Sub
Private Sub MSFlexGrid2_KeyDown(KeyCode As Integer, Shift As
       Integer)
If KeyCode = 46 Then
MSFlexGrid2.Text = ""
End If
End Sub
Private Sub MSFlexGrid2_KeyPress(KeyAscii As Integer)
MSFlexGrid2.Text = MSFlexGrid2.Text + Chr(KeyAscii)
End Sub
Private Sub MSFlexGrid3_KeyDown(KeyCode As Integer, Shift As
       Integer)
If KeyCode = 46 Then
MSFlexGrid3.Text = ""
End If
End Sub
Private Sub MSFlexGrid3_KeyPress(KeyAscii As Integer)
MSFlexGrid3.Text = MSFlexGrid3.Text + Chr(KeyAscii)
End Sub
Private Sub MSFlexGrid4_KeyDown(KeyCode As Integer, Shift As
       Integer)
If KeyCode = 46 Then
MSFlexGrid4.Text = ""
End If
End Sub
Private Sub MSFlexGrid4_KeyPress(KeyAscii As Integer)
MSFlexGrid4.Text = MSFlexGrid4.Text + Chr(KeyAscii)
End Sub
Private Sub MSFlexGrid5_KeyDown(KeyCode As Integer, Shift As
       Integer)
If KeyCode = 46 Then
MSFlexGrid5.Text = ""
End If
```

```
End Sub
Private Sub MSFlexGrid5_KeyPress(KeyAscii As Integer)
MSFlexGrid5.Text = MSFlexGrid5.Text + Chr(KeyAscii)
End Sub
Private Sub MSFlexGrid6_KeyDown(KeyCode As Integer, Shift As
       Integer)
If KeyCode = 46 Then
MSFlexGrid6.Text = ""
End If.Parameters - 9
End Sub
Private Sub MSFlexGrid6_KeyPress(KeyAscii As Integer)
MSFlexGrid6.Text = MSFlexGrid6.Text + Chr(KeyAscii)
End Sub
Private Function hydromod(pmod, etomod, detcapmod, sssminmod,
       sssmaxmod, detinimod, sssinimod
, gwinimod, alfamod, betamod, gamamod, deepmod, detendmod,
       sssendmod, gwendmod, infmod, permo
d, qsmod, qssmod, qgwmod)
detendmod = detinimod + pmod - etomod
Select Case detendmod
Case Is < 0
ets = etomod - (detinimod + pmod)
etssp = sssinimod - sssminmod
If ets < etssp Then
et = etomod
sssendmod = sssinimod - ets
infmod = 0
permod = 0
qsmod = 0
qssmod = 0
Else
et = pmod + detinimod + etssp
sssendmod = sssminmod
infmod = 0
permod = 0
qsmod = 0
qssmod = 0
End If
detendmod = 0
GoTo 100 'Enson olarak ilave edildi....
'Case Is = 0
'et = etomod
'sssendmod = sssinimod
'infmod = 0
'permod = 0
'qsmod = 0
'qssmod = 0
```

```
'Case Is < detcapmod
'et = etomod
'sssendmod = sssinimod
'infmod = 0
'permod = 0
'qsmod = 0
'qssmod = 0
Case Is <= detcapmod 'yukarýdaki remleri kaldýrýrsan < iþareti
       kalkacak
et = etomod
sssendmod = sssinimod
infmod = 0
permod = 0
qsmod = 0
qssmod = 0
Case Is > detcapmod
detendmod = detcapmod
et = etomod
qsmod = alfamod * (detinimod + pmod - et - detcapmod)
infmod = (1 - alfamod) * (detinimod + pmod - et - detcapmod)
sssendmod = sssinimod + infmod
If sssendmod > sssmaxmod Then
sssendmod = sssmaxmod
qssmod = betamod * (sssinimod + infmod - sssmaxmod)
permod = (1 - betamod) * (sssinimod + infmod - sssmaxmod).Parameters
       - 10
Else
qssmod = 0
permod = 0
End If
End Select
100 'en son olarak ilave edildi......
gwendmod = (gwinimod + permod - gamamod * gwinimod / 2) / (1 +
       gamamod / 2)
If gwendmod < 0 Then gwendmod = 0
qgwmod = gamamod * (1 - deepmod) * (gwinimod + gwendmod) / 2
End Function.Start - 1
Private Sub Command1_Click()
Unload Start
System.Show
End Sub.System - 1
Private Sub Command1_Click()
systempath = CurDir
Files.Show
Unload System
End Sub
Private Sub Dir1_Change()
```

```
ChDir (Dir1.Path)
Label1.Caption = CurDir
File1.Path = CurDir
End Sub
Private Sub Drive1_Change()
ChDrive (Drive1.Drive)
Dir1.Path = Drive1.Drive
End Sub
Private Sub Form_Load()
Label1.Caption = CurDir
End Sub.MainModule - 1
Global systempath As String 'path of file system
Global ncol As Long 'number of colums
Global nrow As Long 'number of rows
Global wt(45000) As Integer
Global rn(45000) As Integer
Global lnd(45000) As Integer
Global sl(45000) As Integer
Global dst(45000) As Single
Global stp(3650), yr(3650), mon(3650), dy(3650) As Single
Global p(5, 3650), evap(5, 3650), qobs(3650) As Single
Global eto(10, 3650) As Single
Global evapcoe(10, 12), detcap(10, 12) As Single
Global alfa(10, 12), beta(10), gamma(10), deep(10) As Single
Global smin(10), smax(10) As Single
Global detini(10), sini(10), gwini(10) As Single
Global mrg(300, 300) As Long
Global m(300, 300) As Integer
Global typ(100) As Long 'Types of classification
Global nk As Integer 'Number of classified overlayed image
Global por(100) As Single
Global nolc As Integer
Global nosl As Integer
Global simdays As Integer
Global inf(100, 3650), per(100, 3650) As Single
Global qs(100, 3650), qss(100, 3650), qgw(100, 3650), qtot(100,
       3650) As Single
Global qsur(3650), qsub(3650), qgro(3650), qbasin(3650) As Single
```